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7th AIVC Conference

Occupant Interaction with Ventilation Systems

Proceedings

Air Infiltration and Ventilation Centre
Old Bracknell Lane West, Bracknell,
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Annex V Air Infiltration and Ventilation Centre

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7th AIC Conference

Occupant Interaction with Ventilation Systems

(held at Moat House International Hotel,
Stratford-upon-Avon, UK
29 September – 2 October 1986)

Proceedings

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Programme was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

The International Energy Agency sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, etc. The differences and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

Annex V Air Infiltration and Ventilation Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration and Ventilation Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and based on a knowledge of work already done to give direction and firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
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PAPER 1

REQUIREMENTS FOR ADEQUATE AND USER-ACCEPTABLE VENTILATION INSTALLATIONS IN DWELLINGS

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SYNOPSIS

Before 1970 the ventilation of dwellings was considered a thing hardly worth thinking of, because it took place more-or less satisfactorily in the then generally rather un-tight buildings. Besides, far lower numbers and quantities of hazardous chemicals were employed in building materials and households then than they are today, and measuring techniques were not developed.

After the oil crisis of 1973, ventilation was discovered as a main source of energy losses. Consequently, strong efforts were made and successes could be claimed in reducing the ventilation losses through airtightening of the buildings.

The next phase in the ventilation scene - the one in which we still find ourselves today - brought up the additional topics of hygienic indoor air quality and condensation problems. Control of both problem areas requires action on two fronts: on one side against any avoidable inside pollution sources and on the other side against excessively low ventilation rates.

After years of intensive studies on indoor air pollution sources, pollution levels, condensation effects, building airtightness, and air change rates, we are now at the point to discover that no solution whatsoever to the ventilation problem is possible if compatibility with user comfort and user habits are not properly taken into account. User compatibility of a ventilation strategy under todays conditions in dwellings must in fact be understood as a requirement equivalent to the purely functional ones of pollutant removal and of economy.

It is tried in this paper to summarize on the general requirements for user compatibility, the latter having been widely neglected so far. Features of improved systems are given.

1. FUNCTIONAL ADEQUACY

A ventilation system - be it of the natural or of the mechanical kind -must be functional, that means it should fulfill its duties properly. Some of the duties are in competition with each other, so that compromises are to be made.

First of all there are the requirements which are the <u>very justification for ventilation</u> at all:

1. fresh air supply to occupants
2. removal of pollutants
3. dehumidification
4. combustion air supply (if applicable)
5. odour removal.

Then there are "secondary" functional requirements, aimed at making ventilation <u>affordable and feasible:</u>

6. energy conservation
7. cost effectiveness
8. retrofit ability.

The first group of requirements is satisfied all the better of course, the higher an air change rate is established. For the second group the contrary is true.

But the air change rate is only one parameter of influence on the removal of harmful or unwanted components in the room air. The second parameter is the air circulation pattern in a ventilated space. In the mechanically ventilated space of fig. 1a for instance, rather good mixing of the space air is obtained, providing equal pollutant distribution at any point in the space. With pattern b, and the same flow rate, most of the ventilation air bypasses the lower part of the space, failing to remove pollutants originating from there. In fig. 1c, a displacement-like ventilation pattern is obtained resulting in very good <u>pollutant removal effectiveness</u> for all locations in the <u>space which are not lying downstream</u> of a pollution source, a point which is to be elaborated on an individual basis in the particular case.

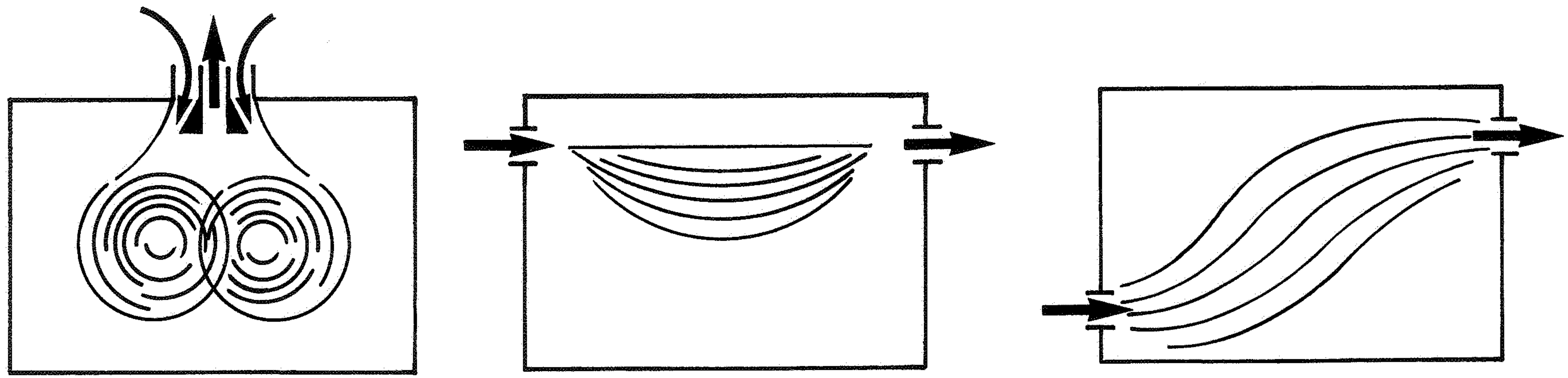
The common definition for the pollutant removal effectiveness is illustrated e.g. by Sandberg (1):

$$\varepsilon = \frac{\text{overconcentration exhaust air}}{\text{overconcentration entering air}} = \frac{C_e - C_o}{C_{ri} - C_o}$$

The indices of C mean:

e	exhaust air
o	outside air
r_i	room air at location i in the space.

For case a (complete mixing) $\varepsilon = 1$ is obtained: Ventilation schemes today in use show a rather poor effec-



a) b) c)

Figure 1: Different ventilation systems result in different ventilation efficiencies

tiveness (this holds true not only for window ventilation), ranging often around 1 or below.

Ventilation effectiveness is **the** key to systems compatible with both requirements 1 ... 5 (pollutant removal and fresh air supply) and 6 ... 7 (energy and cost economy). It deserves far more attention than it is generally paid today, and offers ample room for the development of more effective systems. AIC Technical Note 17 (2) gives a good resumeê and bibliography on ventilation strategies though it does not include publications after 1983 such as e.g. (3) or (5).

Another important point with any improved ventilation system is retrofitability. In Germany for instance, the average age of a residential building is about 70 years. Therefore if real progress is to be made in the ventilation scenario within a foreseeable future, high priority must be given to retrofits.

In dwellings equipped with flued combustion appliances (fireplaces, stoves, gas boilers etc.) compatibility of those appliances with the ventilation system is to be established. No extract-only ventilation is then allowed (not even a range hood!) and the building envelope untightness should be at least in the order of 15 m^3/h at 50 Pa per kW heating load of a stove (open fireplaces require a considerably higher untightness).

A particular case are radon emissions from the soil. No mechanical extract-only ventilation systems are allowed in such cases. Instead, slightly overpressured combined exhaust and supply systems will perform best and prevent radon from entering the ventilated space.

2. USER COMPATIBILITY

Functional adequacy of a ventilation system is one requirement, but as already outlined, user compatibility is a necessary completion. Experiences within the German research programm "Ventilation in Residential Buildings" ("Lüftung im Wohnungsbau") (4) and with other investigations have shown, that there is indeed a high probability of inhabitants rejecting or of conteracting ventilation systems which do not comply with users expectations.

Regarding user compatibility, rather low marks had to be given to most natural and mechanical ventilation systems. Natural ventilation requires to much attendance and offers poor control options. Main complaints of nearly every mechanical system concerned noise and draught.

The following requirements are to be satisfied in order to comply with users expectations:

9. avoidance of draught effects
10. tolerance of ill-attendance
11. minimal maintenance requirements
12. low noise level
13. freedom to interfere
14. familiarisation with a system

Requirements 13 and 14 refer to psychological rather than to physical sensations of a user, which nevertheless are often decisive for acceptance or rejection of a system:

- the user should never feel oppressed by a ventilation system, but always have the feeling of freedom of interference

- the great majority of people are rather conservative in their habits, thus appropriate instruction and motivation is a must with any new techniques.

Requirements particularly critical with natural ventilation systems are (in the order of importance) 10, 9, 11, whilst with mechanical systems 9, 12, 14, 13, 11 have priority.

3. FEATURES OF IMPROVED NATURAL VENTILATION SYSTEMS

In the previous section on functional adequacy it was shown that maximizing ventilation effectiveness is the most promising option to reconcile the contradictory requirements of pollutant removal and economy. Because maximizing ventilation effectiveness allows air exchange rates to be reduced, and because draught and noise effects have a strong correlation with flow rates, user compatibility too benefits from improved ventilation effectiveness. Indeed: **for the design of any ventilation system its effectiveness is of ultimate significance** under almost every aspect and should be given first priority.

Tolerance of ill-attendance is a hard task to fulfill with natural ventilation systems, if energy economy is to be observed. Some kind of automatic control of the opening cross sections seems unavoidable (controlled natural ventilation). In its simplest form this could mean windows or ventilation openings controlled by the outside temperature. Probably better would be a feedback control system with the humidity (in dwellings) or carbon dioxide (CO_2) (in public buildings) as controlled variables.

If automatic control is considered too much an expense but users proper attendance expected to be a thing one can count on (previous experience does not prove that), considerable improvement on the opening mechanisms of present natural ventilation devices and intensive instruction campaigns to the public on adequate ventilation behaviour will be a prerequisite.

Improved natural ventilation systems should have the following features:

- windows or ventilation openings should be located so that displacement ventilation is supported and no draught felt in the main occupational zone of rooms

- preferably automatic control of the opening cross section of at least one ventilation device should be provided; outside temperature or (better) humidity or CO_2 should be the controlled variable

- manual control of the opening cross section to be provided in discrete steps with markers specifying the room size ventilatable under reference conditions in the respective position

- ventilation openings to be arranged always in pairs, with maximum vertical distance (one above floor, one under ceiling) to exploit the stack effect in the absence of wind as driving force

- contamination effects of ventilation openings should be minimized, easy cleaning made possible by suitable design

- in spaces with flued combustion appliances, a defined building untightness should be established as specified above.

4. FEATURES OF IMPROVED MECHANICAL VENTILATION SYSTEMS

What had been said about ventilation effectiveness with natural systems holds also true for mechanical systems: the higher the effectiveness, the lower the flow rates allowed, diminishing the problems of draught, noise, heating and auxiliary power demand, and equipment size (cost!).

In spite of the fact that with mechanical systems a good ventilation effectiveness can be established much more easily than with natural systems, most systems investigated in (4) and in other research works had severe shortcomings. Main complaints were with regard to:

- draught effects
- noise level
- odour transmission from kitchen/bathrooms
- equipment contamination and no regular service provisions
- design ratings not established
- high auxiliary energy consumption
- user has no interference option (feels oppressed)
- interference with combustion equipment.

In general, solutions with single fans for individual rooms should be avoided with mechanical ventilation systems and central systems be provided instead integrated into the entity of all hydraulically coupled rooms. Otherwise low ventilation effectiveness, poor economy and lack of comfort are programmed.

Two risk situations deserve particular attention: if either radon problems exist or if flued combustion appliances are used in the space under consideration, no exhaust-only ventilation is allowed. Combined supply-and-exhaust systems are then to be used instead working with small supply air excess, providing an overpressure of a few Pa in the ventilated space.

From the point of view of ventilation effectiveness (displacement ventilation to be aimed at) as well as from physiological effects (overheated air is felt "stale" and "not fresh") it seems necessary to avoid overheating of the supply air with ventilation systems.

In order to obtain an effective, economical, and comfortable (and thus user-accepted) ventilation system, the following points should be considered with system and equipment design:

System Design

- restrict design ratings to base requirement (windows for peak load)
- supply air inlets at low level (out of direct occupational zone)
- large cross section of inlets for low air velocity
- avoid occupational zones downstream of pollution sources
- supply air temperature slightly below average room temperature
- exhaust-only systems require properly located supply air inlets
- exhaust air outlets at ceiling of rooms and close to contamination source
- filters required for every air intake
- system should work properly without attendance
- offer manual interference **option** (acceptance!)
- compatibility heating/ventilation system to be evaluated
- acceptance test for every installation

Equipment Design

- satisfactory efficiency of ventilators/motors
- available units not be overrated for average dwellings (100 m^3/h and below required)
- use air ducts and air inlets with low hydraulic losses (noise, power)
- warning light for filter contamination
- filter cleaning procedure to accommodate user
- complete module for simple and low cost installation
- units for retrofits required
- design for more cost effective production.

5. CONCLUSIONS

With new building materials and with todays often excessive use of household chemicals pollution sources in dwellings have multiplied. New construction standards and restrictive ventilation habits of the occupants as a consequence of energy conservation efforts on the other side have reduced natural ventilation rates in buildings, sometimes below a level sufficient for pollutant or water vapour removal.

As a consequence, mechanical ventilation systems have found widespread introduction in a number of countries, whilst little effort has been spent on the improvement of natural ventilation devices. It is obvious, that occupants comfort and acceptance has so far not found appropriate consideration with the design of ventilation systems of any kind.

If real progress is to be made regarding indoor air quality the following points must be given much more weight in future:

- ventilation effectiveness
- integrated system approach:
  - o pollution removal
  - o energy conservation
  - o comfort
- improved natural ventilation devices
- retrofit ability.

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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PAPER 2

VENTILATION, AIR INFILTRATION AND BUILDING OCCUPANT BEHAVIOR

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SYNOPSIS

The role of the occupant in buildings energy use has been evident in studies in many countries. Our experience since the early 1970's has indicated that energy use can vary by at least a factor of two solely on how the occupant operates the house or apartment. This often involves window use. For example, window and door openings, to cool an overheated dwelling, can take place at any time of the year. This paper describes work at Princeton which measured occupant ventilation behavior, and which provided feedback in an attempt to modify behavior.

Experiments have been conducted about the effect of informing the occupant as to when outdoor temperature is low enough that window opening would be the better choice than employing mechanical cooling methods. A small blue light visible to the occupants was used to supply this guidance, in conjunction with feedback to the occupants about cost.

In a large multifamily building, regular visual inspection of window openings, sometimes supplemented with infrared scanning, were used to identify the prevalence of these actions. Fan pressurization tests in the apartments indicated very tight construction with the windows closed. When comfort and perceived ventilation needs conflict with energy conservation, poor temperature regulation can be the culprit.

In another study, data were collected through open-ended interviews and a survey in the same multifamily building. Interviews asked about beliefs concerning need for fresh air, stuffiness, and perceived thermal comfort. In this building, which most residents considered too warm in the wintertime, window or door opening was typically used to reduce indoor temperature. Blower door tests were used to estimate infiltration in a single apartment at differing window apertures while energy balance calculations based on measured energy consumption and temperatures were used to estimate infiltration for the entire building. Tenants' reports of their perceptions are used to interpret the observed and reported ventilation behavior. Tenant perceptions are also related to measurement-based estimates of air infiltration rates.

1. INTRODUCTION

From the beginning of our studies of energy conservation in buildings in the early 1970's at the Center for Energy and Environmental Studies, it was very evident that the occupant played a major role in energy use in the home by the way in which the home was operated. Our initial research into energy use was based on the analysis of monthly utility billing data, where clearly there was at least two-to-one variation in energy use for the total sample of 209 townhouses as well as for the 28 with identical orientation and design.[1] In a later series of measurements, even after 25% energy savings retrofits, there was still a wide spread in the energy appetite over the group of 30 houses that were being constantly monitored (hourly data from twelve channels of energy-related sensors) as shown in Figure 1. It was at that point in our monitoring effort that the highest energy user moved, (number 1 in the figure), and the new occupant promptly caused the home energy use to drop to the low end of our 30-house sample.

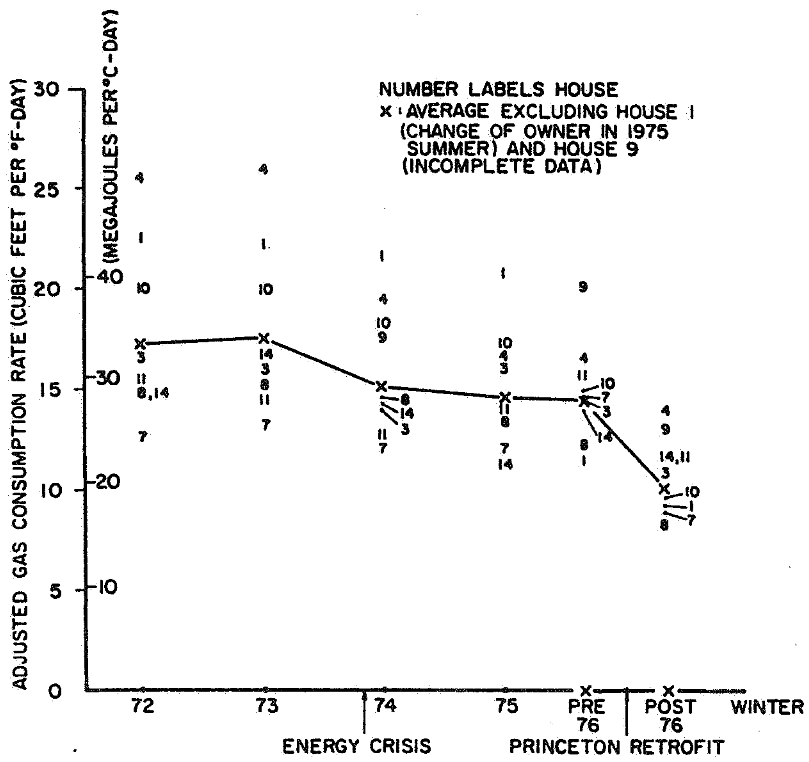

Figure 1. Occupant effects on the consumption of energy in the home during an energy retrofit study. These are nine identical townhouses from our monitored sample of thirty.

As our research extended from the Twin Rivers townhouses to older homes, and now to multi-family buildings, the role of the occupant continues to be an important part of the energy use research. To further substantiate that major energy consequences result from occupant effects, Figure 2 illustrates the repeated two-to-one type influence of occupants in a number of housing developments throughout the State of New Jersey.[2] In each neighborhood the same house construction was compared, building tightness was checked with blower doors, and heating system efficiency was checked using the latest instrumented auditing techniques.[3] Even with these items "controlled", occupant effects proved important. Occupant influence on energy use are not only an American phenomenon as shown by the review of occupant effects in the IEA Annex III handbook Guiding Principles Concerning Design of Experiments, Instrumentation, and Measuring Techniques.[4]

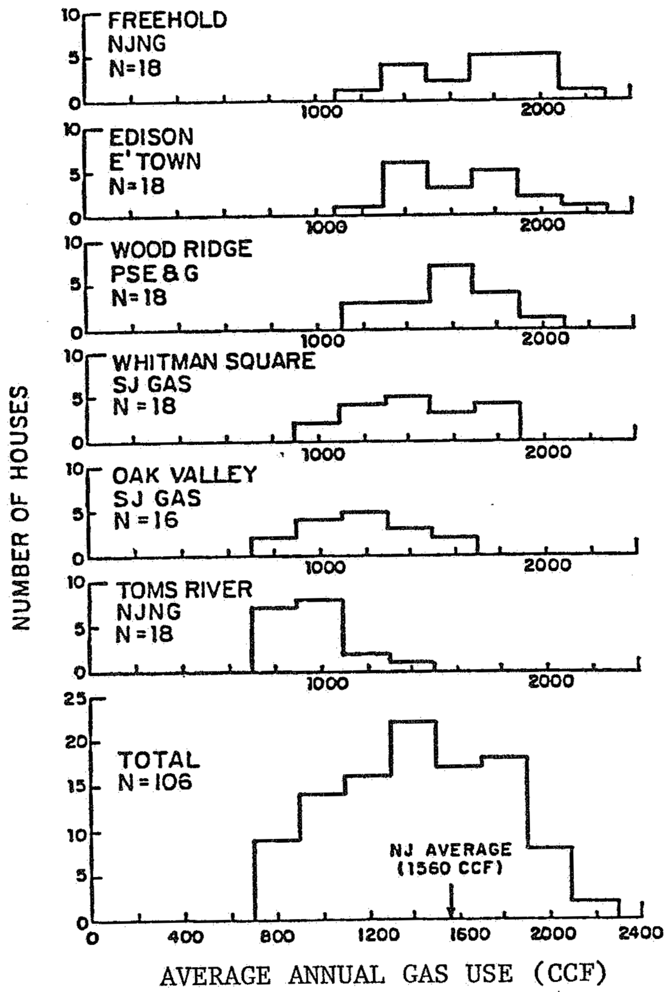

Figure 2. Histograms of estimated annual gas consumption for the six New Jersey Modules before the retrofits. Estimates predict the gas consumption during a year of "typical" weather (that is, a nine-year average temperature profile) based on the actual meter readings during 1978 and 1979.

2. OCCUPANT AWARENESS

One of the ways to attempt to reduce the energy waste associated with inappropriate occupant energy-related actions would be through an information campaign. Although we are often more prone to think of the heating season as a time when window habits can cause large increases in energy consumption in a dwelling, summer and the cooling season is another major opportunity for energy savings. However, the strategies differ sharply. Realizing there are periods, especially in the Southeastern United States, when windows should remain closed 24 hours a day, since the temperature never drops below 25°C and relative humidities of 70% or greater are the norm -- in many other areas there are extended periods when cooling would be more efficient if the windows were opened. When windows remain closed with complete reliance on air conditioning, heat generated within the building and residuals from solar radiation can cause the air conditioning system to run far into the night. Instrumented observations of ten heat pump homes[5] pointed out that air conditioning was still evident at outside temperatures of 7°C! Long before such nighttime temperatures were reached, it would have made sense to open windows.

In order to inform the occupant when window openings made sense and running the air conditioner did not, experiments were conducted by Seligman et al[6] using a "small blue light". The approach was as follows: an outside thermostat was placed in a location where it could measure temperature free from solar effects; the thermostat was connected to a blue light located in the kitchen near the telephone; the electrical connection was such that only when the air conditioner was operating would it be possible to activate the blue light, provided that the thermostat setting was exceeded.

The system interaction with the homeowner was that if the outside temperature was less than 20°C, and the air conditioner was still operating, the blue light would flash. In order to stop the light from flashing the occupant needed to turn off the air conditioner. The occupant was then anticipated to open the windows if additional cooling were required. When the outside temperature was above 20°C the light would not flash, no matter whether the air conditioning was on or off.

The study also involved feedback as a means of transmitting information to the homeowner as to whether they were consuming too much energy. Thermostat control was emphasized as the best way to reach energy conserving goals. Waste-indicating feedback from the research team about the total household energy use was a way to urge the homeowners to modify their thermostat settings to reduce energy consumption.

Forty residents were chosen to be part of the study which included four conditions: blue light, feedback, blue light plus feedback, and control. The feedback was given three times each week by reading electric meters and then displaying the updated energy use graph on a 15 by 23 centimeter card attached to the kitchen window. Consumption per cooling degree hour was computed for each house prior to the study, and predicted consumption was based only on the consumption per degree hour index. Feedback information was based only upon the most recent days. The experiment was conducted in late summer, mid-August to mid-September, when air conditioning use is prevalent in New Jersey.

Prior to the experiment there were no significant differences between the groups. During the test period, only those days in which the outside temperature dropped below 20°C were included in the analysis, since this was the operational point for the blue light.

The results from these tests are summarized in Table 1 and point out 15.7% less electrical use for the blue light homeowners. The feedback alone had less effect on saving energy. Attitudes of the blue light homeowners ranged from enthusiastic to feeling that the flashing light was an intruder in their home. Certainly when one considers the heat pump study, mentioned previously, an indicator of what outside conditions are present and how they can reduce energy use is clearly needed.

<u>Table 1</u>
Mean Daily Electric Consumption (kWh)
Feedback and Blue Light Signaling Device

	Blue Light Feedback	Feedback Alone	Blue Light Alone	Control
Sample size	10	10	10	10
During treatment*	18.30 (2.96)	20.61 (5.69)	18.24 (4.50)	22.76 (6.02)

Note: Standard deviations are given in parentheses.
*Adjusted for pretreatment differences by analysis of covariance.

3. MULTIFAMILY STUDIES

What is often lost when one moves to a multifamily building is the degree of occupant control over room temperatures. In even a preliminary study of multifamily buildings, one discovers that in the middle of the heating season many buildings have a significant number of windows at least partly open. If there was any doubt that heat was being lost, and energy wasted, one only need to use outside infrared thermography to document the losses.[7] The thermograms shown in Figure 3 pointed out how the warm room air exits and cold air enters individual windows in two apartment buildings; and depends upon relative location from the neutral plane for the relative flow rates.[1]

Although window replacement is often a popular energy retrofit from a window tightness standpoint, it could not be justified in the building being tested. The blower door tests in individual apartments indicated air exchange rates of less than 3 ACH for the existing casement windows.[7] With the windows closed, the ventilation level from air infiltration would be marginal.

To look at what are the actual infiltration rates taking place with the occupants controlling window openings requires sophisticated instrumentation. Bohac et al[8] have just completed a preliminary survey using constant concentration tracer gas (CCTG) equipment[9-11] to measure a test apartment and those apartments above and below and on either side. The study points out that although a seasonal-average air infiltration rate for an entire multifamily building may be estimated from a calculation of transmission losses and analysis of building data, such estimates usually suffer from regression parameters that are not well determined.[12] For the particular multifamily building under study an air infiltration rate of 1.6 ACH was estimated, with an uncertainty almost as large, as shown in Figure 4.

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[1]Opening upper windows tends to exhaust air, while opening lower windows tends to supply air to the building via the stack effect. Of course, unsteady effects and wind pressures can modify conditions for any given window. The higher the building, the greater the stack effect if good air flow communication exists between floors.

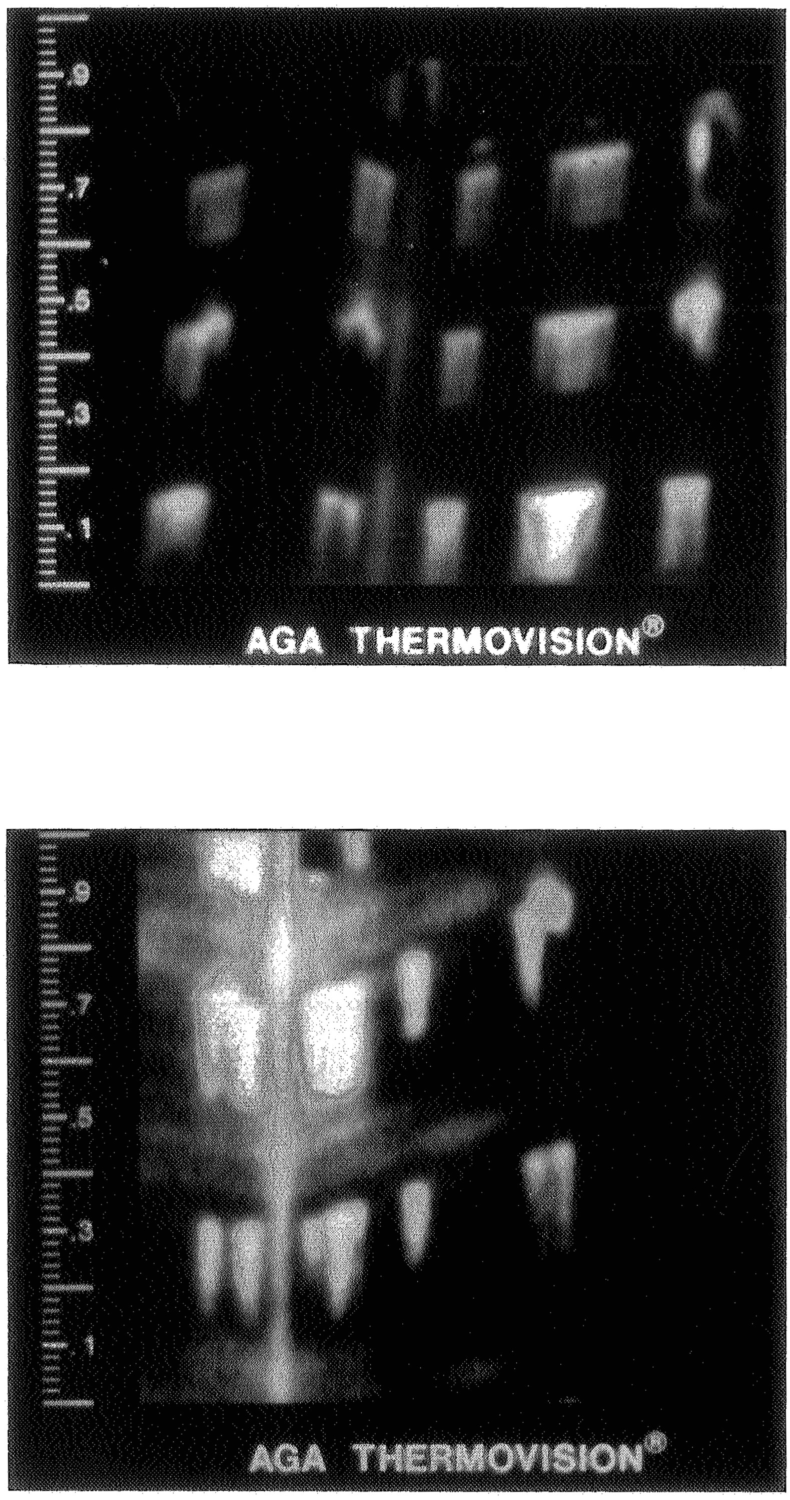


Figure 3. Thermograms of two multifamily buildings pointing out air infiltration related energy loss and variations in window flow pattern with building height.

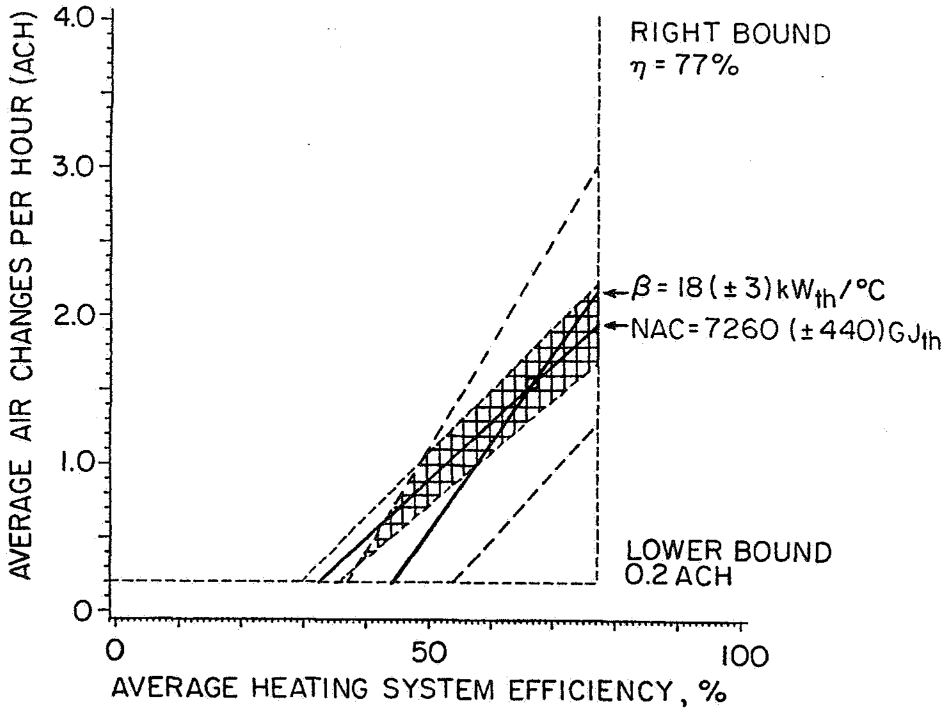


Figure 4. Matching transmission loss energy use in a multifamily building to the heating system efficiency to provide ranges of possible air infiltration. The lower air infiltration bound was established with fan pressurization.

These measurements were based on normalized annual consumption, NAC, and a building energy loss coefficient, B. Direct measurement with the CCTG system shows air infiltration in the 0.1-0.2 range, with windows closed, but increasing rapidly to 2.5-3.8 ACH with a 5 cm. window openings. The variation over time was very dynamic as occupants in the surrounding apartments opened and closed windows as shown in Figure 5.

To evaluate the flow of air in the stairwells, Bohac et al[8] found constant injection of tracer gas to be a very useful technique. Again window openings were the key parameter, increasing the air infiltration rates by a factor of about 20.

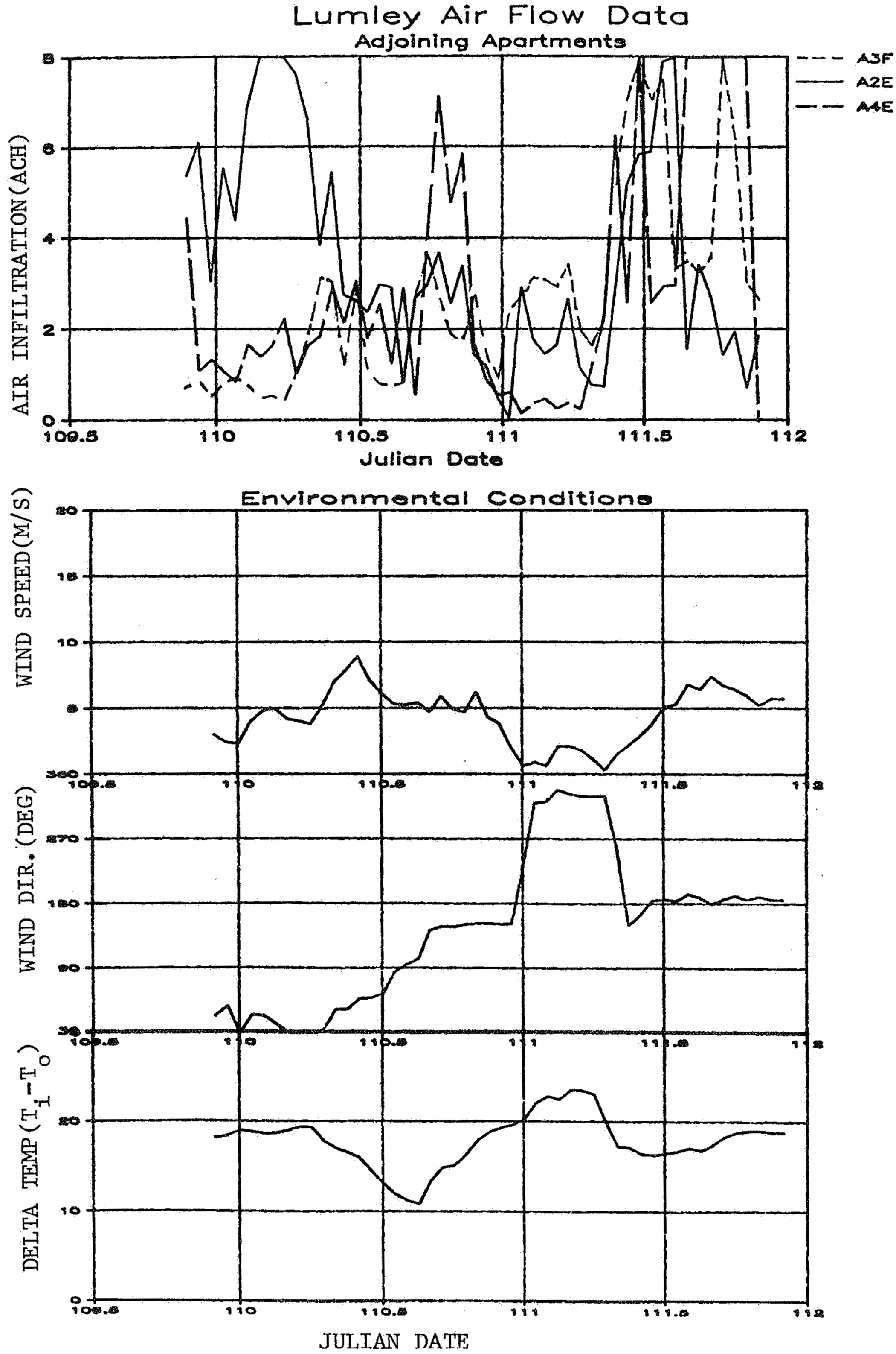


Figure 5. Air infiltration variations due to occupant and weather effects in three apartments monitored with constant concentration tracer gas equipment.

4. INTERVIEWING THE TENANTS

To obtain a better idea of why the residents were opening windows in mid-winter and in general, their reasons for the heating and cooling management within the apartments, two sets of interviews were conducted. First was a set of twelve open-ended ethnographic interviews, designed to orient us to the ways which tenants thought about ventilation, window opening, and heating their apartments during the winter. Based on that information, a survey questionnaire was written up which was then used to interview all the residents (53 of the 57 occupied apartments). The results of those interviews are presented both as percentage answers from the survey, and as quotations when we feel that they are representative and assist in an understanding of the tenants' perceptions and motivations. Both are drawn from more complete reports of these investigations.[13,14] As we describe below, the large amount of window opening behavior is due to overheating of the building, tenants desire for "fresh air" lack of other effective control mechanisms, and the tenants' interaction with the boiler operator.

Based on measured indoor air temperature of 26°C (79F) we suspected that more heat was being provided to the apartments than most residents wanted. This was confirmed in the survey, where 61% said they were sometimes too hot, while only 22% said they were sometimes too cold.

In these apartments, the control mechanism designed for tenant operation is the radiator valve. However, this was not the control mechanism favored by the tenants. First, some did not know about it or thought they were not supposed to use it -- in the 12 ethnographic interviews, two did not know there was a valve which controlled the heat, and four more did not think it was something which they could control Thus, half did not even consider the radiator valve as a control mechanism available to them. Also in the survey we asked about several strategies for controlling the environment. Percentages saying they used each strategy are:

Use of windows	84%
Use of radiator valves	35%
Calling maintenance	29%
Use stove for heating	25%

When we asked the reasons for leaving the windows open, we used the questions based on reasons which had been given frequently during the ethnographic interviews:

Leave windows open for fresh air	90%
Have to open a window because too tight or stuffy	51%
Have to open a window because there is too much heat	53%

Thus, while overheating is one important reason for opening windows, "fresh air" is an even more important one in frequency (although the aperture for fresh air is reported to be smaller than the aperture used to relieve overheating).

Most tenants described "fresh air" as being healthy, and as being important for a comfortable environment in their apartments. A few were specific about the opening needed for fresh air, one describing it as 4 to 6 inches (10-15 cm) and another as about half a foot (15 cm), others less specifically saying they left it "cracked". The amount of aperture for fresh air is not described as being something they varied through the heating season or in response to environmental conditions. Such aperture related ventilation rates have been measured and are shown in Figure 6.

Although we see that tenant-perceived need for "fresh air" was very important in this building, it may be a greater factor here than in other buildings. The first reason for this is the previously-mentioned low measured infiltration rates with all the windows closed. Since the measured rate is below the currently proposed American ventilation standard of 0.35 ACH applicable to this building, the residents' intuition that they need fresh air corresponds to the best engineering analysis available today. The second reason that "fresh air" may be more important in this building than average dwellings is that the residents are elderly, and many of the families of their childhood heated with wood or coal. Given the emissions levels of the traditional American wood and coal stoves, these people would have been correct in believing that some window opening was important for good health. We believe that there is not as much emphasis on fresh air by younger Americans, though we have not surveyed young people to verify this.

A final question is, why is the building overheated? To understand the high ventilation rates, it is crucial to understand overheating, since the combination of overheating and poor apartment-level controls are primary causes of the open windows and thus the high ventilation rate. Reports from other researchers studying US multifamily buildings also report large amounts of window opening, and thus it may be of general interest beyond the particular building we are studying.

Overheating seems to be due to the functioning of the boiler operator and the tenants, in which they interact and each work to optimize only relative to their local controls and feedback sources. The boiler operator responds to tenant complaints. He could respond by going up to the apartment to check for blocked pipes or nonfunctioning radiator valves, etc. However, since this would require a trip and interaction with an annoyed tenant, it seems that he more commonly adjusts a zone valve in the boiler room. The zone valve will raise the temperatures in from 10 to 20 apartments (depending on the zone), but it is a very easy adjustment to make. This zone adjustment is an inefficient response to a single complaint, since many or most of the tenants affected would have already been comfortable (or already too hot). However, the boiler operator is not provided any financial disincentive, nor does he even have any record or report showing him the energy consequence of this action.

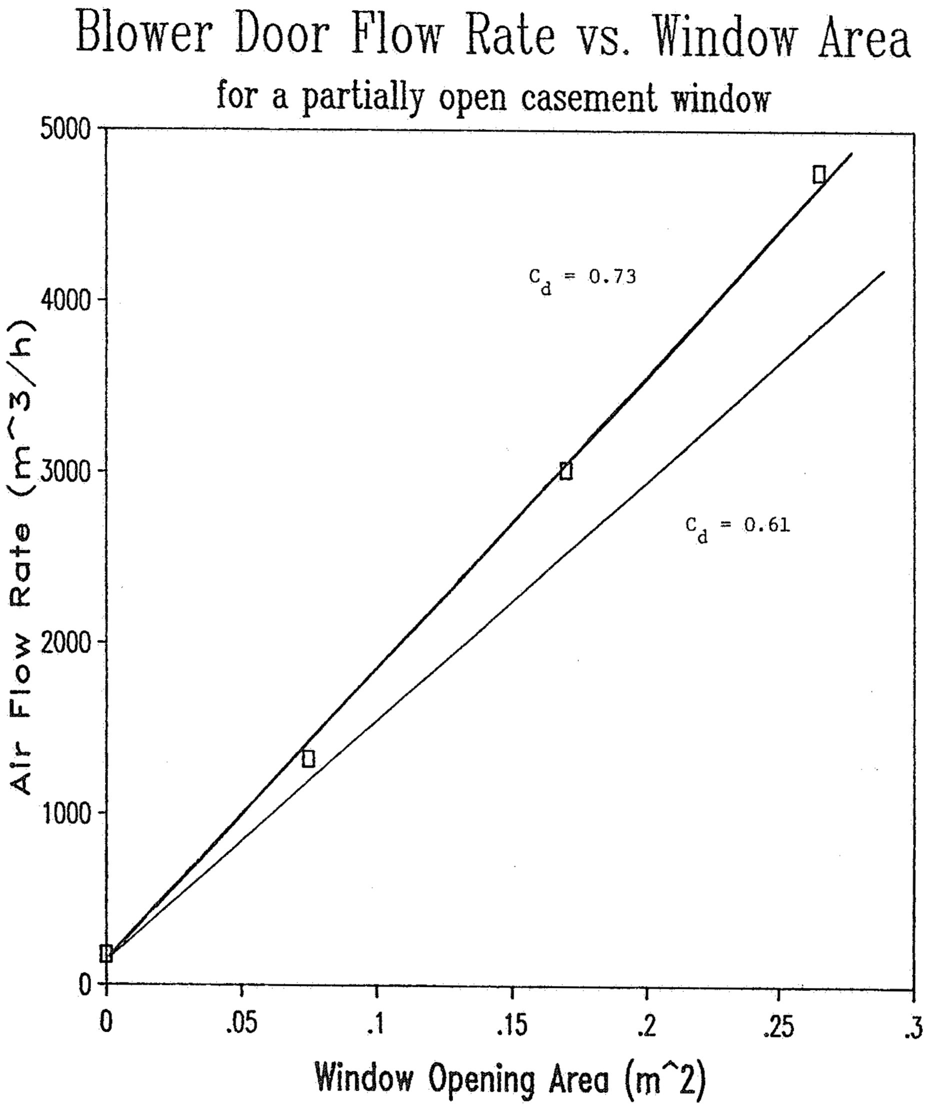


Figure 6. Ventilation rate measured at four window apertures, with pressure held constant.[15] (Inferred coefficient of discharge is 0.73, in comparison to theoretical flow of 0.61 for a sharp-edged orifice.)

For their part, the tenants whose apartments are too hot can either complain, shut the radiator valves, or open the windows. Many residents do not want to be labeled a "complainer" and the maintenance staff may discourage complaints, which mean extra work. Further, many of the low-income elderly do not want to complain for fear of being "put out". Some residents do use the radiator valves, but, as mentioned previously, many either cannot turn the radiator valves or do not consider them as an option. Even with the valves off, the rooms are surrounded by overheated apartments, and may still be too hot. This leaves the windows as an option which is attractive in the residents terms. Windows are easy to use, cool the apartment quickly, don't require complaints, and additionally provide "fresh air".

In short, the boiler operator operates the system on the basis of avoiding complaints and minimizing effort, in the absence of financial feedback. The tenants operate on the basis of local adjustment (the windows to reduce temperature) and complaints only when absolutely necessary (when it is too cold, not when it is too hot).

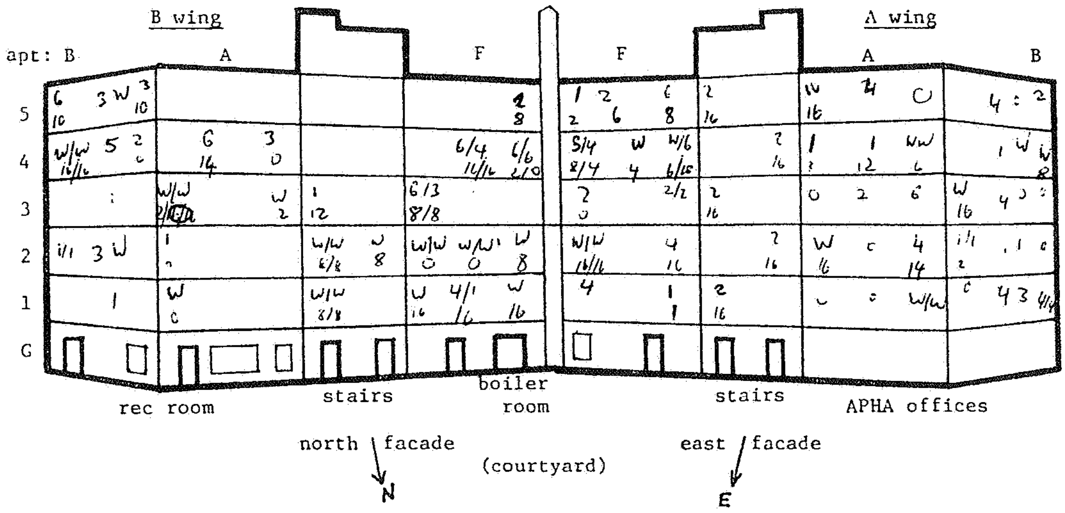
Two further areas of research are planned or ongoing: quantification of number and amount of window openings, and study of the interactions between the boiler operator and the housing authority which runs the building. Window openings have been measured throughout the heating season in a visual window survey. This is performed by marking a pair of mimeographed sheets as shown in Figure 7, which show each side of the building, with all windows drawn. The researcher visually scans each row of windows, marking on the sheet the ones which are open and the approximate apertures of each. These data will be analyzed to determined seasonal patterns and their relationship to boiler operation and possible estimates of air infiltration/ventilation levels and to assess any changes which occur as a result of retrofits to the system or changes in operation.

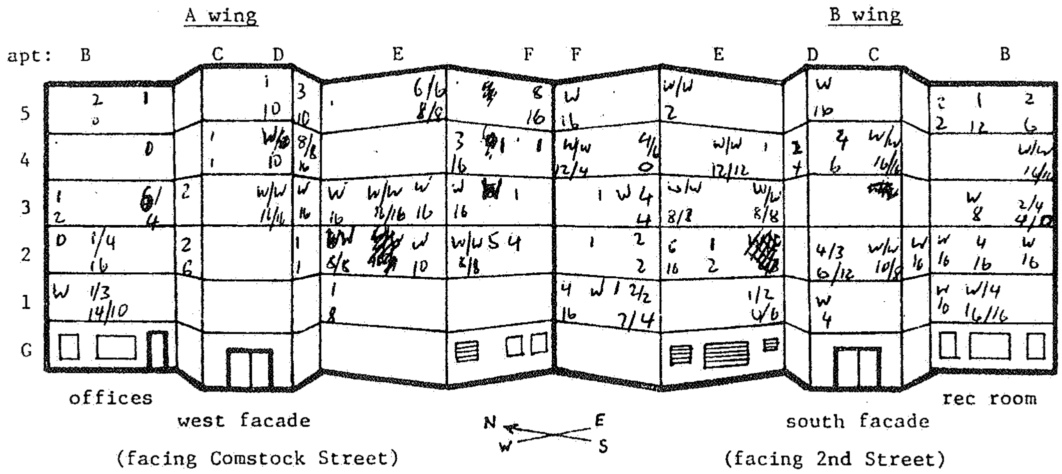
The second area for continued research concerns the relationship between the boiler operator and the housing authority. Some of the management decisions of the operator can have serious financial effects on the management, but there seems to be no feedback mechanism, much less incentive to maintain efficient operation. We plan further interviews with the boiler operator and interviews with management, to determine the reasons for this and potential solutions.

Princeton University
Center for Energy and Environmental Studies

WINDOW SURVEY
Lumley Homes
Asbury Park, N.J.

outer / storm window survey taken by PB + DF at 6 am on 5/1/86





WEATHER CONDITIONS: temperature 12.5 sky mostly sunny wind past 2 m/s

jmd 18 Jan 86

Figure 7. Example window survey sheets. Researcher has marked each open window with aperture in inches, or with "W" for wide open.

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
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PAPER 3

A PRELIMINARY STUDY OF WINDOW OPENING IN 18 LOW ENERGY HOUSES

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Synopsis

An energy efficiency monitoring programme was carried out from 1984 to 1986 by the South London Consortium Energy Group, United Kingdom Department of Energy, with assistance from British Gas, Watson House, as part of a demonstration project funded by the United Kingdom Department of Energy, the EEC and SLC Energy Group. 18 occupied low energy houses were thoroughly instrumented in order to monitor energy usage and occupant behaviour. Data collected included temperatues in each room of the house, window usage determined from microswitches on every openable window, individual energy consumptions for heating, hot water, cooking and electrical appliances, and detailed weather monitoring. Humidity measurements and ventilation tests were also performed.

Data was stored as hourly averages of 2-second readings over the entire monitoring period. This enables a comparison to be made between window opening patterns of occupants recorded on daily, weekly and seasonal timescales. These window opening patterns are discussed with respect to the levels of occupancy, building energy consumption, occupant activity, comfort, perceived need for ventilation, and external weather conditions.

The discussion of these preliminary results leads to a critical assessment of the installed warm air heating and supply ventilating system, and the differing reactions of some occupants to energy conservation and air quality.

Suggestions are made concerning changes in system design to maximise the air quality within the building whilst minimising ventilation heat losses for differing levels of occupancy.

The data collected reinforces the established criteria for window opening behaviour. The detailed level of data collected should, on more thorough analysis, provide a further contribution to these criteria, as indicated in the text.

Introduction

The energy efficiency monitoring of 18 low energy houses by the SLC Energy Group was designed to record the performance of the house design with respect to occupant behaviour. The logging of window opening times was an integral part of this exercise. The amounts of data produced as hourly summaries over a period of greater than 18 months provides a level of detail which will take a considerable time to analyse fully. This paper looks at the overall trends in window opening behaviour with respect to current knowledge on the subject, and includes examples of more detailed data, which will no doubt produce further information in the future. This information is used to consider the occupants' perception of the quality of air in the dwelling, and how that perception is likely to be influenced by modifications to the ventilation system. Future analysis will look at the energy implications of the opening data and how the energy losses are affected by mechanical ventilation systems. This is the ultimate objective of this work.

Previous work by DICK, BRUNDRETT et al,[1,2,3] has related domestic window opening behaviour to prevailing weather conditions and social grouping, which is well reinforced by other researchers. More recently, the window opening behaviour patterns and reasons behind the specific behaviour of the occupants is attracting more attention. This is important because if energy savings are to be made by reducing occupant window opening with mechanical ventilation systems, the reasons behind existing behaviour need to be investigated (MEUNIER et al [4]). Such work has already been started, and preliminary results from instrumentation of a large block of naturally ventilated flats have been analysed (PHAFF et al [5]).

These detailed analyses are required because although window opening correlates closely with prevailing weather conditions, the reasons behind the frequency of window opening is likely to be a balance between the external weather conditions and the perceived need for ventilation of the occupants.

The SLC/British Gas study was carried out in 18 low energy houses with warm air heating systems providing partial ventilation during the heating season. Comparison of window opening behaviour in these houses with different building types should result in the identification of the motives and range of responses to those stimulae that are the source of motivation for occupants changing their requirements for ventilation.

The Test Houses

The 18 test houses are energy-efficient 3-bedroom designs with a high level of evenly distributed insulation. They are built in three North-South oriented terraces to maximise solar gain to the living rooms and solar panels. Double glazing and draught-stripping is used throughout, and a draught lobby is included for both the front and rear doors. The warm air heating system is designed to give even house temperatures, redistributing solar gains throughout the house by recirculating air. A fresh air supply to the heating system is provided from a loft air intake, giving about 0.5 air changes per hour. There are no return air paths from the kitchen or bathroom, ventilators in these rooms providing an exit for stale air. Floor plans of the houses are shown in Figure 1, together with a list of the energy saving features of the design.

The logging system consists of microprocessors in each house taking two second readings of all the parameters in the house, from which they produce hourly averages when interrogated by a central computer. The measurements taken in each house are as follows:

(i) 7 room temperatures

(ii) central heating "on" time

(iii) gas consumption (cooking, heating and hot water)

(iv) electricity consumption

(v) window opening times (microswitches on all 10 openable windows)

In addition, weather data is collected including:

(i) air temperature

(ii) ground temperature

(iii) solar gain

(iv) wind speed

(v) wind direction

(vi) relative humidity

Close contact is kept with the occupants of the houses, and their reactions are informally monitored. A questionnaire regarding window opening attitudes will be circulated when monitoring has ceased, to avoid any influence on window opening behaviour patterns.

The infiltration rates of the houses were measured, and are shown in Figure 2. When the heating system is on, this gives typical ventilation rates of 0.8 air changes per hour. (ETHERIDGE)

Window Opening Patterns

This preliminary study reviews the annual window opening characteristics of the houses on a monthly basis, and compares the simple statistical correlations with those of Brundrett [2]. The window opening data for individual houses is then reviewed and examples of obviously different bahaviour of different occupants is looked at in more detail. These behavioural examples are then looked at from weekly intervals over a three month period, and some are further looked at using daily data. More detailed investigation including detailed statistical analysis will be reported at a later date when a thorough computer analysis of the large amount of available data is completed

Mean Annual Window Opening Patterns

Figure 3 shows the mean window opening hours per month for all 18 houses plotted over an 18 month period. Also plotted are mean ambient temperature, solar gain, relative humidity and energy consumption for all the houses. The correlation coefficients between window opening, ambient temperature, solar gain and mean house energy consumptions are all relatively good, as would be expected from previous work. The correlation coefficient and regression equations are as follows:

TABLE 1

VARIABLES	CORRELATION COEFFICIENT	REGRESSION EQUATION
Window opening (hrs) vs ambient air temperature (°C)	0.90	HRS=-120+63x°C
Window opening (hrs) vs monthly solar gain (MWm^{-2})	0.84	HRS=0.96+0.26 MWm^{-2}
Ambient air temperature (°C) vs mean energy consumption (kWh)	-0.97	kWh=2475-106x°C
Window opening (hrs) vs mean energy consumption (kWh	-0.84	HRS=1282-0.54kWh

Individual House Annual Window Opening Patterns

Figure 4 shows a selection of the mean annual window opening patterns for some chosen individual houses. These particular curves have been chosen to show the large range of window opening activity between different houses over the logging period.

House number 28 only has any significant window opening in the lounge alone during the summer of 1984 (the hottest Summer in England for many years). The only other window opening in House 28 was in the bathroom in Winter - this never exceeded 2 hours total per month. At the other extreme, house 18 used all its openable windows extensively, many of the windows staying open virtually all the time outside the heating season. The exceptions were the lounge, kitchen and bathroom windows. The lounge window was only opened in the peak of summer, and the bathroom window was used extensively during the heating season and particularly in Spring and Autumn. The kitchen window was used to a variable extent throughout the year, with little use in winter months.

Between these two extremes lie a large range of window opening behaviour, with many patterns which deviate significantly from the trend which correlates well with ambient temperature. For example, the peaks are indicated on the graphs for houses 19 and 25. These examples are looked at in more detail in the next section.

Individual Window Opening Patterns for Chosen Houses

Figures 5 to 8 show the relative window open times for each room in some chosen houses in order to show the variation in window opening behaviour during the 18 month period considered. Also shown on these graphs are the houses' energy usage on a monthly basis, for comparison.

Figure 5 shows the pattern of house 18, which used all the openable windows extensively. The general trend follows external temperatures well, but there are several notable features throughout the seasons. The warm summer of 1984 encouraged all the bedrooms to have at least one window open for greater than 50% of the time.

It is expected that analysis of daily window opening patterns would reveal overnight opening to cool bedrooms at night. Then the window opening generally decreases with the approach of the heating season, with the exception of the bathroom window, which peaks in the intermediate seasons, probably due to the low heating on times and higher ambient atmospheric water vapour levels causing increased condensation. The highest levels of window opening in the winter are in the bedrooms and bathroom, most likely stimulated by occupants perception of air quality.

Figure 6 shows the window opening pattern for house 28. This house had a very low energy consumption throughout the year, and associated low average internal house temperatures of down to 10°C in winter. The heating system was not used, and casual gains from cooking and other electrical appliance operation was the only source of heating, averaging 400 kWh per month - equivalent to the other houses' casual gains. The only significant window opening was in the lounge and one bedroom during summer 1984. A small amount of bathroom window opening occurred in the spring of 1985.

Figure 7 shows that the pattern of window opening in house 19 is dominated by bathroom window opening between the heating seasons, when the heating system was not on. This either demonstrates the householders' reluctance to open windows in the winter, or it may be a reflection that the supply mechanical ventilation combined with the heating system provides adequate ventilation for the bathroom in winter and spring seasons.

Figure 8 shows the inconsistant window opening patterns of house 25. The windows in the kitchen and bedroom 2 follow a predictable seasonal pattern, but bedrooms 1 and 2 and the bathroom are inconsistant. These radical changes in behaviour during the year may be due to long term visitors to the house who have different window opening habits, or who stimulate a desire for increased air quality by the occupiers. Such inexplicable peaks occur in several of the monitored houses, and fall into no identifiable pattern.

House number 33 is worthy of comment, as the bathroom window is opened to a similar level all year round, averaging 3 hours per day, apparently independant of weather conditions and other stimulae.

Window Opening - Autumn 1985

Figure 9 shows the 18 house weekly mean window opening hours and prevailing weather conditions for autumn 1985. The window opening reduces consistantly with temperature, apart from week 5, where the wind speed increased substantially, although the mean temperature rose 1.5°C. For three weeks in November, the mean temperature was below 4°C, relatively cold for the time of year. The next three weeks in December were mild, about 10°C, but window opening did not follow this temperature increase, even though ventilation supplied by the heating system reduced. Perhaps the cold period in November had provoked the belief that winter had begun, and occupiers were reluctant to increase window opening behaviour as a result of this expectation.

However, the occupants of house 27, whose window opening behaviour correlates closely with ambient temperature throughout the 18 month period monitored, appeared to respond to the increase of temperature with an increase in bathroom window opening (See Figures 10 and 11).

Daily Window Opening Patterns

Presented in this section are some patterns of window opening on a daily basis. These are presented as examples which show how the window opening behaviour and energy consumptions can be linked to occupant activity. Examples only are presented because the vast amount of data available will require extensive computer analysis before detailed results are obtainable. (Approximately 10,000 daily behaviour pattern graphs are available.) Variations in these daily patterns are expected to correlate with family size and activity (BRUNDRETT[2]).

Figure 12 shows some 24-hour window opening patterns for house 27. Figure 12a shows the central heating system fire for an extended period prior to the bathroom window being opened and a peak in electrical consumption. This pattern is typical of washing activity, the central heating providing the hot water for bathing, the electricity consumption rising for a supplementary bathroom heater or hair dryer, and the bathroom window opened in the mild March weather to encourage moisture removal.

Figure 12b shows the kitchen window opening after the start of a peak in electricity consumption (2.5 kW) at 1300 on a mild Sunday. Kitchen window opening continued through the evening with lower peaks in electricity consumption of 1 kW. In Figure 12c on a cold February day, kitchen and bathroom window opening coincides with electricity consumption peaks of up to 4 kW, and also long central heating on times indicating near simultaneous cooking and bathing, although a 2 kW electrical peak results in no window opening later that day.

Summary of Preliminary Results for Chosen Houses

Several characteristics of window opening behaviour have been described, together with probably stimulae for the behaviour. The four main stimulae appear to be energy conservation, perception of air quality, moisture dispersal and cooling in Summer. Some of the houses' occupants behaviour patterns can be categorised according to their apparent primary concern. This, of course, alters with the seasons. Table 2 shows the correlation and regression equations for external temperature with respect to window opening and energy consumption of some individual houses.

House number 18 had the highest frequency of open windows with 1100 window open hours per month on average. All windows were used and the opening patterns follow seasonal variations in temperature, apart from the interseasonal bathroom window opening. The regression equation suggests a linear increase of 114 hours window opening per °C abgove 2°C per month. In practice, a linear curve fit is not an accurate reflection of behaviour, as different stimuli for window opening are likely to be relevant in different temperature ranges (BRUNDRETT [2]). It does, however, give an impression of the sensitivity of the householders behaviour to external temperature.

House 25 also used windows extensively. This, and the high mean indoor temperature, probably represents the highest ventilation heat loss through the windows for the dwellings monitored. This house has a very irregular pattern of annual window opening behaviour, as already described, with isolated peaks of window opening in guest bedrooms and the bathroom. The energy implications of this behaviour will be reported in future work.

Houses 19 and 33 have a relatively low frequency of window opening. The correlations with temperature are low, and their regression lines have low gradients. This implies, along with their lower energy consumptions, that the window opening in these houses is less temperature dependant. Windows will tend to be closed unless there is a specific need for them to be open. In both houses, the bathroom window is the most frequently opened. The occupants may well be more concerned with condensation than the degree of freshness of the air in the house. (House 19 also appears to have minimal window opening habits at ambient temperatures below a threshold temperature of 10°C -see Figure 13).

The mean level of window opening is lower than that measured by Brundrett [2,3] and the sensitivity to temperature is also lower. This is to be expected as partial mechnical ventilation is supplied to the test houses. Care will be required on more detailed analysis because of the non-continuos nature of Brundrett's data.

Conclusions

From a combination of annual, seasonal and daily window opening patterns, many types of behaviour pattern have been observed. Some of these patterns can be associated with responses to different stimuli such as energy conservation, perception of air quality, moisture dispersal and thermal comfort. The following list of characteristics have associated with them the identification numbers of the houses whose window openings appear to be influenced by them.

1) Nearly all the houses opened windows in the height of summer for cooling, particularly in bedrooms overnight.

2) Large inconsistancies of window opening pattern occurs in some bedrooms (assumed to be guest bedrooms)(e.g. houses 25, 28, 33). These have associated peaks in bathrooms in some houses.

3) Some houses close all windows through winter (e.g.house 19)

4) Some houses reach a minimum window opening level in winter, which can be associated with a threshold temperature. (e.g. houses 18, 20, 25, 27, 33)

5) Some houses have high levels of window opening in intermediate seasons, particularly in bathrooms. (e.g. house 18)

6) Lower levels of window opening than previous work [1,2,3] were encountered which is possibly due to the partial mechanical ventilation supply system in the houses monitored.

The data produces good correlations between external temperature, energy use and window opening frequency, as expected from previous work, but more detailed analysis is required of the conditions under which different stimuli result in window opening for different inhabitants.
A more detailed analysis of the energy consumptions associated with the window opening behaviour will be done in the future. This work will have to take into account the fact that in common with most surveys the extent of window opening was not measured.

The supply ventilation provided by the heating system was not adequate all year round for most of the households. The variations in window opening may correlate with the size and ages of the families living in the houses. (A questionnair should resolve this question at a later date.) It appeared that The ventilation provided by the heating system in the intermediate seasons was not capable of fully controlling bathroom humidity/condensation. In winter, the reduction in bathroom window opening may be due to occupants not tolerating draughts, or the heating system providing adequate ventilation through higher supply flow rates of ambient air with lower water contents. Ventilation for bathrooms in intermediate seasons would probably result from supply ventilation being provided through the heating system whenever the time clock is "on", rather than whenever the room thermostat calls for heat.

Acknowledgements

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TABLE 2 : PRELIMINARY STATISTICS FOR CHOSEN HOUSES

HOUSE NUMBER	MEAN INDOOR TEMPERATURE °C	MEAN MONTHLY ENERGY CONSUMPTION (kWh)	CORRELATION COEFFICIENT	REGRESSION EQUATION (kWh = a + b x Ta)	MONTHLY MEAN HOURS WINDOW OPEN (hrs)	CORRELATION COEFFICIENT	REGRESSION EQUATION (hrs = a + b x Ta)
18	19.6	FULL 18 MONTH DATA NOT AVAILABLE			1100	0.87	-203 + 114 Ta °C
19	19.6	1163	-0.85	2003 - 73 Ta °C	205	0.63	-159 + 32 Ta °C
25	22.5	1442	-0.91	2674 - 107 Ta °C	830	0.91	-142 + 85 Ta °C
33	19.4	862	-0.94	1714 - 74 Ta °C	298	0.61	6 + 25 Ta °C
34	21.4	1685	0.96	3562 - 164 Ta °C	492	0.88	-461 + 83 Ta °C
MEAN OF + ALL 18 HOUSES	-	-	0.97	2475 - 106 Ta °C	-	0.90	-120 + 63 Ta °C *

Ta is Ambient Temperature.

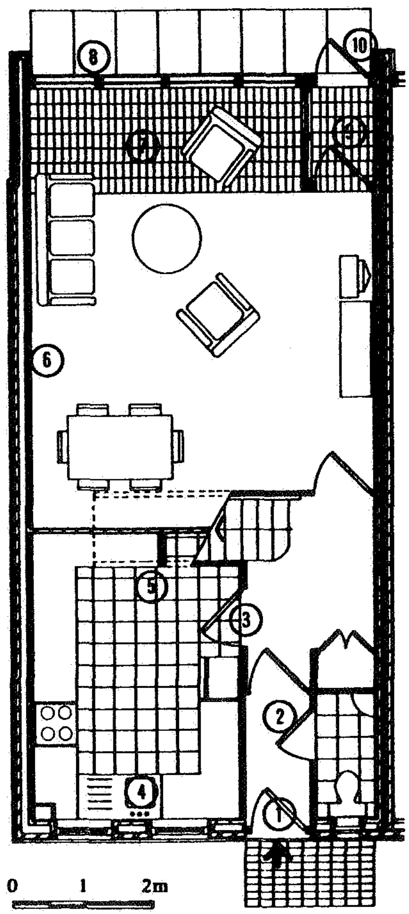
* This compares with Brundretts [2] of - 150 + 97 Ta°C.

+ Mean includes night-time window opening which is a significant proportion of total not included by Brandrett [2].

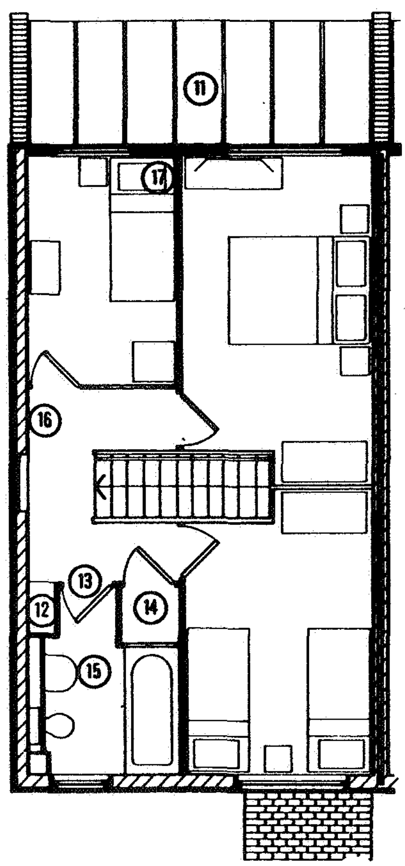
Fig. 1 FEATURES OF THE DESIGN

Features of the Energy Saving Design which can be identified within the Demonstration House – 6 Colvin Close, 68-72 Lawrie Park Road, London SE26.

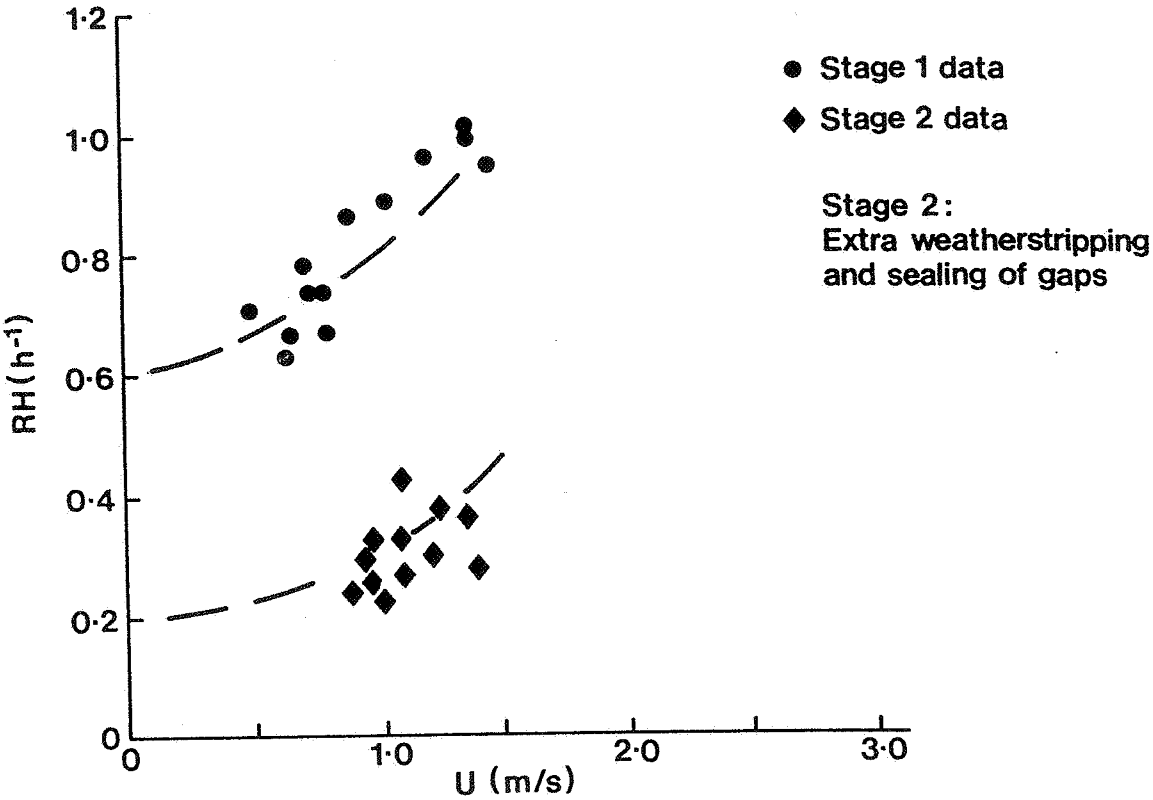
1. Draught-stripped front door.
2. Draught lobby.
3. Draught-stripped kitchen door to reduce water vapour entering rest of the house.
4. Three taps on sink – tap with yellow top supplies solar heated water.
5. Warm air outlet.
6. External wall-cavity insulation plus Thermalboard dry-lining.
7. Passive solar gain here. Some heat stored in floor and wall and released later. This area could be turned into Conservatory by addition of internal wall.
8. Draught-stripped windows. Double glazing.
9. Rear draught lobby.
10. Draught-stripped back door.
11. (View from outside or above.) Solar panels for water heating. Solar heated water stored in cylinder in roof space.
12. Warm Air Heating/Ventilation unit. Takes in fresh air, mixes with recirculated air, heats and distributes through ducts.
13. Draught-stripped bathroom door to reduce water vapour entering rest of the house.
14. Gas water heater. Fed from Solar cylinder so as to reduce amount of gas required to achieve required temperature.
15. Three taps on bath and washbasin. Taps with yellow tops provide solar-heated water.
16. External wall-insulating blockwork with Thermalboard inside and cladding externally.
17. External wall-insulated timber frame, cladding externally.



GROUND FLOOR



FIRST FLOOR



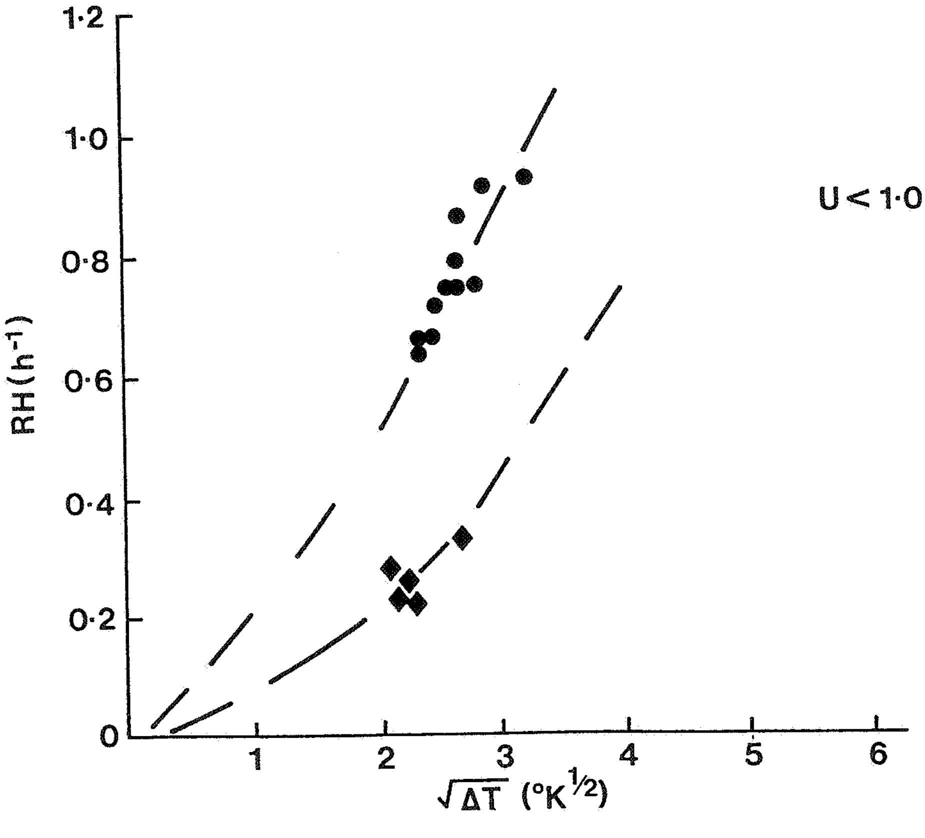


Fig. 2 VENTILATION RATES-PRELIMINARY DATA (VENTS CLOSED)

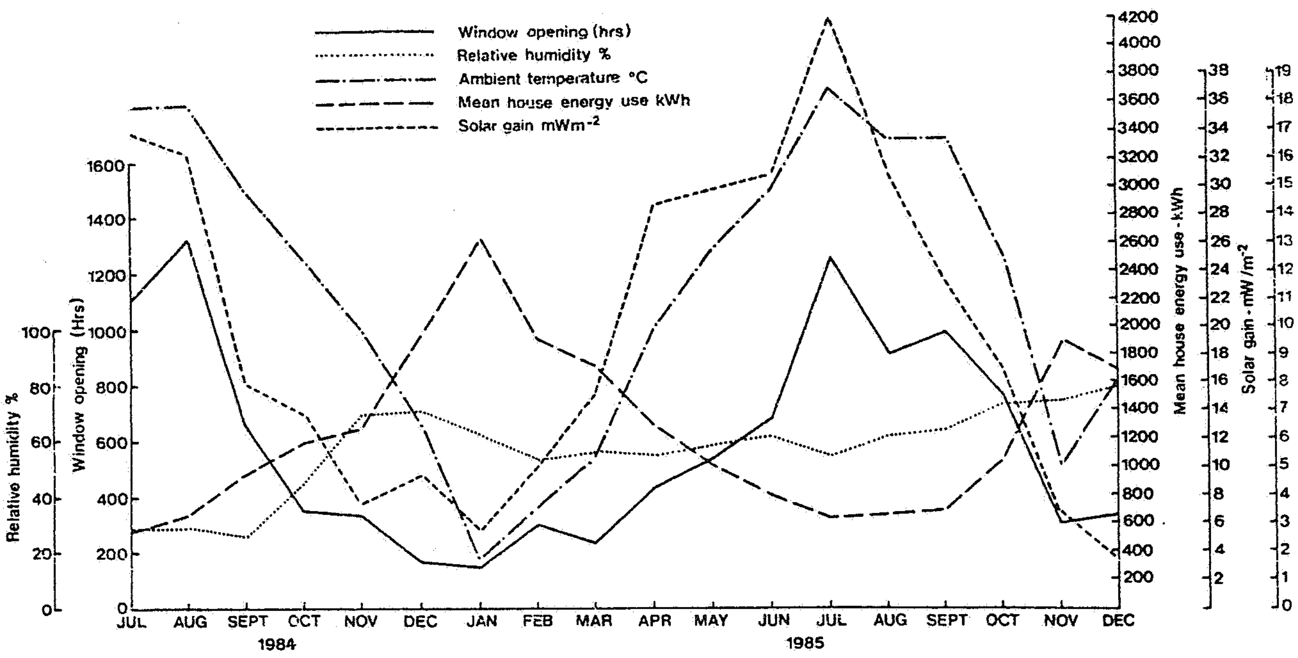


Fig.3 MEAN MONTHLY WINDOW OPENING TIME 1984/5 COMPARISON WITH AMBIENT TEMPERATURE, SOLAR GAIN, RELATIVE HUMIDITY AND MEAN ENERGY USE

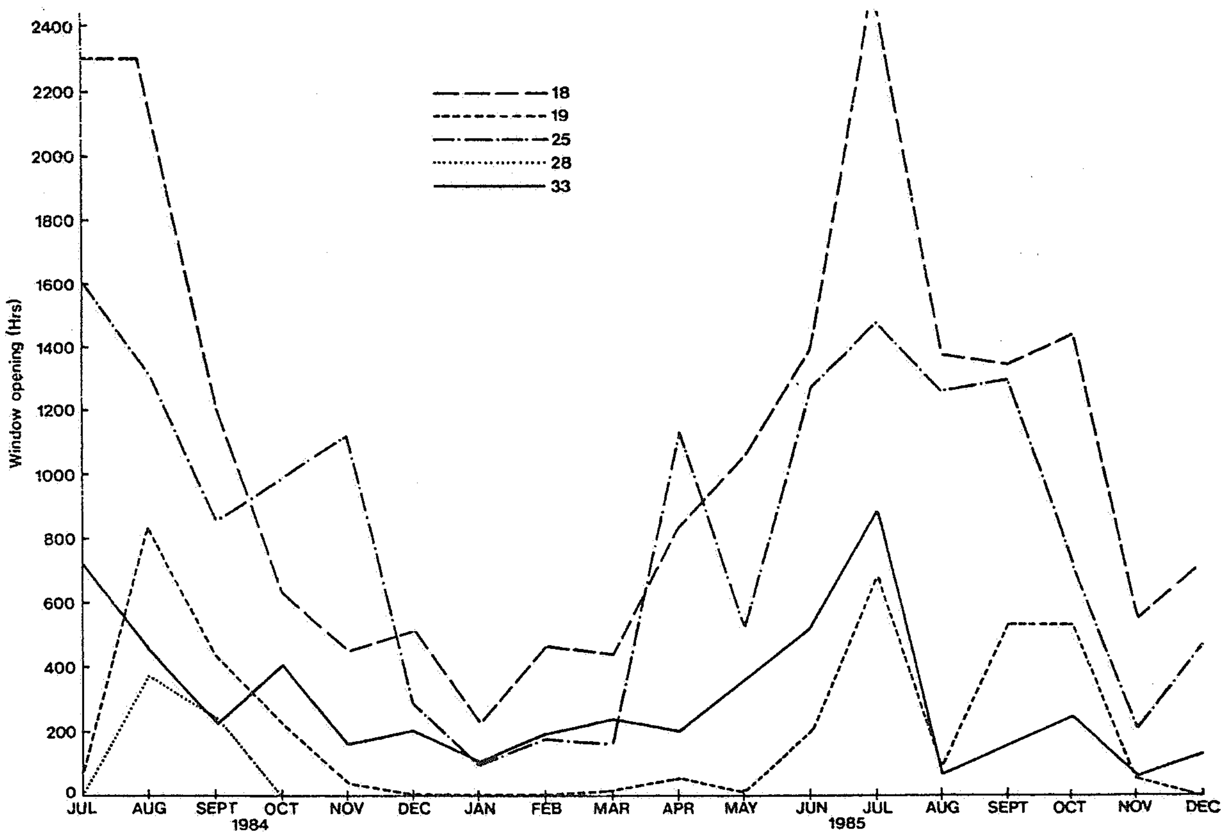


FIG.4 MEAN MONTHLY WINDOW OPENING - INDIVIDUAL HOUSES

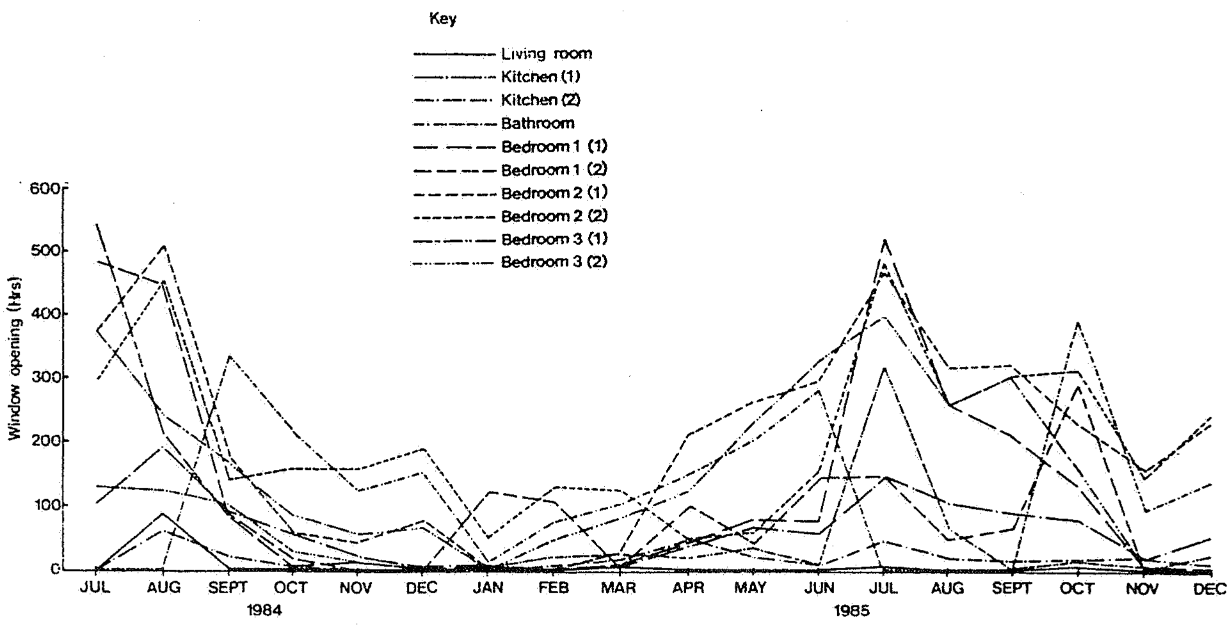


FIG. 5 INDIVIDUAL WINDOW OPENING PATTERNS FOR HOUSE 18

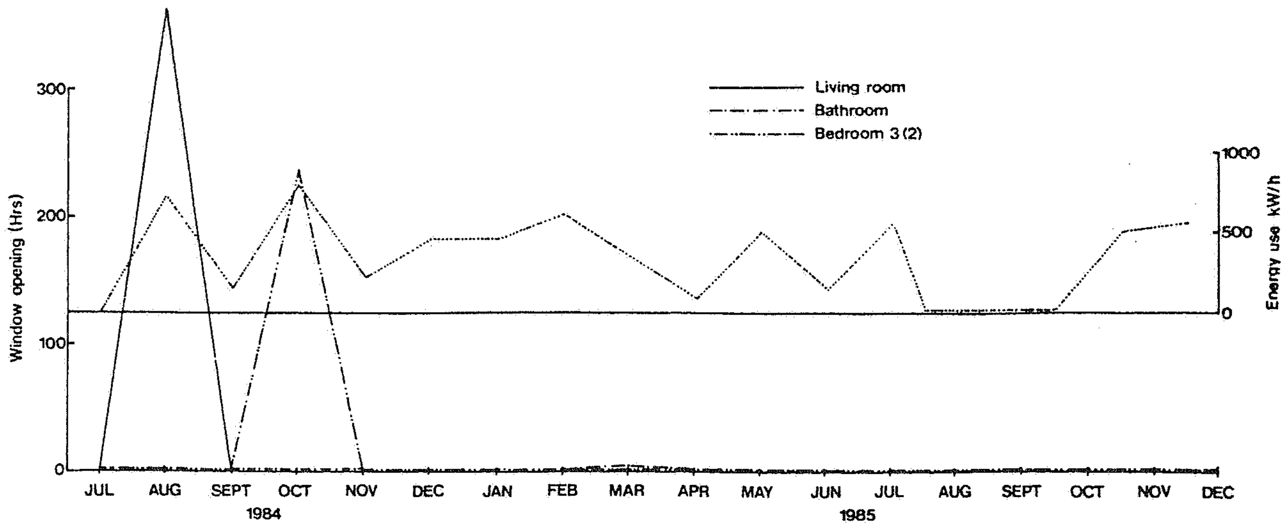


FIG. 6 INDIVIDUAL WINDOW OPENING PATTERNS FOR HOUSE 28

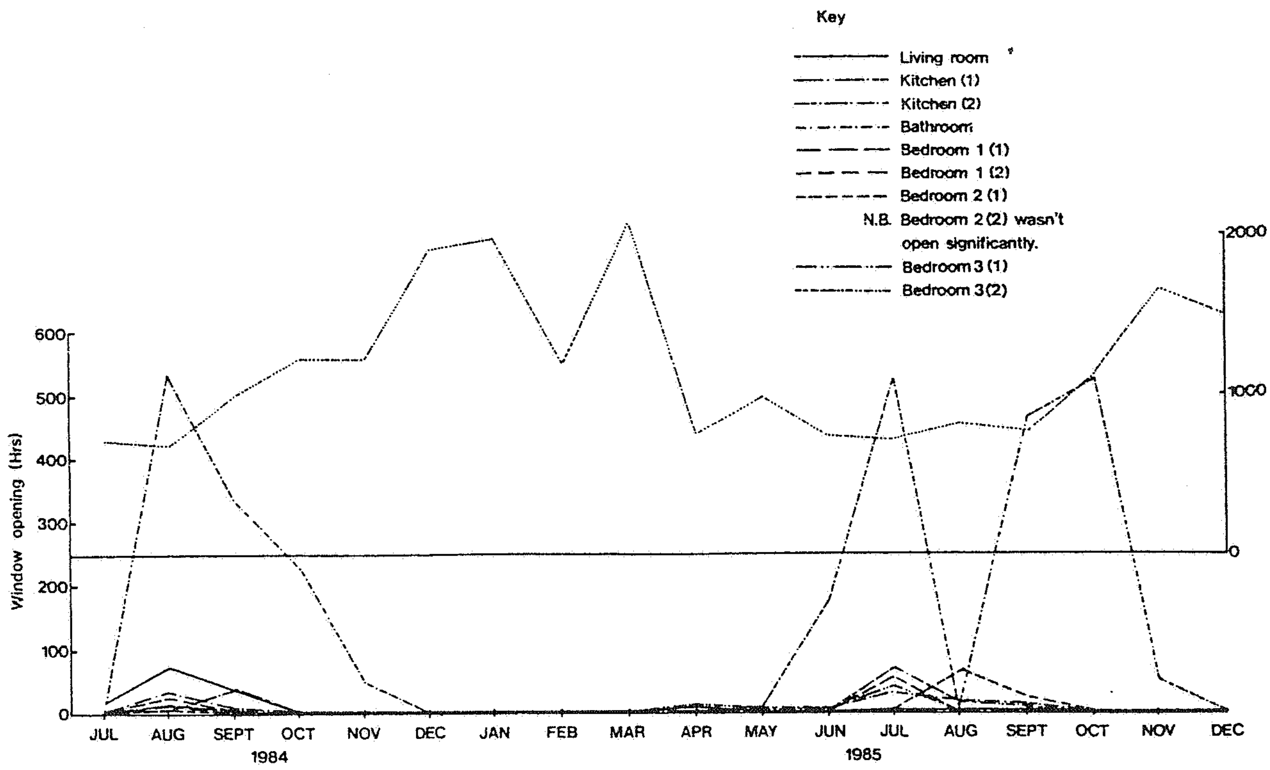


FIG. 7 INDIVIDUAL WINDOW OPENING PATTERNS FOR HOUSE 19

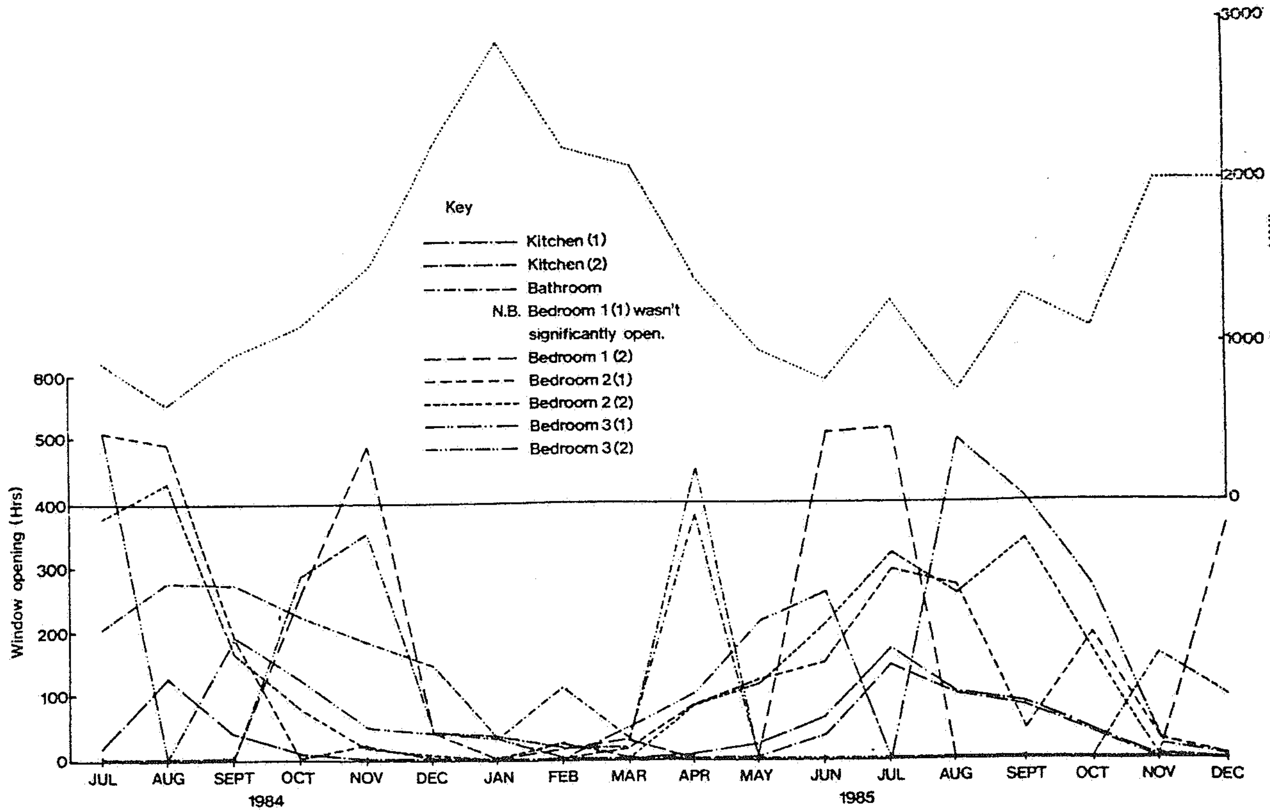


FIG. 8 INDIVIDUAL WINDOW OPENING PATTERNS FOR 25

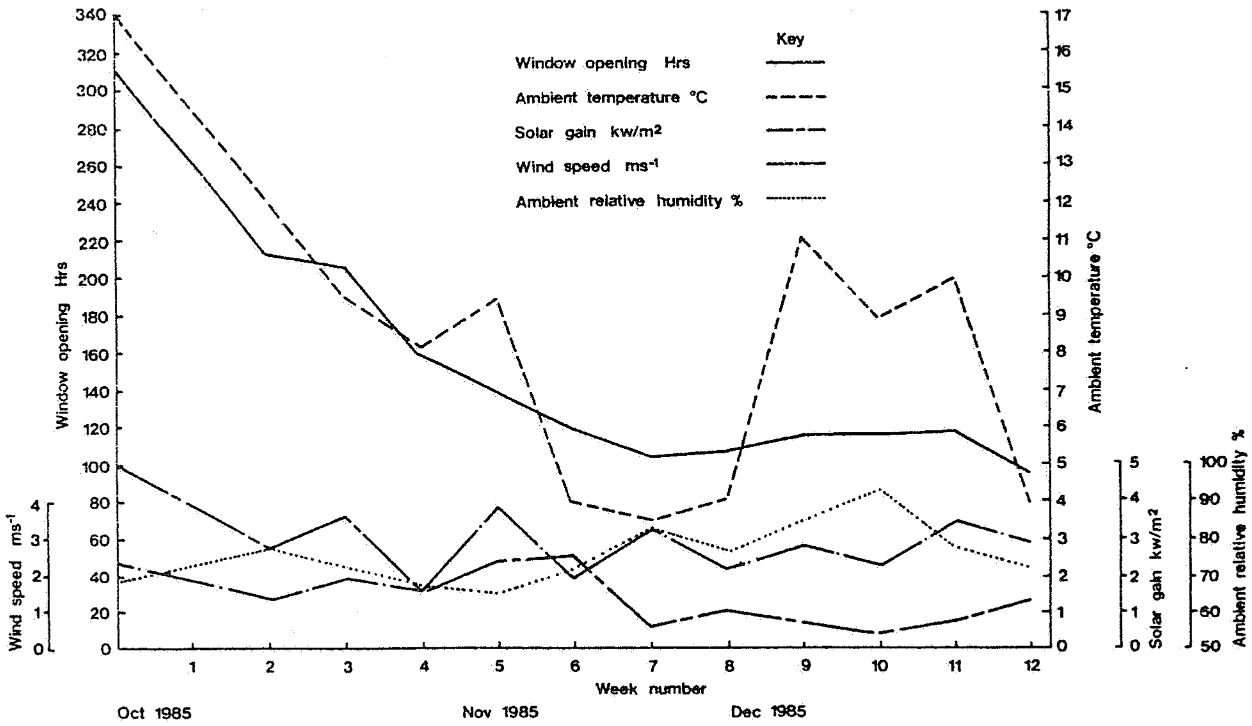


FIG. 9. MEAN AUTUMN WINDOW OPENING 1985 COMPARED WITH AMBIENT TEMPERATURE, RELATIVE HUMIDITY, SOLAR GAIN & WIND SPEED

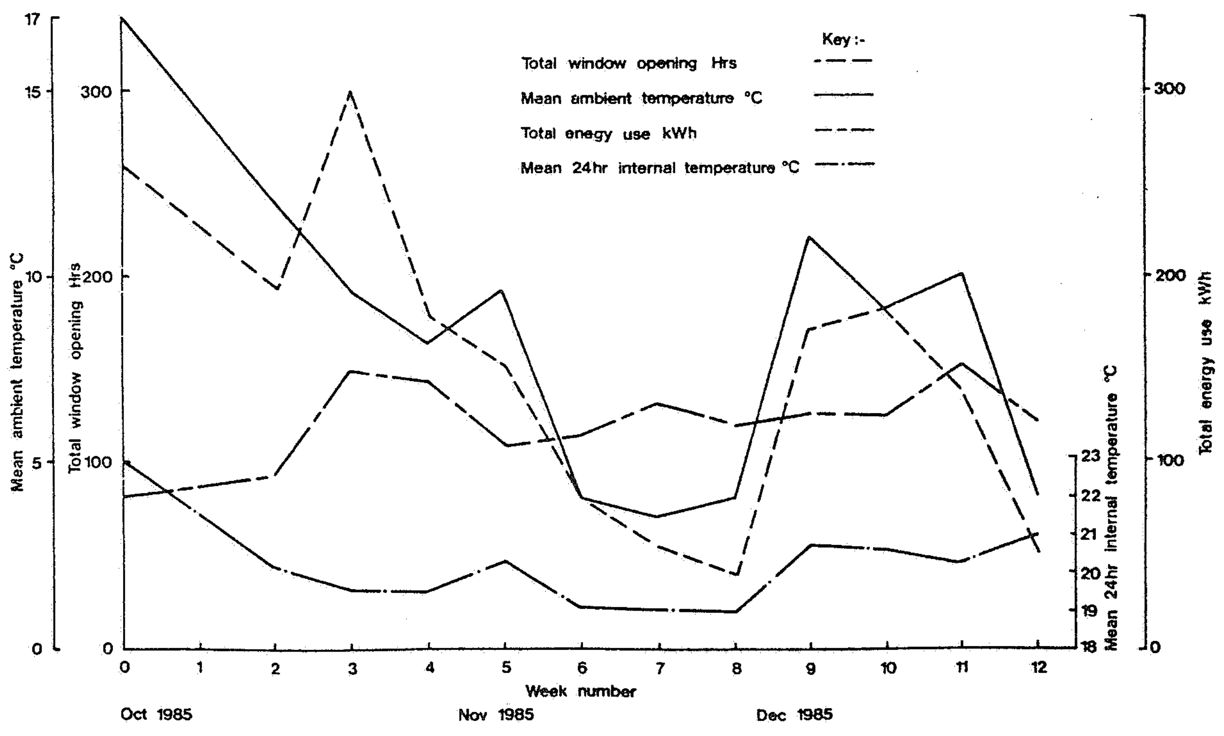


FIG. 10. AUTUMN WINDOW OPENING IN HOUSE 27

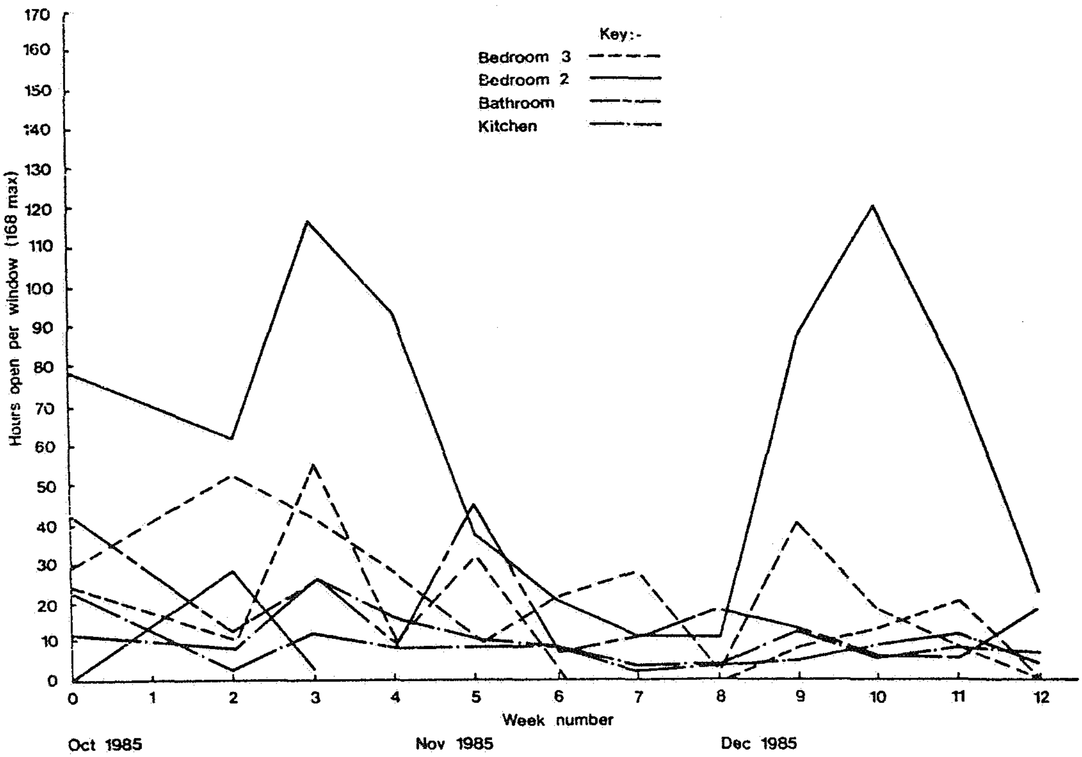


FIG. 11. INDIVIDUAL WINDOW OPENING PATTERN FOR HOUSE 27 (AUTUMN 1985)

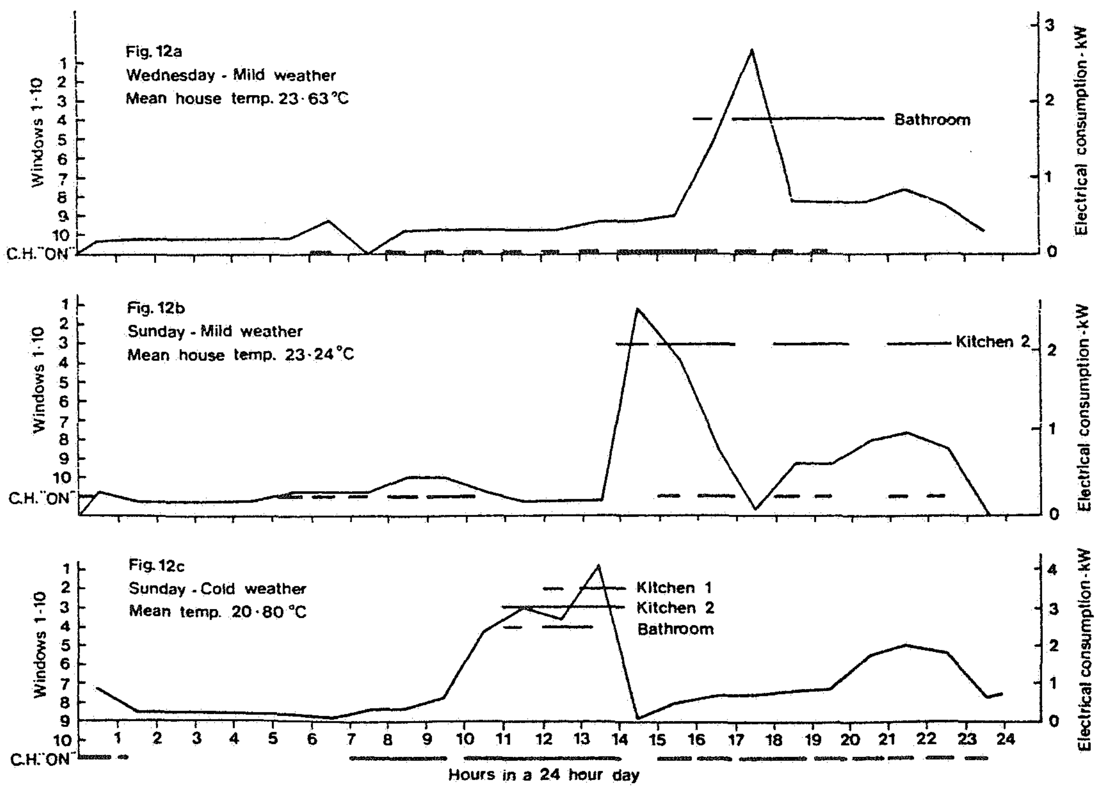


Fig.12 DAILY WINDOW OPENING PATTERNS - HOUSE 27

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
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PAPER 4

OCCUPANTS' INFLUENCE ON AIR CHANGE IN DWELLINGS

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Synopsis

The occupants' behaviour is one of the parameters which has the greatest influence on the air change in the dwelling. This applies both to naturally and to mechanically ventilated dwellings. On the basis of continuous measurement of the air change in 25 dwellings, the relation between the ventilation system and air change and between the number of occupants and air change is discussed. The air change in the 25 dwellings has been measured for a period of about one week during occupancy. The measuring principle applied is "the method with constant concentration of tracer gas". Even though the average air change for occupied dwellings is higher than the rate normally recommended in Denmark, some 20% of the dwellings have, nevertheless, an extremely low rate of air change. Only a small percentage of the dwellings have ventilation systems that can be adjusted to provide the desired rate of air change. The mechanical ventilation system usually gives too high a rate of air change, while the natural ventilation system usually provides too low a rate. Improved control of the total air change would achieve both energy savings and a better indoor climate.

Introduction

Previously it was the weather that had the greatest influence on the air change in the dwellings, but today it is left more up to ourselves to regulate this.

The influence of the outdoor climate on the air change has decreased concurrently with the dwellings becoming better tightened, and the holes remaining in the climate screen are today inadequate to produce the required degree of air change in the dwellings.

How do we solve the problem of ventilation and how good are the occupants at adjusting the air change according to their needs? These questions will be discussed on the basis of air change measurements in 25 occupied dwellings.

Measuring Method

The air change in each of the 25 dwellings was measured continuously during approx. one week with computer controlled measuring equipment. The measuring method applied was the "constant concentration of tracer gas".

The principle behind measuring with "constant concentration of tracer gas" is that a constant concentration of tracer gas is maintained in the rooms that are to be measured. The air change rate is then determined on the basis of how much tracer gas has to be let into the rooms to maintain the original concentration. We used the tracer gas SF_6 and the concentration in the rooms was maintained at 5 PPM.

In order to ensure that the dwellings could be used normally as regards closing of internal doors, measuring points were placed in each room in the dwelling. This also makes it possible to measure in which rooms the outdoor air enters the dwelling.

Composition of the Measurement Group

Of the 25 dwellings in the measurement group, 16 were equipped with natural ventilation, 3 with mechanical exhaust systems and 6 with both injection and exhaust systems. In most of the naturally ventilated dwellings there were vents from bathroom, toilet and kitchen.

Classifying the measurement according to type of building, it is seen that there were 9 measurements in apartment blocks of more than 12 storeys and 16 measurements in housing units of 1 or 2 storeys. No measurements were conducted in medium-rise apartment blocks.

The average size of the dwelling was 104 m^2, while the average number of occupants was 2.8 - roughly corresponding to the national average for Denmark.

The mean room temperature for the measurements was 21 ^{o}C; the outdoor temperature 1 ^{o}C; and wind velocity 4.9 m/sec. The outdoor temperature was slightly lower and the wind velocity higher than the average values for the heating season in Denmark.

Influence of the Occupants

In the article, air change rates measured in occupied dwelling are designated "total air change" and air change rates measured in locked up, unoccupied dwellings are designated "basic air change" (outdoor valves, doors, windows and ventilation systems closed).

As it is not possible to measure the basic air change and total air change rate at the same time, the basic air change rate is only measured once in each dwelling. The basic air change rate is measured for approx. 2 hours.

In figure 1 can be seen the influence of the users on the air change in the 16 naturally ventilated dwellings:

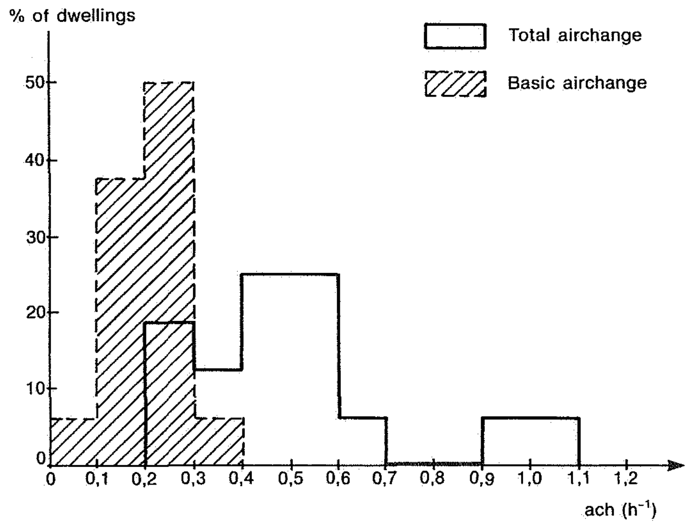

Fig. 1 Basic air change and average total air change for 16 naturally ventilated dwellings.

On average, the basic air change rate in the naturally ventilated dwellings is 0,19 times/h and the total air change rate 0.51 times/h, i.e. 63% of the total air change can be attributed to the behaviour of the occupants.

Even though the average total air change rate is close to the 0.5 times/h which is recommended in Denmark, the deviation in the values is so great that the air change in many of the dwellings is unacceptable. Over 30% of the naturally ventilated dwellings have a total air change rate of less than 0.4 times/h and in such a climate as Denmark's this will normally lead to problems with moisture.

In the mechanically ventilated dwellings, the air change is generally considerably higher than in the naturally ventilated dwellings. In fig. 2 the two ventilation systems have been compared.

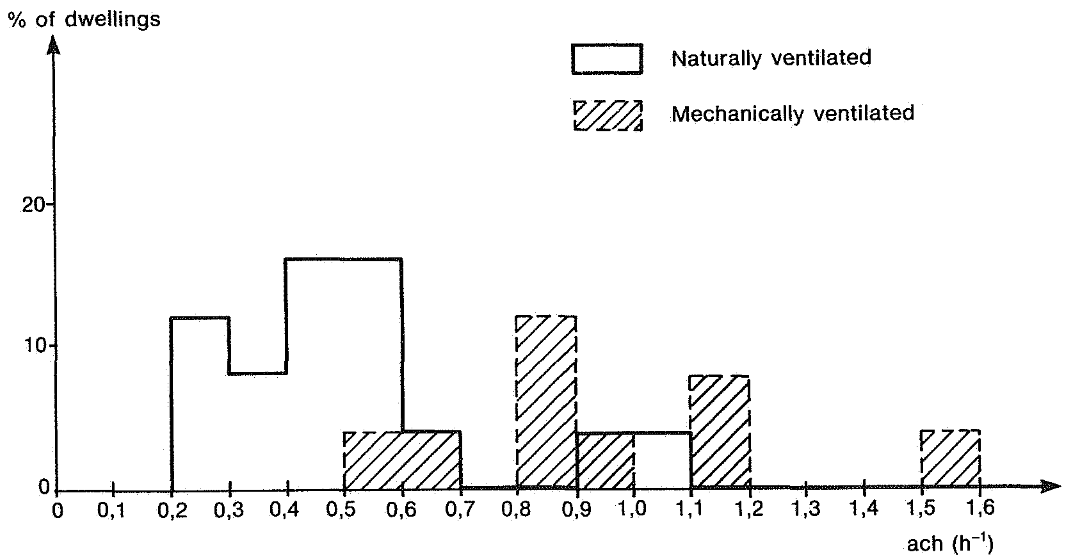

Fig. 2 Average total air change for the 16 naturally ventilated dwellings and the 9 mechanically ventilated dwellings.

The average total air change rate for the mechanically ventilated dwellings is 0.93 times/h, which is almost twice that of the naturally ventilated dwellings. Mechanical ventilation systems are normally dimensioned to provide all of the air change required. In addition to this there will always be a basic air change which depends on the tightness of the dwelling, influences from the climate and the ventilation system as well as an air change influenced by the behaviour of the occupants.

Calculated on the basis of the 6 dwellings where the dimension values for the ventilation system are known, the total air change turns out to be 70% higher than what was aimed at.

By looking at how the total air change varies according to time in a single dwelling, the occupant's influence on the air change can clearly be followed. In fig. 3 an example is shown of the variation of the air change for a one-family house with mechanical ventilation.

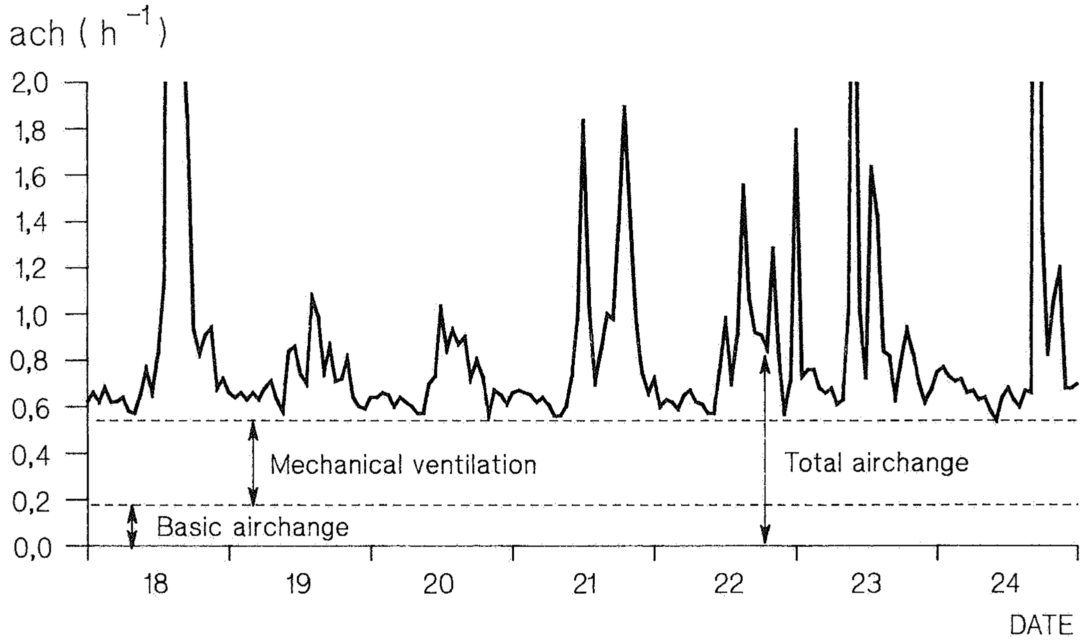

Fig. 3 The total air change as a function of time for a one-family house with mechanical injection and exhaust systems. The size of the basic air change and the performance of the ventilation system is shown on the figure.

The Behaviour of the Occupants

As is seen from figure 1, there is a considerable difference in the total air change between the individual dwellings. As the basic air change is fairly similar, it is the behaviour of the users which causes these large differences.

In order to get an idea of what influences the occupants' habits regarding ventilation and what is irrelevant, the following 4 assumptions have been tested for the 16 naturally ventilated dwellings:

- the total air change in times/h is a function of the number of occupants

- the total air change in m^3/h is a function of the number of occupants

- the total air change depends on the outdoor temperature

- the total air change depends on the room temperature

In figs. 4 and 5 the total air change rate can be seen as a function of the number of occupants; in fig. 6 as a function of the outdoor temperature; in fig. 7 as a function of the room temperature.

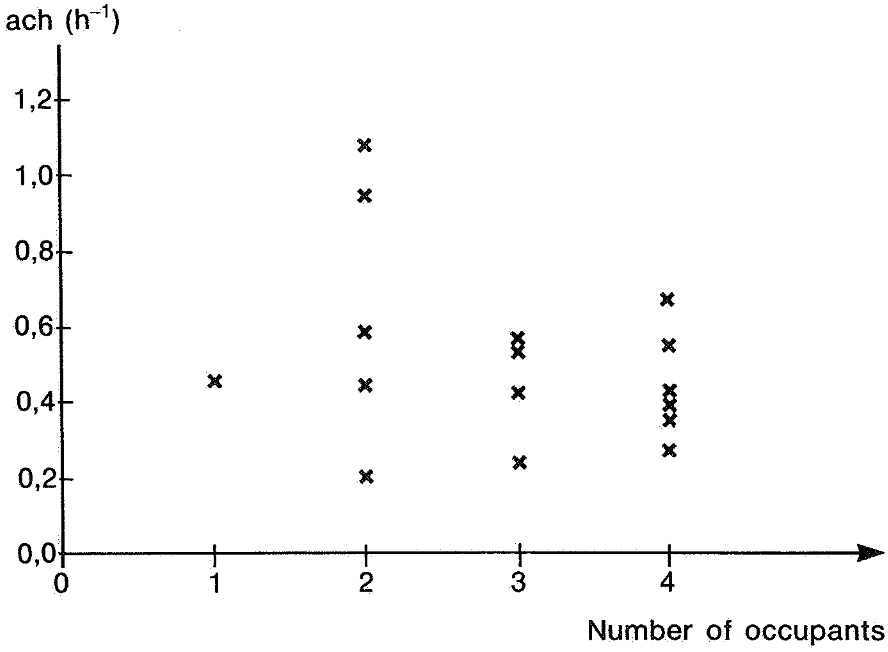

Fig. 4 Average total air change as a function of the number of occupants for the 16 naturally ventilated dwellings.

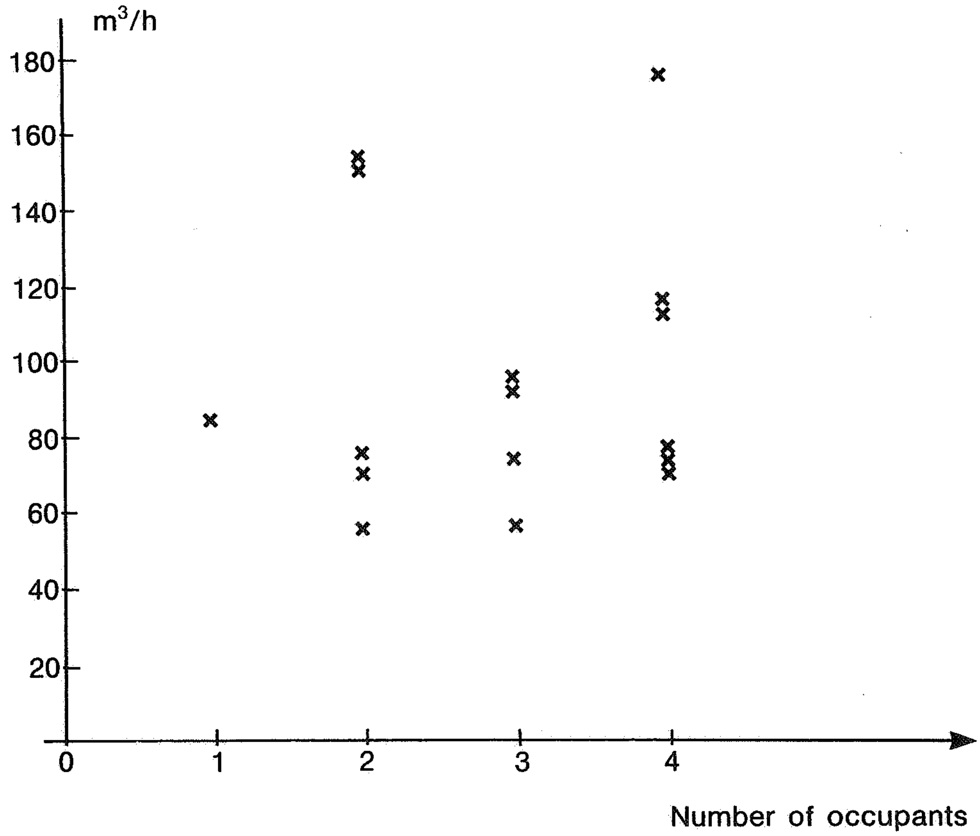

Fig. 5 Average total air change as a function of the number of occupants for the 16 naturally ventilated dwellings.

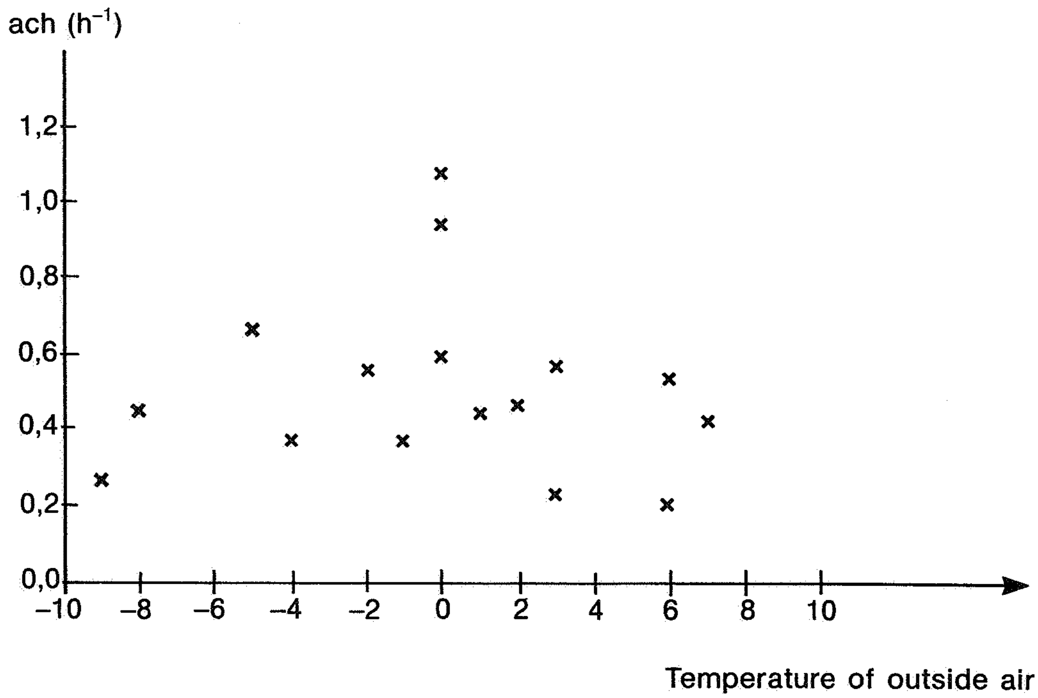

Fig. 6 Average total air change as a function of the outdoor temperature for the 16 naturally ventilated dwellings.

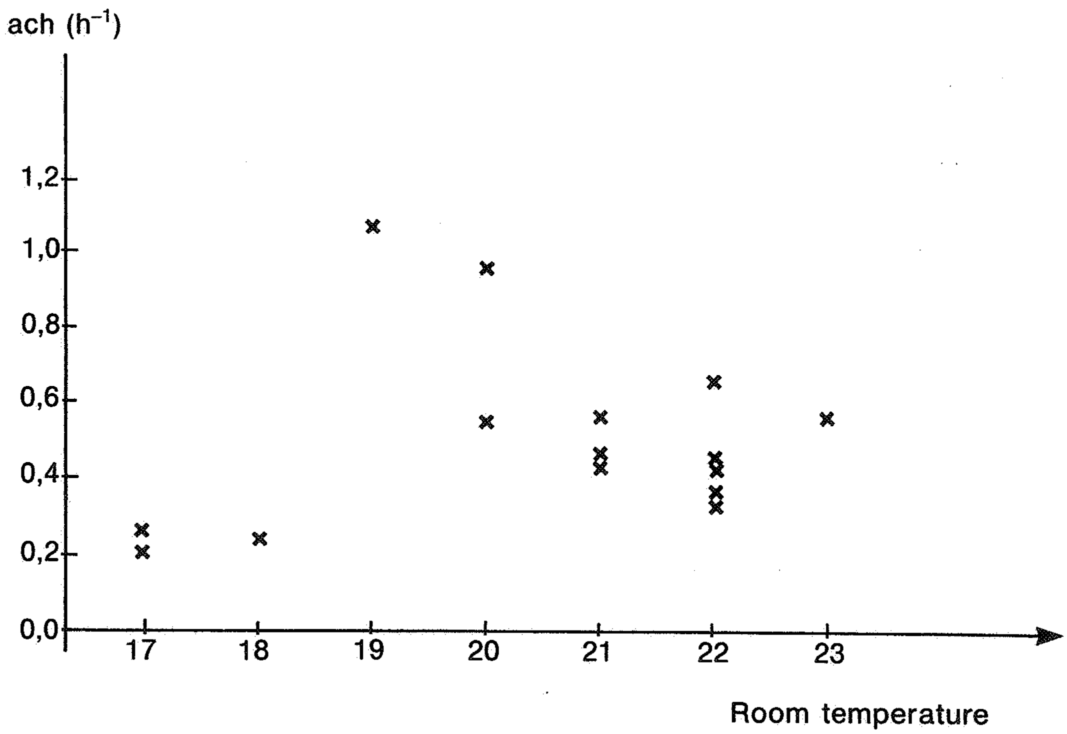

Fig. 7 Average total air change as a function of the room temperature for the 16 naturally ventilated dwellings.

From figures 4 to 7 it can be seen that the measurement results do not support any of the four assumptions about conditions that influence the ventilation habits of the occupants.

It is worth noticing, however, that the group in figure 7 is split into 2, a "comfort" group with an average to large air change or average to high room temperature, and an "energy-saving" group with low air change and low room temperature. All three members of the "energy-saving" group experienced considerable problems with heavy condensation of water vapour on the inside of the double-glazed windows.

Where Does the Air Enter?

Not all rooms receive the same amount of outdoor air. In 2-storey dwellings, the outdoor air will normally enter the dwelling by the lowest floor and then leave again from the uppermost floor.

In the 16 naturally ventilated dwellings, which have an average air change rate of 0.51 times/h, the average outdoor air change rate for the bedroom is 0.66 times/h and the average outdoor air change rate for the living room 0.36 times/h.

Conclusion

Measurement of air change rates in occupied dwellings shows that the occupants' behaviour has a very considerable influence on the total air change rate.

In the 16 naturally ventilated dwellings the users on average provide 63% of the total air change, but also in the mechanically ventilated dwellings, the user influence is considerable.

There is a very large difference in the air change rate from dwelling to dwelling. A difference which cannot be explained by differences in the tightness of the dwellings or the number of occupants. With the limited number and widely differing types of dwellings, which have been investigated here, it has not been possible to explain the large variations in the total air change.

The average total air change rate for the dwellings measured is 0.66 times per hour. Even though this rate is higher than the 0.5 times per hour recommended in Denmark, 20% of the dwellings measured had a total air change rate which was so low that indoor climate problems could easily arise.

Generally speaking, the occupants do not have sufficient possibility of regulating the air change in Danish dwellings. The only choice an occupant has is often either to open a door or a window or not to air the dwelling at all. Smaller ventilation openings which can be opened at varying levels and which are placed so that they can use the stack effect are seldom. Also in the mechanically ventilated dwellings, the regulation possibilities are limited, as the ventilation system, even set at the lowest level, normally gives a larger air change than required.

The measuring method used has proved to be most suitable for continuous measurement of the greatly varying air changes found in occupied dwellings.

References

B. Kvisgaard, P.F. Collet and J. Kure: Research on fresh air change rate: 1. Technological Institute, Copenhagen 1985.

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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PAPER 5

THE INFLUENCE OF OCCUPANT BEHAVIOUR ON INDOOR AIR QUALITY - A CASE STUDY

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Synopsis: A balanced ventilation system with heat recovery was designed and installed into an 11 storey prefabricated blockbuilding. Monitoring of the system operation was accomplished during a year. Operational characteristics, quantified energy saving, indoor climate parameters and the effect of occupants'behaviour on those were determined and analysed. Temperature runs during durable window opening and cooking periods were monitored and on the basis of the results comparison between the new experimental and the traditional reference system was made. From the point of view of efficient ventilation, perfect effluent removal and energy saving operation the developed system proved to be better than the reference one.
The need for the more detailed investigation of the occupants' activities and their influences on the indoor air quality has also arisen. Finally proposals for some modifications and the wide utilization of the system were made.

1. Introduction: A five-year research and development project was launched in 1980 in Hungary, financed by the Ministry for Building and Urban Development, to develop a new energy saving ventilation system for multistorey blockbuildings. The presently widely used ventilation systems are of suction type, outlets positioned in the kitchens, bathrooms and lavatories and fresh air supply is realized through the cracks of the windows. Due to the official measures to install and use airtight windows for the sake of energy saving, problems with the decreased ventilation rate had arisen.

   The need for a balanced ventilation originated from this and beside the demands of necessary and enough air change rate, proper flow patterns inside the flat and low noise level, the system had to meet the requirements of the energy saving operation as well.
   The system had to conform to the characteristics of the prefabricated building technology.
   The five-year R and D activity realized through the following steps: system analysis, choice of the most suitable one, draft then detailed design into an experimental house /in that time under construction/, manufacturing and installing, experimental running and comprehensive monitoring during a year, evaluation of the experiments and proposal for wide utilization. Beyond the system analysis, indoor air quality measurements and the examination of the effects of several occupants' activities were also aimed.

2. System description, operation and monitoring

The experimental object was a section of an 11 storey blockbuilding made of prefabricated wall-panels and of other prefabricated elements. The section consisted of 3 flats /see Fig.2./. Among the 33 dwellings each ventilated by the system, 6 of them in 3 storeys were instrumented with sensors for measurements.

For the sake of comparison a neighboring similar section of the building was also measured as reference. In this section the traditional suction-type ventilation system was operated.
The main unit of the experimental system was a rooftop ventilation unit. The Fig.1. shows the plan view of the roof of the section, the ventilation box and the distributing duct network. The pipes were connected to the vertical ducts placed in the ventilation shafts.

The Fig.2. shows the plan views of the dwellings, the distributing network for fresh air supply and the exhausted air outlets. The fresh heated air was supplied into the rooms above the doors, through adjustable inlet grids.
The suction outlets for exhausting were placed in the kitchen, bathroom and lavatory. For the sake of proper inside flow pattern the inner doors were equipped with permeable opening-grids.

In the reference section the suction-type ventilation system was the same as the exhausting part of the experimental one. The fresh air supply there, was provided through the cracks of the windows. The main unit of the experimental system consisted of the following parts: 2 fans, fresh air grid, filter, air-to-air recuperative heat exchanger for recovery, re-heater battery supplied by the warm water district heating system, shutters for by-pass out of the heating season. The ventilation systems operated continuously through the days without interruption. The air change rate was about 0.6, the fresh and exhausted air volumes were balanced in about 100 m3/h (sucked 40 m3/h from kitchen and bathroom, 25 m3/h from lavatory/.

The one-year running of the experimental and reference ventilation systems was monitored. The data acquisition system was automatic in operation and was controlled by a Hewlett-Packard HP-85 desk-top microcomputer.
The temperature-, rel.humidity - and pressure sensors were connected through cables into a scanner controlled by the HP-85.

The collected data in every minute were temporarily stored, then hourly averages were constituted and stored onto the tape-cartridge. Later the data were processed to the necessary form by a suitable program.

3. Results

The measured results were analysed and evaluated from three aspects:

- energetic evaluation,
- examination of indoor air quality produced by the ventilation system,
- effects of the occupants' behaviours on indoor climate.

Since the scope of this paper is intended to focus on the third kind of evaluation the results of the previous ones are presented only in a few words.

From the energetic evaluation the experimental balanced ventilation system proved to be an energy saving one compared to the reference. The measured recovered amount of energy was 90 GJ /Giga-Joule/ per a heating period /180 days in Hungary/.

The average indoor temperatures in the dwellings were in the range of 19-25 centigrade . Unfortunately - due to the badly adjusted central heating system - temperature gradient of 5-6 centigrade through the 11 storeys was found. The inside relative humidity was measured between 35-60 percent.

Beyond the measurement of the temperature and rel. humidity the effect of the air jet blowing from the fresh air inlets was also examined. The air jets coming from the inlets positioned above the doors did not cause unpleasant draught feeling in the occupation zone. The velocities measured within the jet decreased below 0.3 m/s within 0.8 m /distance from the inlet/, i.e. jets decayed rapidly.

To examine the influence of the occupants' behaviour on the indoor air quality some deliberate tests were accomplished. Two kinds of activity were analysed:

- the influence of the durable window opening on indoor temperature run,
- the effect of the cooking on the indoor air,

3.1 The effect of window opening

Fig.3. shows an example to the results, where main characteristic temperature-runs are collected. In this case no window opening occured through the day.

The upper curve shows the change of the warm water temperature going to the radiators /primary temp./. The control is weather and inside temperature dependent and for the sake of energy-saving in night period /from 10 p.m. till 4. a.m./ the system, operates with decreased temperature: about 40-45 centigrade . The lower curve shows the outdoor temperature run.
The curves in the middle show the averaged indoor room temperatures in the staircase, in the flats in 1st, 5th and 11th storeys respectively. The aim of the tests was to determine the changes in room temperature runs caused by deliberate durable window openings.

Fig.4. shows an example. One of the windows of the two rooms of dwellings in the 11th and 1st storeys was open through 1 and 2 hours respectively. Due to the very intensive air change - though the casements of the windows were only partially opened, and the curves represent the average room temperature of the two rooms communicating each other through open doors or permeable openings - remarkable drop /3-6 centigrades/ in the temperatures could be observed.

Decreasing of the opened area of the window to half of the previous setting and on the contrary increasing the duration of the open status /5 hours/, the obtained results could be seen in Fig.5. /reference house, flat in the 1st storey/. Temperature drop is smaller but long-lasting compared to the previous test.

The same opening test was carried out in one of the flats in the 1st storey of the experimental building as well.
The result is presented in Fig.6.
The temperature run and the transitions are smoother compared to the reference.

3.2 The effect of cooking

As can be seen from the Fig.2. the dwellings have relative small kithens. The cooking process for 4 persons - which is the average inhabitant number - can produce large amount of heat, unpleasant vapours and odours.
For the elimination of these ventilation outlets /adjustable valves/ were installed above the cooking stoves. Exhaust hoods above the stoves were not used /unfortunately/.

To obtain sharp differences in the results, Saturdays and Sundays were selected for the tests, because usually in week-ends the families are at home and the cooking activities are also larger.

The observed period was extended from 8 a.m. till 4.pm and indoor kitchen temperature was monitored.

The peak temperature raise - overheating temperature difference - and the decreasing lapse-rate were watched. Comparisons between the two ventilation systems were made.
Some results are shown in figures 7-9. The three curves present the kitchen temperature run for the experiment , the reference building and the outdoor temperature respectively.

4. Conclusions and proposals

The main goal of the presented investigation work was to examine a newly developed balanced ventilation system - with comparison to a reference - and evaluate it's performance, operation and efficiency. However being a well equipped experimental site for comprehensive monitoring, there were possibilities to examine other problems, as well as the consequences of several occupants' activities, measurement of indoor flow patterns etc.

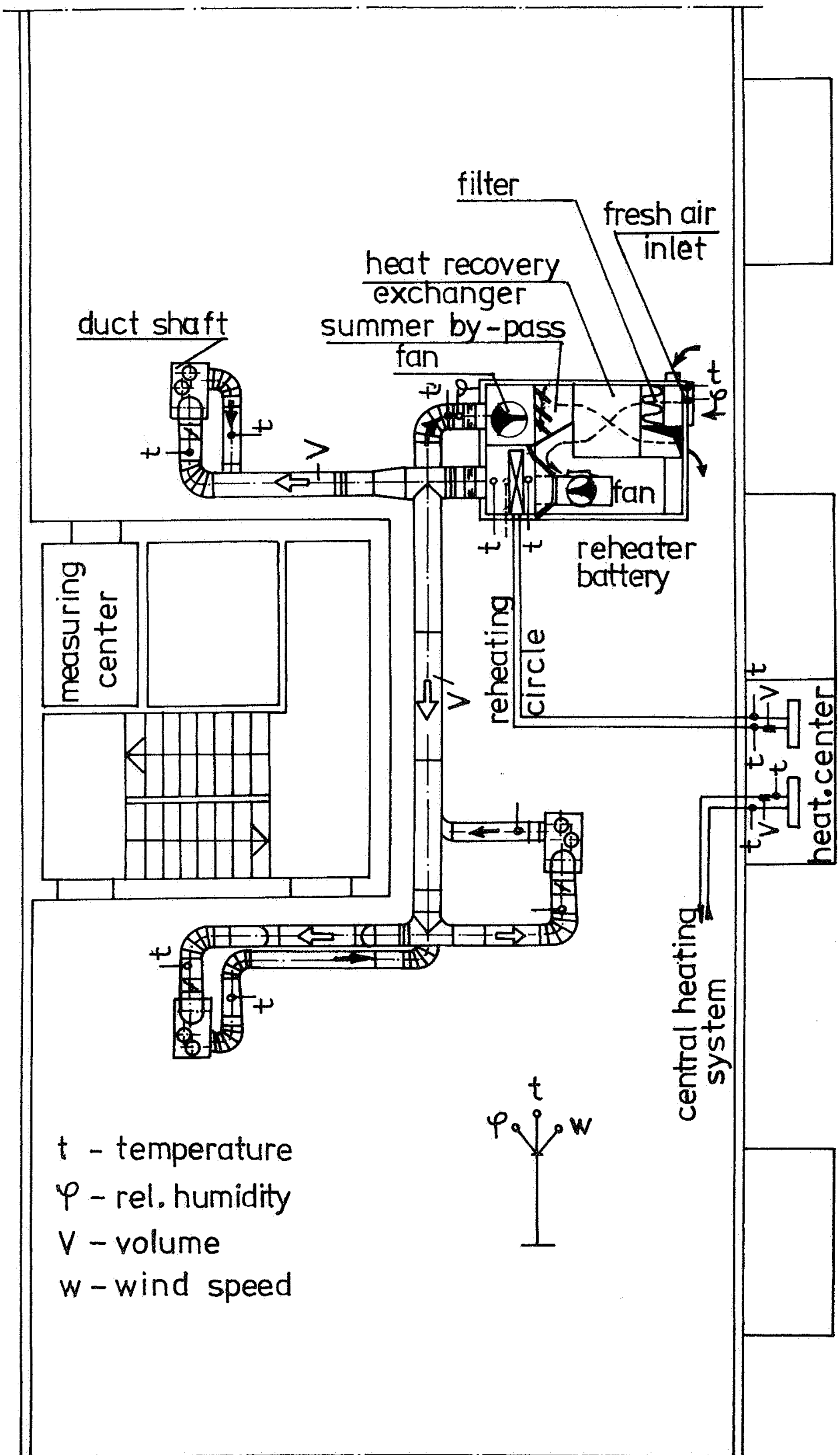
Since the whole monitoring system was installed primarily for the measurement of operational and energetic parameters, therefore more detailed investigation of other phenomena was slightly limited. For example: for the examination of the consequences of window opening and cooking processes more frequent sampling - say in every 15 minutes - would have been needed.

For the more detailed study of the two selected activities the more exact fixing of the several influencing parameters would have been also accomplished e.g. circumstances of the cooking: duration, intensity and detailed program of cooking process, more precise follow up of the decay of the excess heat and contamination etc.
However the measurements carried out produced valuable information on the basic consequences of the examined activities.

Furthermore subjective tests were also made. Some occupants were asked about the ventilation efficiency after cooking and opinions were collected and evaluated. The results of the presented measurements and the responses of the occupants proved the new balanced ventilation system more efficient and perfect compared to the reference one.

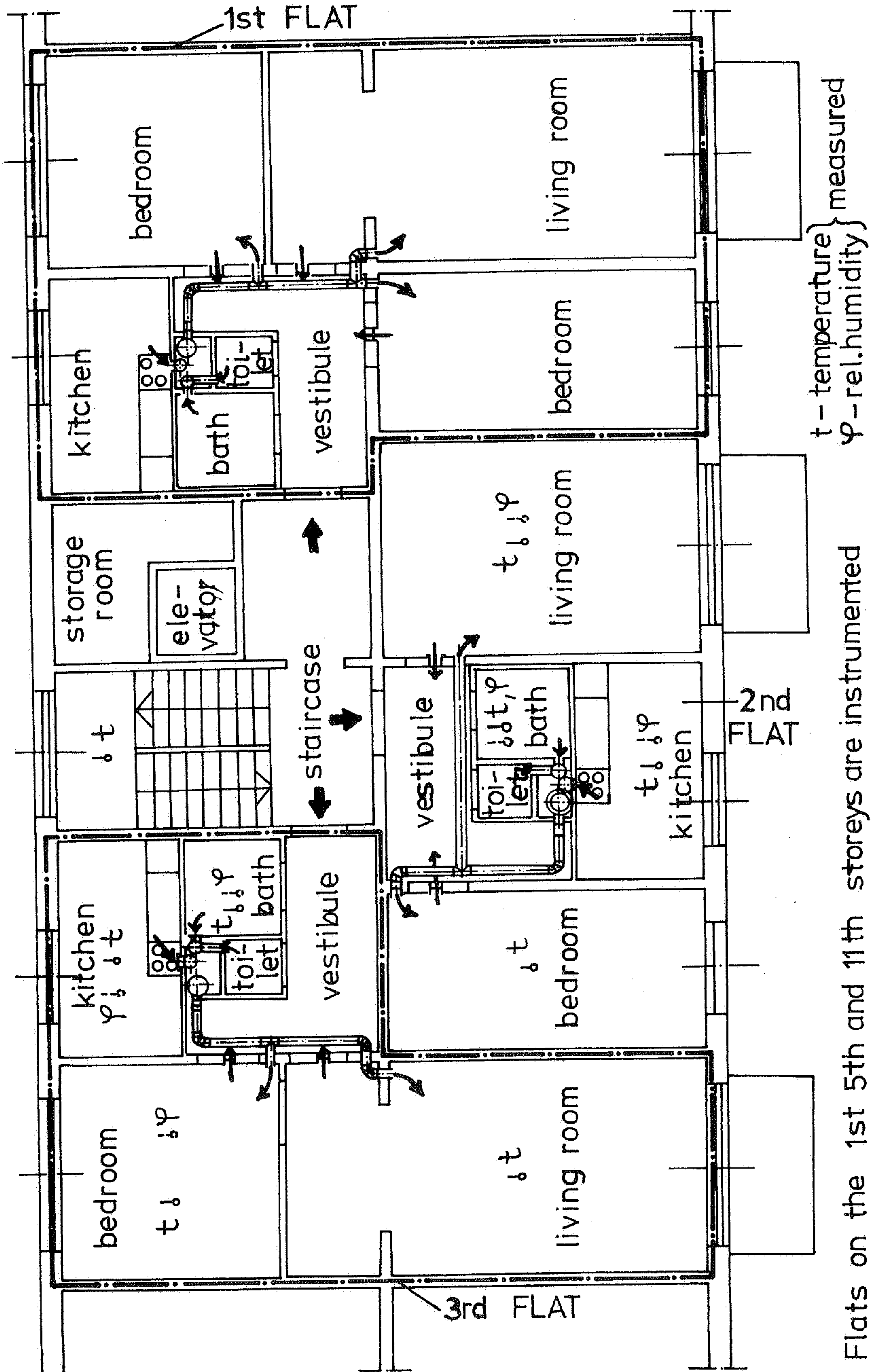
According to the results of the comprehensive examinations the wide-spread utilization of the new system was proposed and the preparation for this has been launched.

The need for the further more detailed investigation of the occupants' activities and their influences on the indoor air quality was also noted.



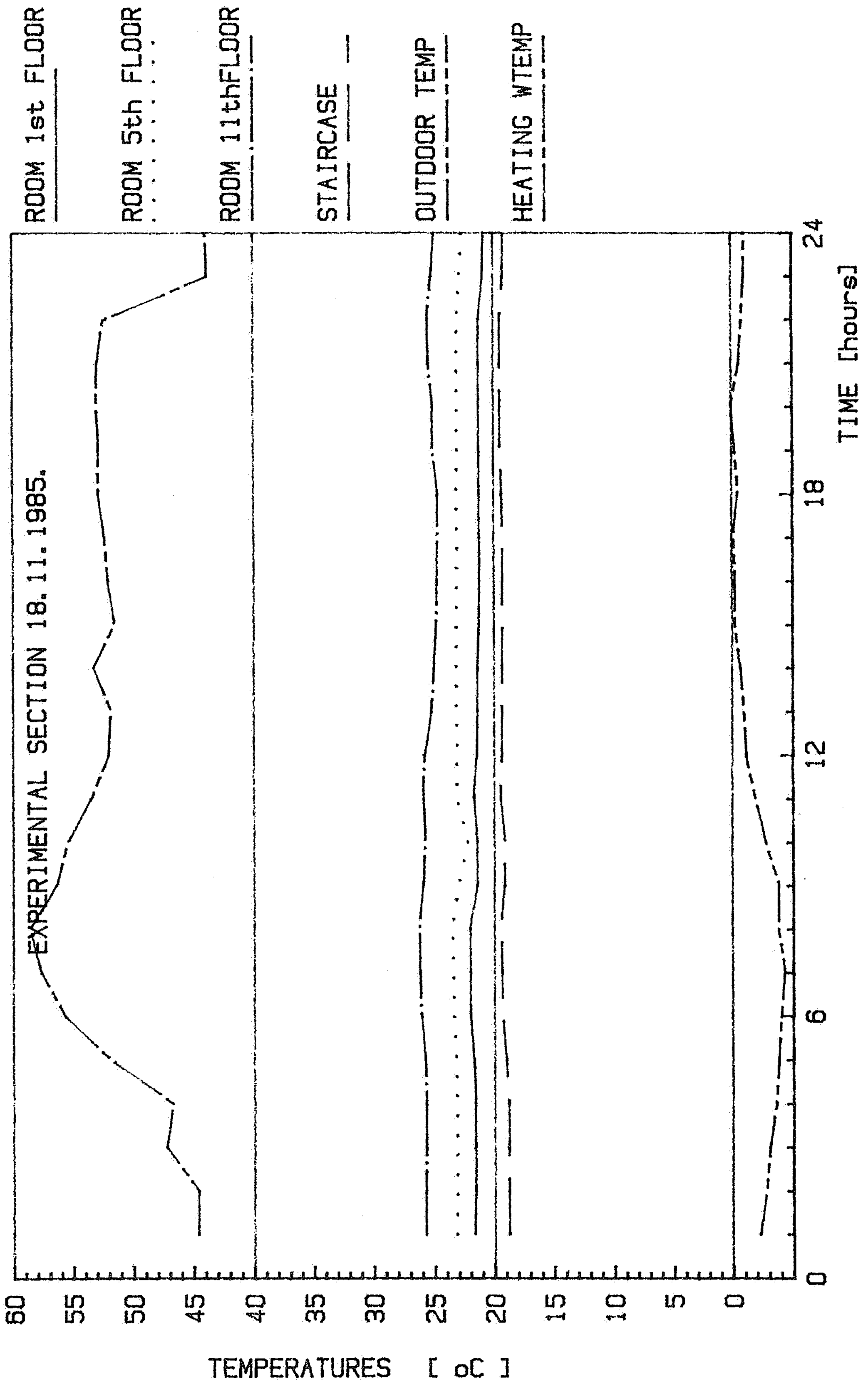
Plan view of the roof, roof-top ventilation unit and duct network

Fig. 1.

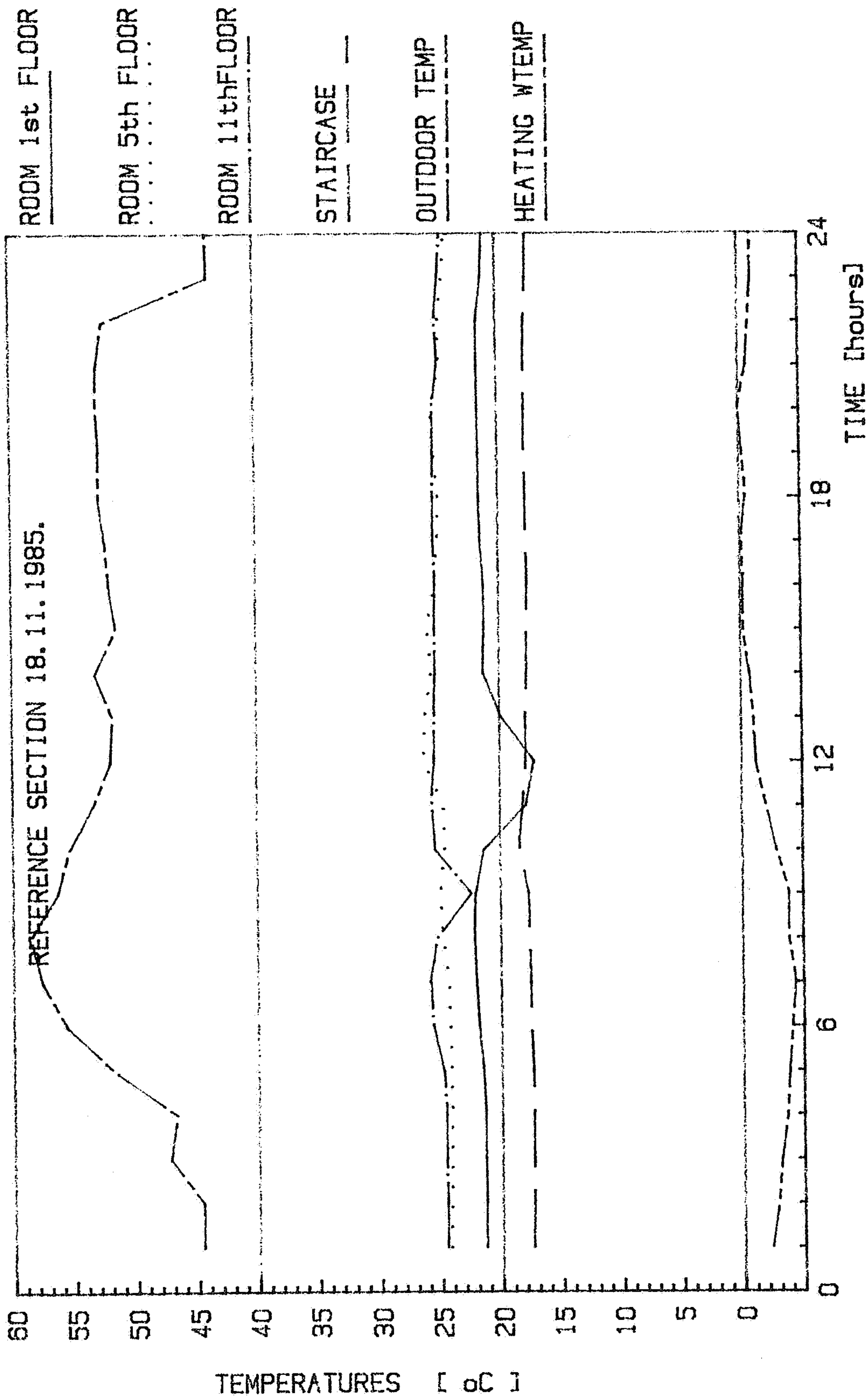


Plan view of the experimental flats with ventilation network

Fig. 2.

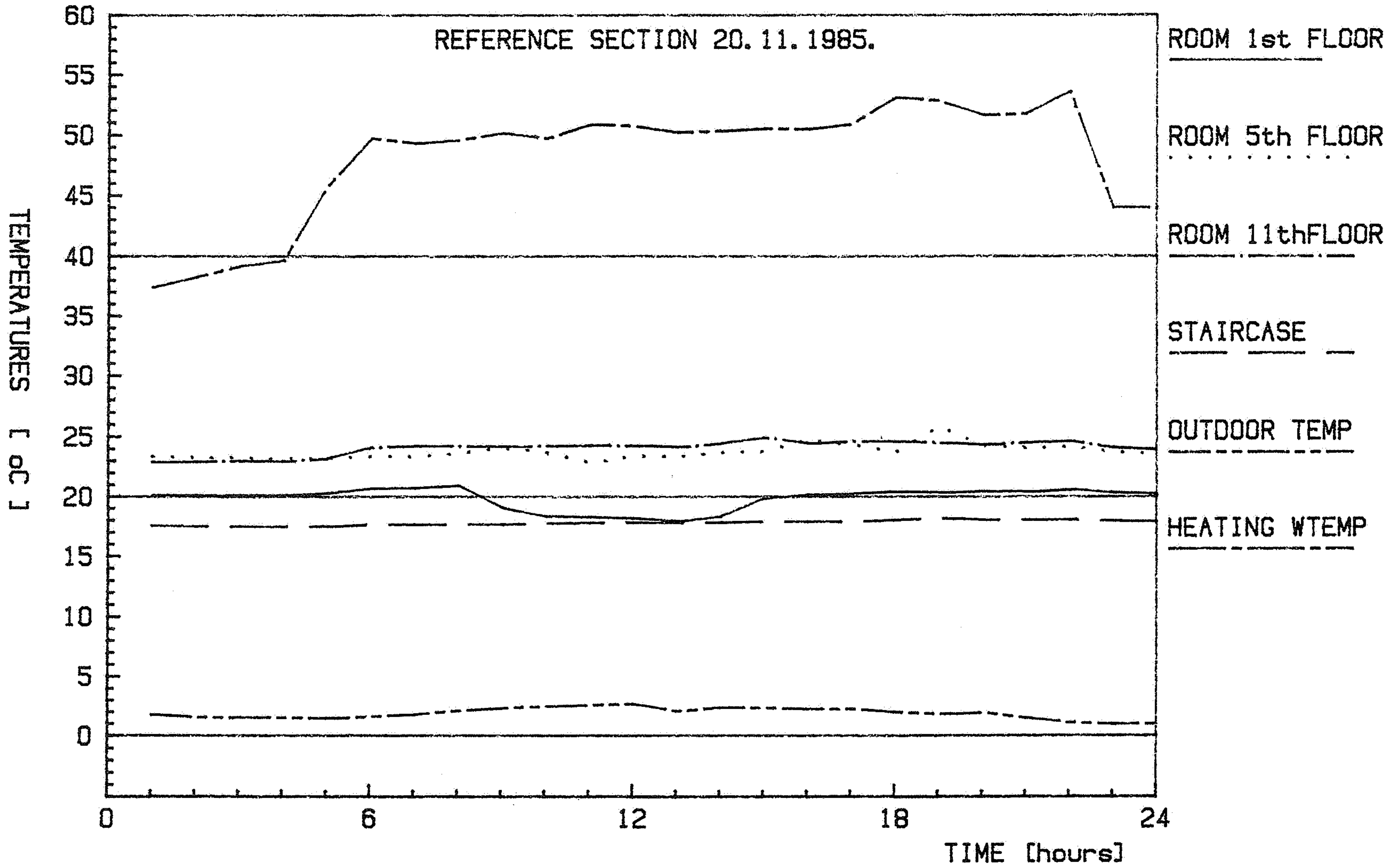


Temperature runs
Fig. 3.



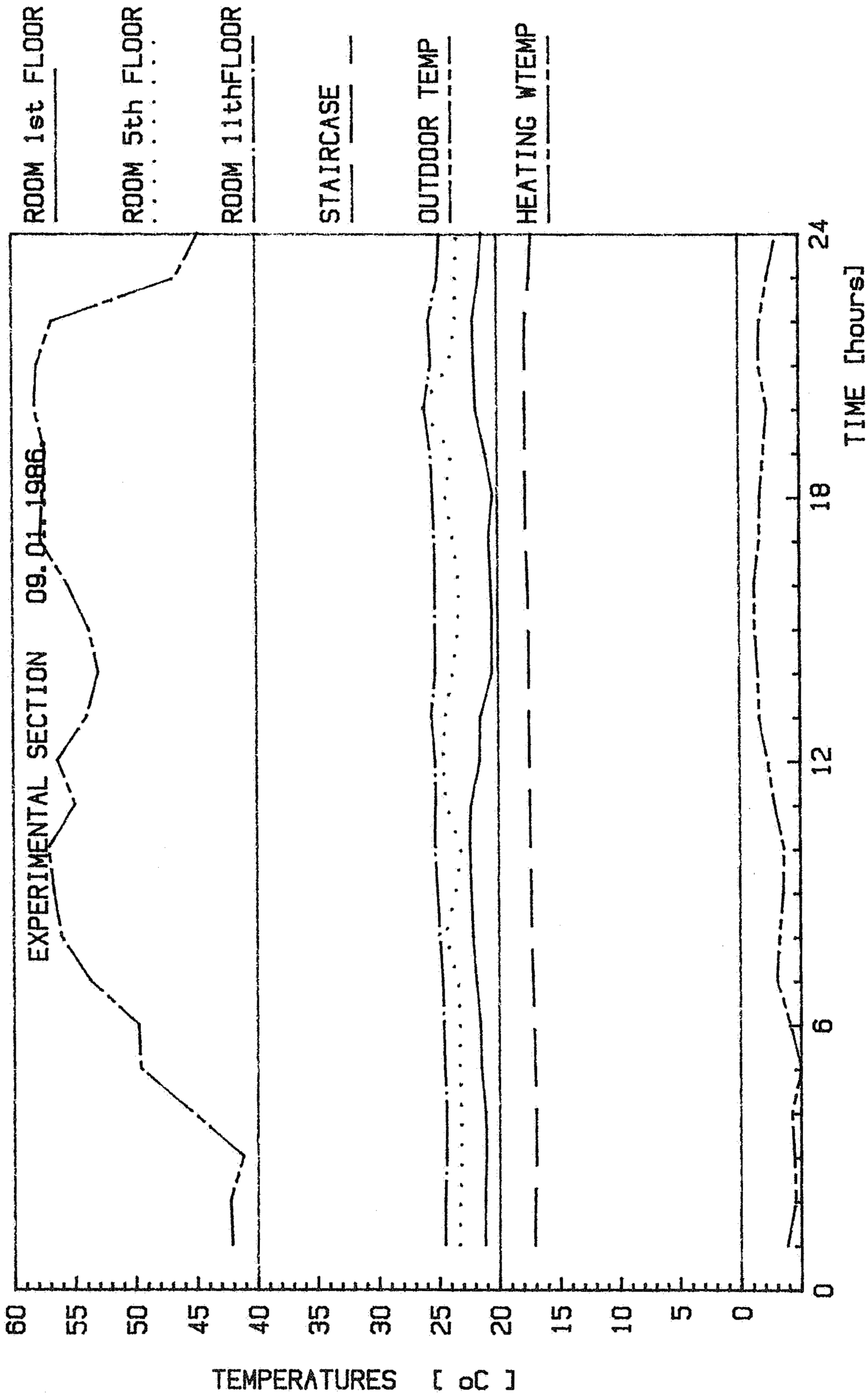
Temperature runs. The effect of window opening

Fig. 4.



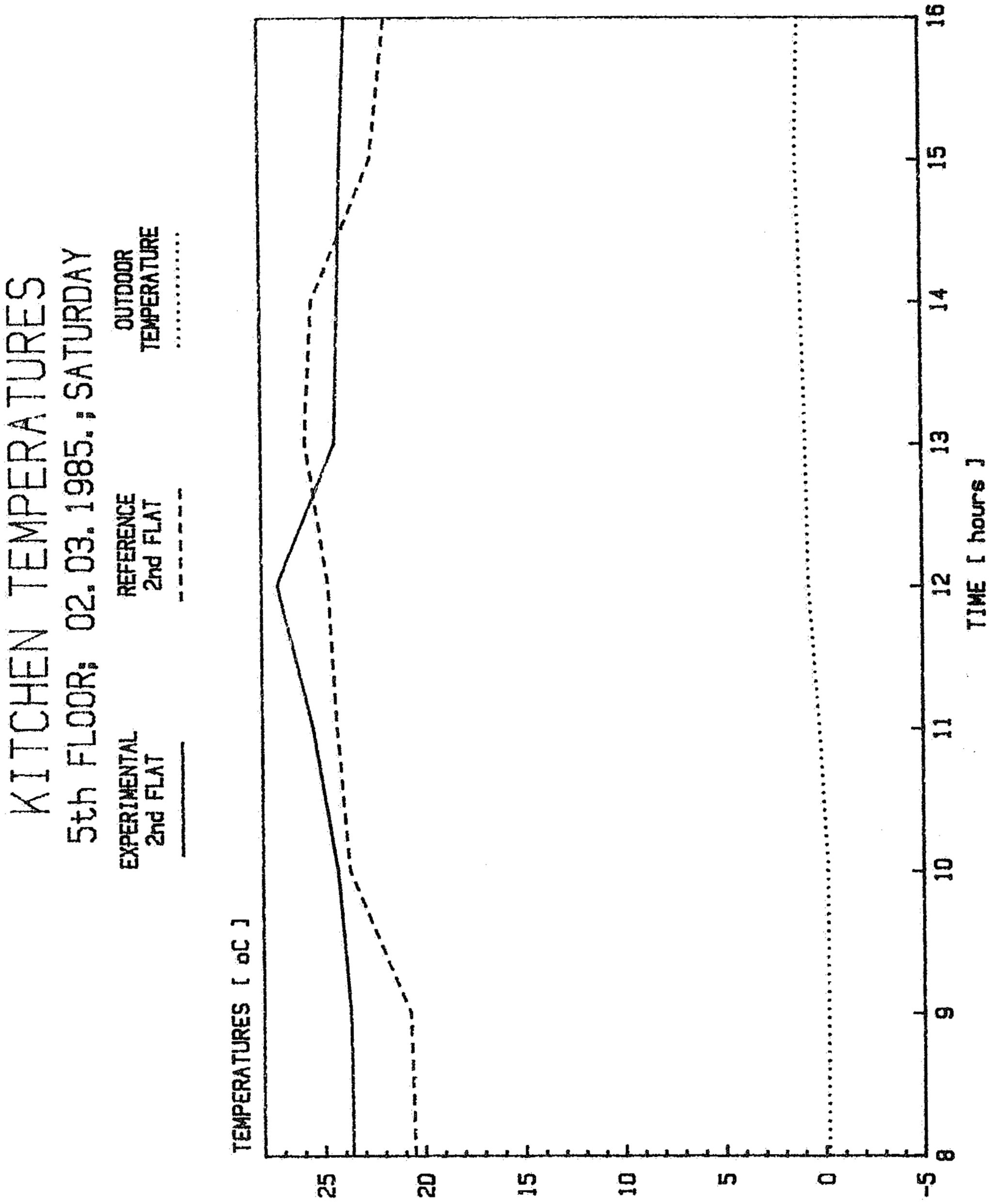
Temperature runs.The effect of window opening

Fig. 5.



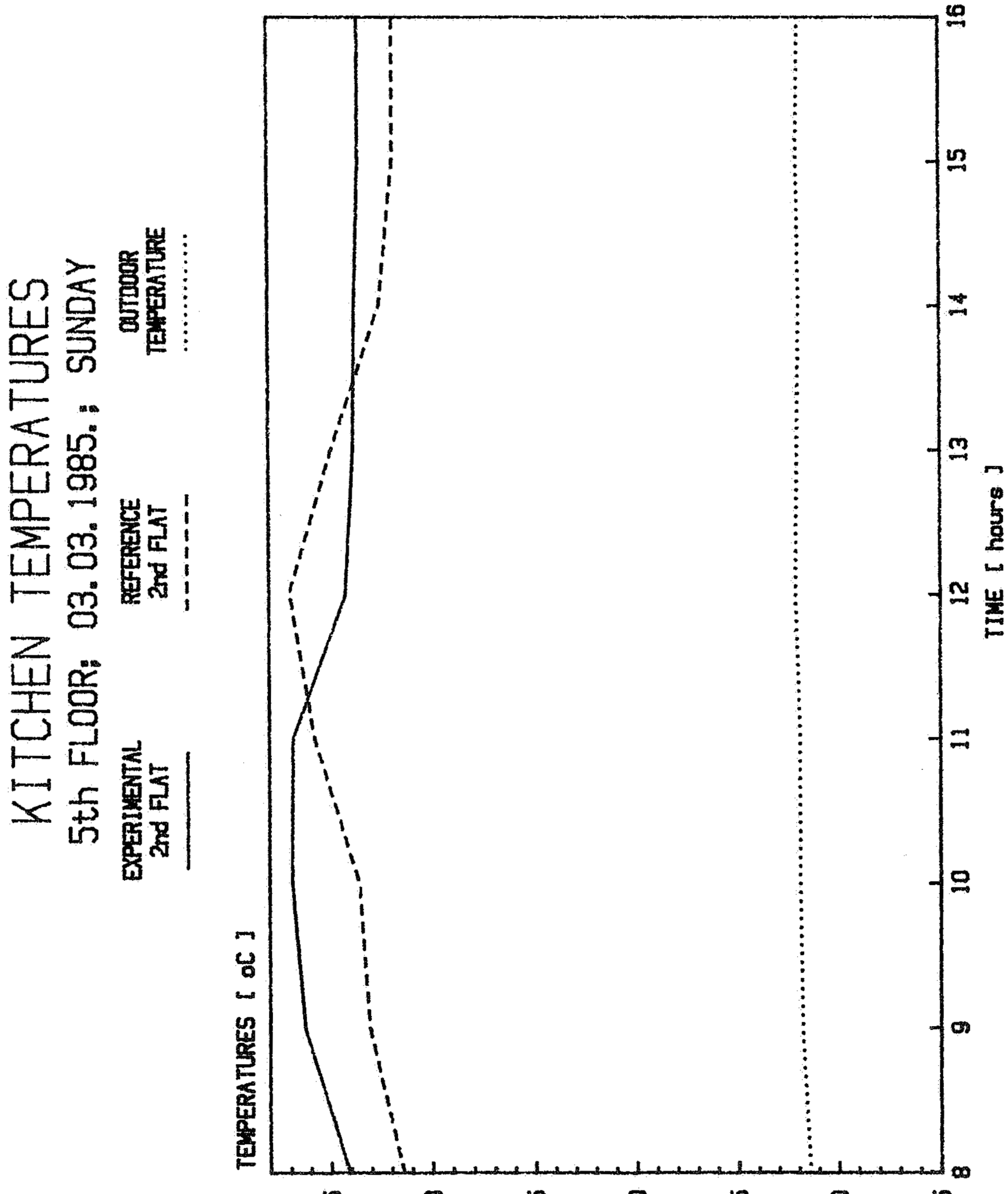
Temperatures runs. The effect of window opening

Fig. 6.



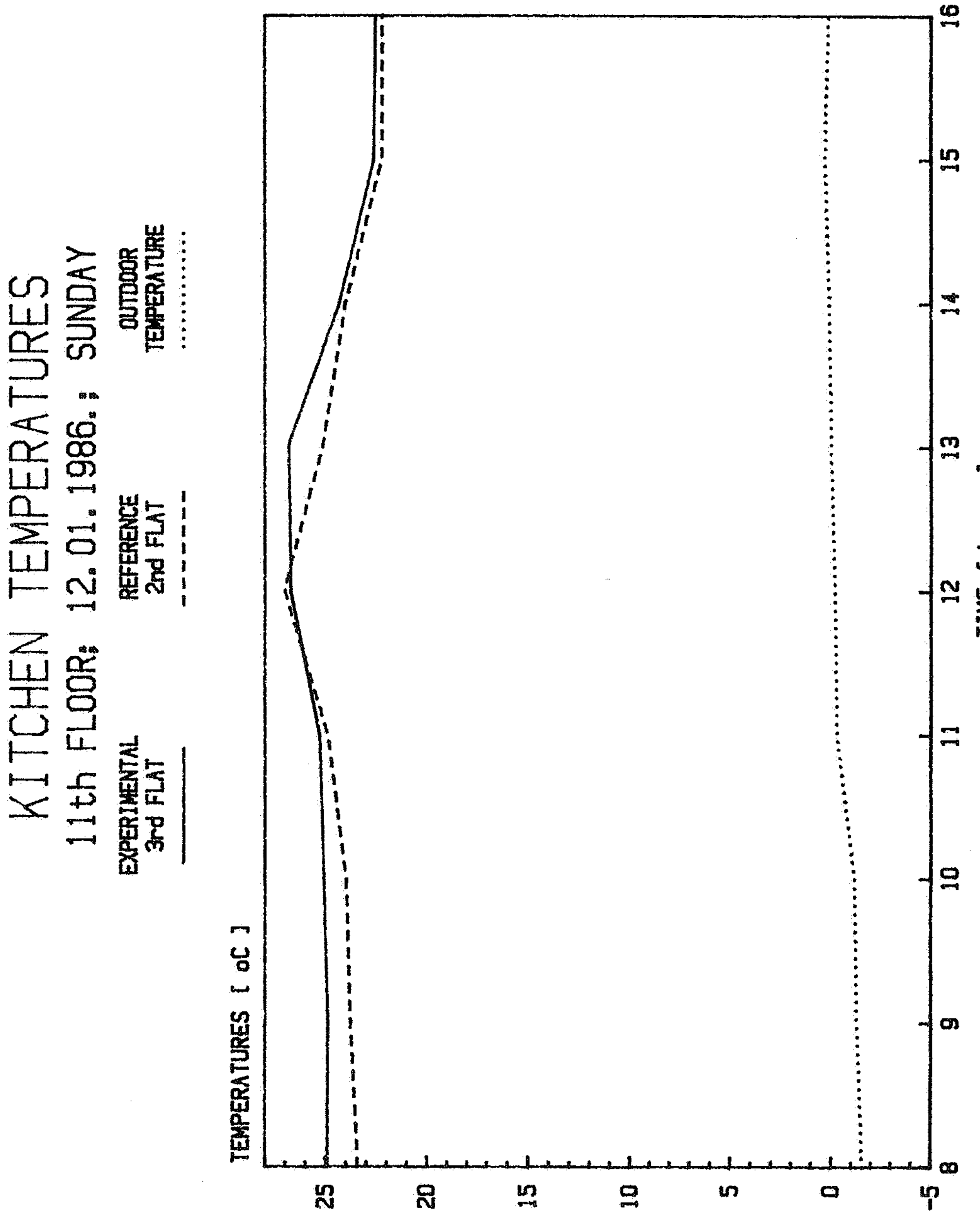
The effect of cooking process

Fig. 7.



The effect of cooking process

Fig. 8.



The effect of cooking process

Fig. 9.

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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PAPER 6

VENTILATION AND OCCUPANT BEHAVIOUR IN TWO APARTMENT BUILDINGS

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SYNOPSIS

In this paper we approach the subject of ventilation and occupant behavior in multifamily buildings by asking three questions: 1) why and how do occupants interact with ventilation in an apartment building, 2) how does the physical environment (i.e., building characteristics and climate) affect the ventilation in an apartment, and 3) what methods can be used to answer the first two questions. To investigate these and other questions, two apartment buildings in Chicago were monitored during the 1985 - 1986 heating season. In addition to collecting data on energy consumption, outdoor temperature, wind speed, and indoor apartment temperatures, we conducted diagnostic measurements and occupant surveys in both buildings. The diagnostic tests measured leakage areas of the individual apartments, both through the exterior envelope and to other apartments. The measured leakage areas are used in conjunction with a multizone air flow model to simulate infiltration and internal air flows under different weather conditions. The occupants were questioned about their attitudes and behavior regarding the comfort, air quality, ventilation, and energy use of their apartments. This paper describes each of the research methods utilized, the results of these efforts, and conclusions that can be drawn about ventilation-occupant interactions in these apartment buildings. The major conclusion of this work is that a multidisciplinary approach is required to understand or predict occupant-ventilation interactions. Such an approach must take into account the physical characteristics of the building and the climate, as well as the preferences and available options of the occupants.

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1. INTRODUCTION

Unlike infiltration, the uncontrolled air flow through leaks in the building envelope, ventilation depends not only on climate and building characteristics, but also on the operation of mechanical systems and on the behavior of the building occupants. We find it interesting that only 35 of the 1858 entries in the Air Infiltration Centre's AIRBASE address the effect of occupancy on ventilation.[1] Work on the subject of occupant interaction with ventilation was being performed in Great Britain as early as 1950.[2,3] More recently, as part of the general interest in the topic of occupant effects on energy use, a number of studies of occupant-ventilation interactions have been made in the other European countries.[4-7] Our work focuses on occupant interactions with ventilation of multifamily buildings in the United States.

In this paper we approach the subject of ventilation and occupant behavior in multifamily buildings by asking three questions: 1) how does the physical environment (i.e., building characteristics and climate) affect the ventilation in an apartment, 2) why and how do occupants interact with ventilation in an apartment building, and 3) what methods can be used to answer the first two questions. To answer these questions we investigated ventilation and occupant behavior in two apartment buildings. Our approach is multidisciplinary, using research techniques from engineering, physics, and the social sciences. These case studies focus on both understanding each building, and evaluating the results obtainable with each of the research techniques.

2. BACKGROUND

The two buildings we are studying are in Chicago, Illinois, and are typical of much of the urban housing stock throughout the north-eastern and north-central United States. These buildings are part of a larger study of retrofit performance in multifamily buildings being conducted by Lawrence Berkeley Laboratory (LBL) and the Center for Neighborhood Technology (CNT), a Chicago based, not-for-profit organization working in energy conservation.

The climate in Chicago is predominately continental, ranging from relatively warm in summer to relatively cold in winter. While temperatures are moderated by the proximity of the Great Lakes, the average temperature in January is -5 ^{o}C. Annual degree days, base 18.5 ^{o}C, are 3600 for heating, and 370 for cooling. The average wind speed, 4.6 m/s, is somewhat higher than the national average. The normal air-conditioning season lasts from about mid-June to early September.[8]

We refer to the two buildings as Albany and Bosworth, after the streets on which they are located; both are in flat-terrain residential neighborhoods, amidst blocks of three-story apartment buildings. The buildings are very similar to each other, and are typical of early 20th-century construction in large U.S. cities. The buildings are three-story brick construction with a central fire wall, and were built in the 1920s. The arrangement of the apartments is similar, symmetrical floor plans with a common entry hall and central stair in front, and separate balconies and outside stairs in back (see Figures 1 and 2). As there are adjacent buildings on two sides, light and air is provided to interior rooms by air shafts, located between the buildings at Bosworth, and on the interior of the building at Albany. Albany is owned jointly by three of the households who rent out the other four apartments. Bosworth is owned by a not-for-profit housing organization, and is managed by two of the households; all of the residents at Bosworth are renters.

The building walls are uninsulated, and there is about 10 cm of insulation in the attic at Albany, and no insulation in the attic at Bosworth. Storm windows were recently installed in both buildings. Both buildings have basements half below grade which contain the boiler, domestic water heater, and laundry facilities. At Albany, half of the basement has been converted into an apartment.

Both buildings are heated by gas-fired steam boilers which are approximately twenty years old, and replace the original coal-fired systems. The distribution system is a single pipe run; the condensate falls by gravity down the same pipe that provides the steam. Because the distribution system relies on natural convection, has a large thermal mass, and does not have individual apartment control, control and balancing of such a system is difficult.[9] Poor system balance, the subject of a parallel study underway by CNT, means that some apartments will be overheated or underheated, depending on the location of the thermostat. (Thermostat relocation alone cannot solve the problem.) While ventilation (and infiltration) may contribute to the non-uniform heating load in the building, it is also one possible means for residents to control the temperature in their apartments, e.g., by opening windows in overheated apartments.

In buildings such as Albany and Bosworth, which have no central mechanical ventilation, the only options for residents to control ventilation are using small fans (especially to promote cooling in summer), and opening and closing doors and windows. Windows, however, provide several functions other than ventilation, and it is important to differentiate these reasons, as occupants may choose to open or close windows for reasons that have nothing to do with ventilation. People open windows for the following reasons (among others):

- to control the inside temperature due to broken or lack of control on heating system, excessive solar gain, poor heat distribution, etc.
- to control air quality, opening windows both on a routine basis, and at specific times, i.e., during cooking, cleaning, etc.
- to control excess humidity during showering, bathing, clothes washing, etc.
- to maintain contact with street: supervise children, talk with friends, listen to activities;
- to follow custom or tradition: windows open at night "because it's healthy", airing every morning for one hour, etc.

Some reasons for not opening windows include:

- windows are difficult or impossible to open (e.g., painted shut);
- security;
- to keep out dirt and insects (especially if they lack screens);
- to prevent heat loss;
- to maintain privacy or keep out unwanted noise.

Previous researchers have found strong correlations between the degree of window opening for airing and the external air temperature. Lyberg found, across several different study samples, a constant value for the product of the number of windows open and the temperature difference between inside and outside (Reference 5). Although these results would indicate that the controlling factor is the temperature of the outdoor air, we suspect that other variables also play an important role.

Many of the reasons for opening windows (and some of the reasons for keeping them closed) seem to relate to some form of occupant comfort. If the occupant is not comfortable with the prevailing indoor climate, he or she will try to modify it in the required direction.[10] However, measuring comfort to predict window opening is not a straightforward problem. Looking only at thermal comfort uncovers numerous physical and psychological factors. On the physical side are such factors as air temperature and movement, relative humidity, mean radiant temperature, activity level, and clothing. On the psychological side are such factors as temperature preference, tolerance, expectation and locus of control (an indication of how much control individuals feel they can exert over their environment). The question of comfort is further complicated by the variety of techniques occupants can use to maximize their comfort. In addition to opening windows to achieve comfort, occupants can change their clothing levels, use auxiliary heating, or complain to the management (or others) to provide more uniform heating.

3. METHODS

Given the complexity of understanding occupant interactions with ventilation, we used several methods to examine the problem. These methods represent different perspectives from which the problem can be approached, which in combination provide a more detailed picture. The methods chosen include 1) long-term monitoring of internal apartment temperatures, 2) short-term diagnostic measurements of air leakage, along with simulation of air flow within the building, and 3) detailed interviews with the occupants about their ventilation-related behavior. Other methods that were considered, but not undertaken because of budget limitations or practical considerations, were: monitoring window openings directly, photographing the buildings at frequent intervals, continuous tracer gas measuring of air flow, and having the occupants keep activity logs.

3.1 *Monitoring*

As mentioned previously, apartments experience different temperatures for a variety of reasons, which include peculiarities of the heating system (broken radiators, valves and vents), different orientation to sun and wind, location in the building with respect to height, buffering by other heated apartments, location of leaks, and modification by the occupants. We expected to see evidence of occupant behavior, such as window opening and the use of auxiliary heating by examining the temperature profiles of the individual apartments.

As part of CNT's research program, Albany and Bosworth were instrumented with data acquisition systems that collected six months of data on indoor apartment temperatures, outdoor temperature, wind conditions, and boiler energy consumption. All data points were stored every 10 minutes, allowing examination of the detailed temperature history of each apartment.

3.2 *Diagnostics and Simulation*

In addition to the monitoring of the apartment temperatures, we were interested in determining the air-flow patterns in the building due to infiltration. Air flow in apartment buildings is more complex than in a single-family structure because air is exchanged not only with the outside, but with the other apartments as well. The implications of inter-apartment flow are that under certain weather conditions, apartments may be exchanging more air with neighboring apartments than with outside, and the resulting stuffy conditions may prompt the residents to open windows to improve the air quality.

Air-flow patterns can be determined either by direct measurement, or by leakage measurements in combination with an air-flow simulation model. Because direct air-flow measurements are both expensive and depend on the building and the weather, we chose to make diagnostic leakage measurements. Blower-door testing of exterior-envelope and inter-apartment leakage was performed in both buildings. Previous measurements in similar construction had shown that as much as 60% of the air leakage is to adjacent apartments.[11]

Leakage measurements in multifamily buildings are relatively new, and as such, have seen little discussion in the literature.[12,13] We used two blower doors, running simultaneously, to make the measurements. The tests were similar to standard single-family blower door tests, except that each apartment's total leakage is measured with and without the adjacent apartments being pressurized. For each apartment test, all adjacent apartments were opened to outside to reduce series resistance effects. This is accomplished either by opening windows and doors, or through the blower-door fan opening in the other apartment. At each apartment/outside pressure difference, the flow was measured first without the second blower door operating, and then with the second blower door operating so as to make the pressure difference between the two apartments equal to zero. The leakage between two apartments is then computed by subtracting the leakage area with the second apartment pressurized from the total leakage area.

The air-leakage data obtained from the blower door tests are used in a multizone air infiltration model to calculate inter-zonal air flows and outside-air infiltration rates under different weather conditions.[14] The simulation model iteratively solves for the pressures and flows throughout the building, using a flow coefficient and exponent to characterize each leakage path.

3.3 *Household Interviews*

To understand how occupants modify apartment ventilation, as well as to examine the reasons why, we interviewed the residents from eleven of the thirteen households in the two buildings. Following ethnographic techniques, the questions were often open ended, allowing the respondents to describe their answers in detail. Many of the questions were based on previous exploratory studies of energy and behavior and were adapted for residents in apartments.[15-17] The interviews took between 30 and 60 minutes, and all but three were conducted in the resident's apartment; the remaining three interviews were conducted at the resident's work place.

The residents were asked about their comfort, clothing, temperature preference, window opening behavior and related activities, attitudes, etc. During the interviews we took notes, and immediately afterwards wrote out as much additional information as was remembered. Although this is more cumbersome than tape recording the interviews, the respondents seemed at ease and eager to participate in the survey. For the remainder of the text, quotation marks are used for those passages that were written down during the interview. Additional comments and notes written after the interviews are often paraphrased.

4. FINDINGS

4.1 *Monitoring Results*

Given the large quantity of data gathered (over six months of seventeen channels per building at ten-minute recording intervals), we examined daily average temperatures for each month, and then selected six to eight two-day periods from each building for more detailed analysis. The sample selection was based upon completeness of data, outside temperature, and day of the week. Four representative samples of the periods examined are shown in Figures 3 through 6. These figures contain plots of individual apartment temperatures versus time (10-minute data samples) in Bosworth and Albany, for two-day periods in February and April.

Figure 3 shows a two-day period for Bosworth in mid-February. The outside temperature averages for these two days are -10 and -9 ^{o}C. A quick examination of this figure shows that the coldest and warmest apartment temperatures differ by approximately 7 K. Looking at the legend, we see that both these apartments are on the first story, and the warm apartment is located directly above the boiler.

A closer examination of the plot provides a good indication of the operation of the building. Starting on the left side of the plot at midnight, the temperatures in all of the apartments decay due to the night setback of the boiler thermostat. The boiler fires again at around 6:00, after which it cycles to maintain relatively constant apartment temperatures until 22:00, when the night setback begins, a pattern which is repeated on the second day. All of the apartment temperatures behave similarly throughout this period, except for apartments 1b and 3a. Apartment 1b differs from the norm from 11:00 to 21:00 on the 10th and starting at 4:00 and 17:00 on the 11th. Apartment 3a behaves irregularly on the 11th.

The anomalous temperature patterns in these two apartments is our first indication that occupants are interacting with the temperature balance in the apartments. Window opening is a likely candidate for the cause of the anomalous temperature profiles. Looking first at apartment 1b, we can hypothesize that as the temperature rose in the morning it reached too high a level at around 11:00, at which point the occupant opened the windows, and then closed them at around 19:00. The temperature rises on the 11th could also be due to window closing. The profile for apartment 3a could also be explained by window opening: upon leaving the apartment at 8:30, the occupant opens some windows to air the apartment, which were closed upon returning at 18:30.

Although the window opening explanations for the temperature profiles seem plausible, the behavior in apartment 1b is puzzling. It is not clear how the windows were closed at 4:00 on the 11th, and then closed again at at 17:00 without any apparent openings in between. Figures 4 and 5 provide some additional evidence that may help explain the profile in Figure 3. Although the profile for apartment 1b in Figure 4 is similar to that in Figure 3, there is one significant difference. During the early hours of February 22, the temperature in 1b does not show the normal decay. This indicates that the occupant is likely to be using some form of auxiliary heating in the middle of the night, as the average outdoor temperature for the 22nd is -2 ^{o}C. The use of auxiliary heating in this apartment is confirmed in Figure 5, where the temperature rises dramatically in the middle of the night, and the boiler has not been on during this period. (The high temperature in 3a throughout this period could be due to continuous auxiliary heating, but we suspect the temperature sensor itself.)

Having confirmed the use of auxiliary heating in apartment 1b, we now question the window-opening explanation for its profile in Figure 3. The temperature rises attributed to closing windows is more likely to have been caused by the use of an auxiliary heater. We note that the initial slope of the temperature rise at 18:30 on February 10 is the same as that on April 20 (see Figure 5). Similarly, the temperature drops attributed to window opening could be caused by the auxiliary heater being turned off.

Figure 6 shows a two-day apartment temperature history for February at Albany. The temperature profiles are similar to those for Bosworth, again clearly showing the decays associated with the night setback of the boiler. The major differences between the two buildings are that the spread between apartment temperatures is smaller for Albany, whereas the boiler control at Bosworth provides smaller temperature oscillations. Figure 6 does not seem to show any window opening behavior, although it does show some auxiliary heating. Apartment 1a is significantly overheated on the night of February 10, and apartment 2b also shows a short temperature spike uncorrelated with boiler operation. The spike in 2b could possibly be from cooking, although there is an unexplained temperature spike in apartment 1b in the middle of the night.

4.2 Diagnostic and Simulation Results

The average leakage areas measured for each apartment were 2460 cm^2 for Bosworth, and 1880 cm^2 for Albany. The corresponding specific leakage areas (leakage area divided by floor area) of 19.0 and 18.8 cm^2/m^2 are surprisingly consistent, and significantly higher than the 13.3 cm^2/m^2 measured in a similar building in Minneapolis (Reference 10). We note that these are total leakage areas; in Bosworth approximately 60% of the leakage area was to other apartments, the remainder being in the exterior envelope. (Due to strong winds during the Albany tests, accurate measurements of inter-apartment leakage were not obtained.)

The leakage values used in the simulation of air flow in Bosworth are shown in Table 1. Taking into account the uncertainty in the measurements, average values were used for all similar flow paths (i.e., all diagonal inter-apartment leakage areas were assumed to be equal, all vertical inter-apartment leakage areas were assumed to be equal, and all horizontal inter-apartment leakage areas were assumed to be equal). As the simulation model uses both a flow coefficient and exponent to describe the leaks, the flow coefficients were determined from the leakage areas, and an average flow exponent of 0.65 was used.

In addition to the flow coefficients and exponents, the model also needs pressure coefficients as input. The pressure coefficients used for these simulations come from wind tunnel tests of a building with similar geometry. A plan of the site, presented in Figure 7, shows the shielding of the Bosworth building. (The wind tunnel site geometry was similar, although not identical, to the Bosworth site.)

Some significant simplifications in the simulation result from the shielding of the Bosworth site. Because the building is completely shielded on both sides, only wind from the front or back of the building will induce air flow through the building. Pressure coefficients are therefore required for only two wind directions, from the back of the building, and from the front of the building. The simulations presented are based on wind arriving from the front of the building (results of simulations for wind arriving from the back of the building differed by only 10%). Also, because wind from the front or back has the same effect in both apartments on the same story, and the stack effect does not create any horizontal pressure gradients, leakage between apartments on the same story does not play a role in the simulations.

The results of the simulations are presented in Figure 8, in which the outside air-flow rate into apartments on each story, and into the basement, are plotted as a function of wind speed. For all simulations, the indoor-outdoor temperature difference is 20 K, which is close to the average indoor-outdoor temperature difference during the heating season.

The results in Figure 8 are not surprising. As expected for a building with large internal leaks between zones, the upper stories do not receive any outdoor air at low wind speeds, all of the outdoor air being drawn into the basement and first story by the stack effect. The drop in outside air flow to the basement with increasing wind speed results from the lack of basement leakage at the front of the building. As the wind speed increases, the depressurization at the rear of the building competes with the stack effect by reducing the pressure difference across the exterior basement leakage sites. It should be noted that almost all the air entering the basement goes to the first-story apartments (a small fraction goes into the staircase). This implies even higher ventilation heat losses for those apartments, as the basement air temperature is somewhere between outdoor temperature and internal apartment temperature.

Figure 8 indicates that the overall air change rate of the building is not excessively high. At the average temperature difference of 20 K, and average Chicago wind speed of 4.6 m/s, the overall air change rate for the building is 0.6 air changes per hour (ach). It should be noted, however, that the average wind speed takes into account wind from all directions. Because only wind from the front or back of the building will induce the simulated flow rates, wind from other directions having even less effect on the ventilation of the building, the average air exchange rate will be even lower than 0.6 ach. In other words, the effective average wind speed will be lower than the 4.6 m/s all-direction average.

Because of this strong directional dependence of wind-induced air flow, the building will be in the stack-dominated region of Figure 8 for a significant fraction of the time. In this stack-dominated, and therefore non-uniform ventilation mode, the upper story apartments will receive little or no outside air, and should thus be stuffier than the first story apartments. Similarly, the first story apartments may seem draftier due to the higher influx of cold outside air. Depending on the UA-value of the building (i.e. conductivity of the building shell), these results also imply that the first story apartments should cool more quickly than the upper story apartments.

4.3 *Survey Results*

The average household size for the two buildings is 2.7 persons, with Bosworth having larger (3.3 persons) households than Albany (2.2 persons). The age distribution is 11 adults and 9 children at Bosworth with an average age of 19 years, and 12 adults and 1 child at Albany, with an average age of 32. The range in occupant ages for the two buildings is 1 - 61 years. Bosworth has three black and three white households; Albany has one black, one Hispanic, and five white households. While education levels are nearly the same for the household survey respondents in the two buildings (an average of 15 years of school for Bosworth, 16 years for Albany), household incomes were significantly different. Reported mean annual household income for six of the seven Albany households was $34,000; at Bosworth only three of the six households reported annual income, with a mean value of $22,000. The household patterns included couples, couples with children, 3-4 single men living together, single women alone, and single women with children. All of the residents had lived previously in apartments, many for a large part of their lives. Both Bosworth and Albany had three households where someone was home during the day.

The survey included a number of questions concerning when and why windows were opened in winter. The most consistent finding for our two buildings was that, in general, the occupants reported that they did not open the windows at all during the winter. The reasons for this were that the residents felt the apartments were already too drafty, that they wanted to keep the heat in, that it was too cold outside, and that it was too much trouble to unseal the plastic and rope caulk just to open the windows. The sealed windows were part of the routine the residents employed to reduce infiltration, which included installation of rope caulk every October, installation of plastic sheets over the inside of the windows (the houses already had exterior storm windows), and stuffing rags around the door frames. One resident kept one window unsealed for ventilation and as a fire escape, "I open it a little when I use that space heater [an unvented kerosene heater]."

Residents reported that in previous apartments they had had to open windows because of over heating in winter, but that this was not a problem for them now, "In other buildings with over-heating problems I have had the windows open all night. I don't feel too guilty opening windows, [but] I doubt if anyone in our buildings would open the windows [in winter]. I think the majority think it's on the cool side." A few residents would open the back door to air the house, for about fifteen minutes during the day, usually on a weekend. Only one resident reported that windows were opened in winter on a regular basis for relieving the stuffiness. In this case the windows were opened once a month, typically at night, just a crack, and for a few minutes. For the most part, the winter pattern of window opening is reflected by the resident who said, "I just wouldn't think when it's that cold to open them."

In contrast to the winter pattern of keeping all the windows sealed and shut, ventilation in summer was always dependent on opening windows and using fans for air movement. Residents relied on combinations of drawing shades, exhausting air, keeping the rooms closed during the day, wearing fewer clothes, drinking cold drinks, and other activities to stay cool. Only one household reported using an air conditioner. They had a window unit in the bedroom that they would use whenever the temperature would rise above 27 ^{o}C. Depending on wind and dirt, windows would be open a lesser degree. Residents of first floor apartments commented especially on dirt intrusion, "The city is dirty. If you keep the windows closed you keep the apartment clean." Others would leave windows open all the time, "morning, afternoon and night, except when it rains, and then only part way." Window fans are sometimes left running during the day when the residents are away so that the apartment won't be so hot when they return in the evening. "I have to leave the fan on [during the day] for him [the dog] because he can't stand the heat."

In addition to the window-opening behavior we were interested in other activities that residents were engaged in that might affect the ventilation or need for ventilation in their apartments. Most of the respondents changed their clothing levels to reflect the temperatures in their apartments. Taking off layers was a typical first response to apartment overheating. Putting on a sweater or flannel shirt was a typical response when it was too cold in the rooms.

On surprising finding was the widespread use of the gas stove as an auxiliary heat source for the apartment. Six of the eleven households reported using the gas stove or oven for auxiliary heating. Typical use was in the early evening in winter and in the early morning before the central system came on. The stove was also used for heating in the fall, before the heating season began. The usual pattern was to heat the kitchen, which was often the coldest and draftiest room. "In the evening when I come home it can be awfully drafty. I have it [the oven] on for 15 minutes. It's supposed to be self-cleaning, so I use that excuse." One resident also has an unvented space heater in the apartment, which is used for an hour or two in the evening.

To further understand related aspects of ventilation, residents were asked questions about drafts, stuffiness, cooking smells from other apartments, and the degree of acoustic isolation.

All residents commented that there were drafts in the apartments, especially around the doors—the back door in particular. The new storm windows had reduced drafts around the windows considerably. However, as mentioned earlier, the residents would still seal the windows in winter to stop drafts. Other reported drafts around the baseboard molding and the walls in the front room. The residents at Bosworth mentioned that the whole building was leaky, and needed tuck-pointing, i.e., the mortar in the exterior walls needs replacing. The enclosed (unheated) back porches at Bosworth were frequently mentioned as being drafty.

Few residents commented that it ever got too stuffy, "we have enough drafts," was a typical response. The kitchen was cited as the most common room to be too stuffy, particularly if the weather (in winter) warmed up. The interior rooms (bathroom and bedrooms) were also found to be stuffy at times. A few residents mentioned that they had condensation between the primary window and the storm window, but in general, moisture was not considered a serious problem. The only respondent that claimed to sometimes have moisture problems was the one that had a humidifier.

We also asked the residents questions about what they could hear from their neighbors, both above and below, as well as next door. We were interested in finding out whether there were direct connections between apartments which could transmit noise, thereby serving as indicators of possible air-flow paths. The residents were asked about what types of sounds they could hear: walking, music (both bass and treble) and conversation, and whether they could distinguish actual words. Our hypothesis was that if high frequency sounds (treble music or distinct words) were heard from a neighboring apartment, there was a greater possibility of direct paths between the units. Of course, whether a resident could hear their neighbor depends on how much noise the neighbor makes, in addition to the presence of any connections between apartments.

The general pattern was that residents were most aware of noises from above, less so from below, and almost not at all from the side. Specifically, upstairs noises included walking and running (especially kids), muffled music, mostly bass, and in one case, distinct conversation. Noises from below were music when it was turned up (mostly bass), and some talking, but not distinct words. Most residents commented that they could hear nothing from the apartment on the same story, "It's amazing how insulated we are crosswise compared to up and down." Residents mentioned that noise in general was not a problem, although it was more evident in summer when windows tended to be open.

5. DISCUSSION

Having examined the results of three different techniques for exploring ventilation and occupant behavior, we uncovered some surprising results and some apparent contradictions. The most surprising result is that, contrary to the results of previous studies, the survey responses indicate that these apartment occupants rarely, if ever, open their windows during the winter. This behavior seems to stem from the large inconvenience associated with window opening, due to sealing measures taken at the start of the winter season. Also, there may be less perceived need by the occupants for window opening as they find the apartments to be quite drafty. A third factor is the severity of the winter climate. The winter design temperature (99%) for Chicago is -22 °C, compared to -15 °C for

Stockholm and -4 °C for London.[18]

Because residents report no window opening activity, we had to re-evaluate the temperature profiles where we suspected window opening was taking place, to see if there were alternative explanations. Of course, survey respondents may not have reported accurately, whether through being unaware of other members of the household's activities, or through the desire to give a "correct answer." Nevertheless, we decided to see if explanations based on the survey results could be used to interpret the measured temperature data.

The survey responses indicate that auxiliary heating is used by the residents in Bosworth apartment 3a "all the time." Looking again at Figure 3, the dip in temperature could then be explained by the residents being out of the house during the middle of the day on February 11th, whereas on the 10th they are probably home and using auxiliary heating all day. This explanation is confirmed by further examination of the survey and monitoring results. The occupants explain that they are usually out on weekdays and home on weekends. This correlates well with the pattern of temperature dips on weekdays only and uniform temperatures on weekends, which was observed upon more detailed examination of the temperature data. Thus, by combining the monitoring and survey results, we have a clearer picture of building operation.

An interesting finding from the comparison of the survey data with the temperature profiles is the correlation between apartment temperatures and the reported temperature preferences of the occupants. People who reported liking colder temperatures live in colder apartments, and people who reported liking warmer temperatures generally live in warmer apartments. While this finding may not be altogether surprising, it does confirm that occupants are able to control—to some extent—the temperatures in their apartments to where they are comfortable.

A comparison of survey results with diagnostic/simulation results does not prove to be conclusive. The simulations indicate that the first story apartments get significantly more (cold) outside air, and are therefore likely to have more drafts. The upper-story apartments, which receive most of their air from the lower-story apartments might be expected to be stuffier than the first story apartments. The survey results do not confirm (nor do they disprove) any of these expected trends. The only correlation found is that the upper-story apartments at Bosworth appear to have somewhat less problems with drafts. The difficulty with such a comparison is the number of confounding effects that tend to mask the effects we expect to see. For example, two of the first story apartments have high temperature preferences, and use auxiliary heating to maintain their comfort. Auxiliary heating may completely mask the effects of outside air drafts.

A comparison of diagnostic/simulation results with measured temperature profiles does provide some interesting confirmations. According to the simulation, the first story apartments should have significantly higher heating loads due to infiltration. Depending on the ratio of infiltration heating load to conduction heating load, we would expect either the first or third story apartment temperatures to decay most quickly when the boiler turns off for night setback. Examination of the temperature profiles in Figures 3 through 5 confirms that the first story apartments cool off more quickly than the rest of the building. This effect is most obvious at Bosworth on the morning of February 22 (see Figure 3), and at Albany on the mornings of February 10 and 11 (see Figure 6). These results illustrate the importance of infiltration to the overall energy balance of these buildings.

6. CONCLUSIONS

The results of our investigations have provided us with a number of findings about ventilation and occupant behavior in these buildings, and about the suitability and applicability of the experimental methods tested. Our major finding is that the ventilation in these buildings cannot be explained by physical models alone, and that understanding behavioral interactions is key to understanding what is going on. While occupant behavior is often difficult to interpret, we have found the occupants' desire to improve comfort to be the driving force behind much of their behavior. Occupants will follow what is for them the path of least resistance to improve comfort, whether this is sealing windows with plastic, using the stove as an auxiliary heater, or complaining to the neighbors. It also became clear that these actions may not be optimal from an energy or economic view point.

We hesitate to generalize these findings to other buildings in different climates and cultures because we have found that our results are different from those published previously. We do feel, however, that an experimental approach that combines different methods provides additional insight into complex problems such as those found in looking at occupant interaction with ventilation systems. In particular, we stress the importance of understanding the specific characteristics of the building and heating system, the local climate, and the behavior of the occupants. In general, the combination of monitoring, diagnostic/simulation, and occupant surveys, seems to be a useful tool for understanding building operation, and for exploring building retrofits designed to reduce energy consumption or improve occupant comfort.

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Table 1. Leakage areas used in air flow simulation for Bosworth.

Location	Effective Leakage Areas [cm^2]
Apartment to Outside	
front	350
side	250
back	400
to roof	570
Apartment to Apartment	
horizontal	225
vertical	460
diagonal	220
Basement to Outside	
front	300
back	800
side	500
Basement to Apartment	700
Stairway to Outside	135/story
Stairway to Apartment	54

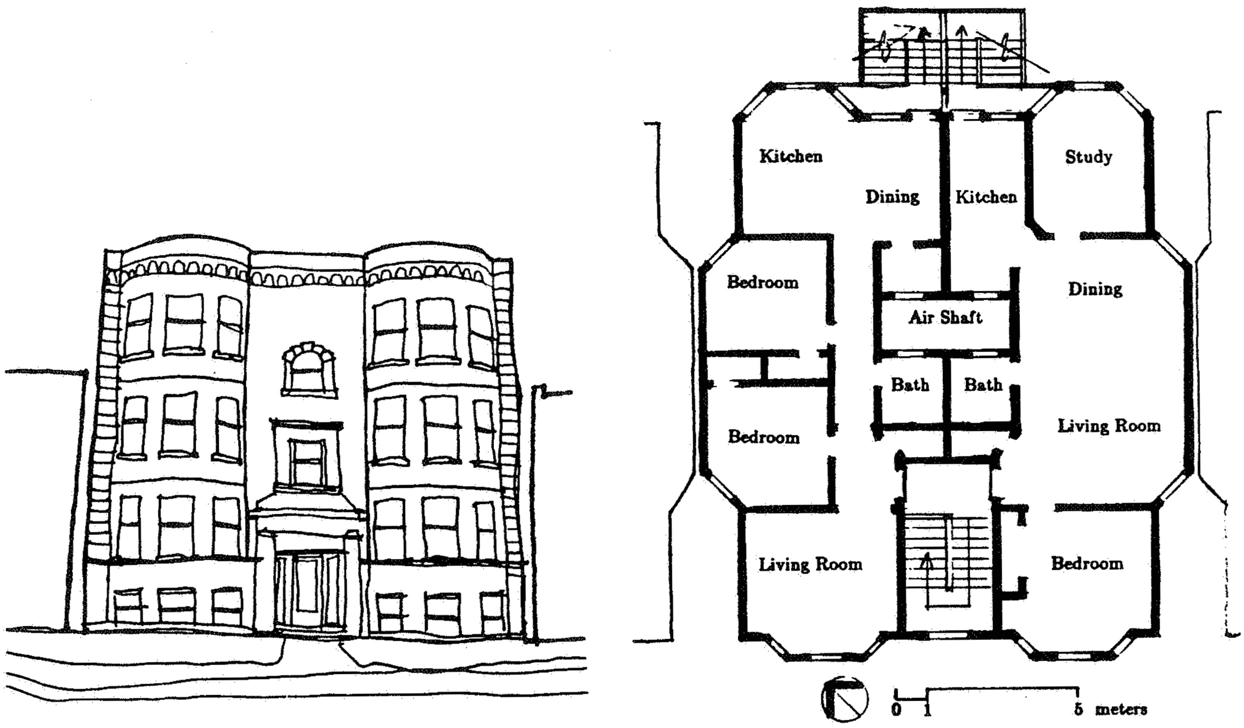

Figure 1. Plan and elevation for Albany, (Chicago, c. 1920).

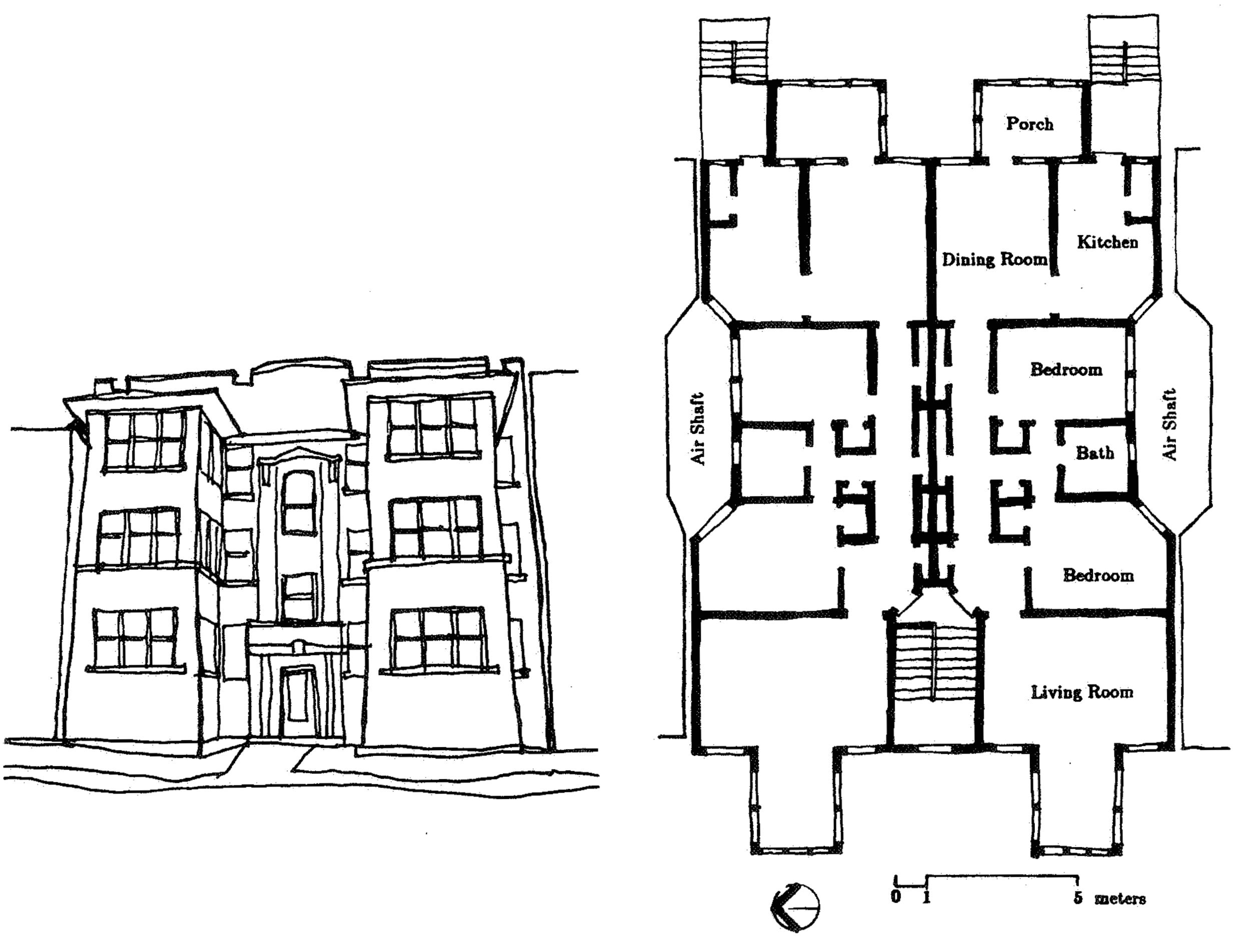

Figure 2. Plan and elevation for Bosworth, (Chicago c. 1920).

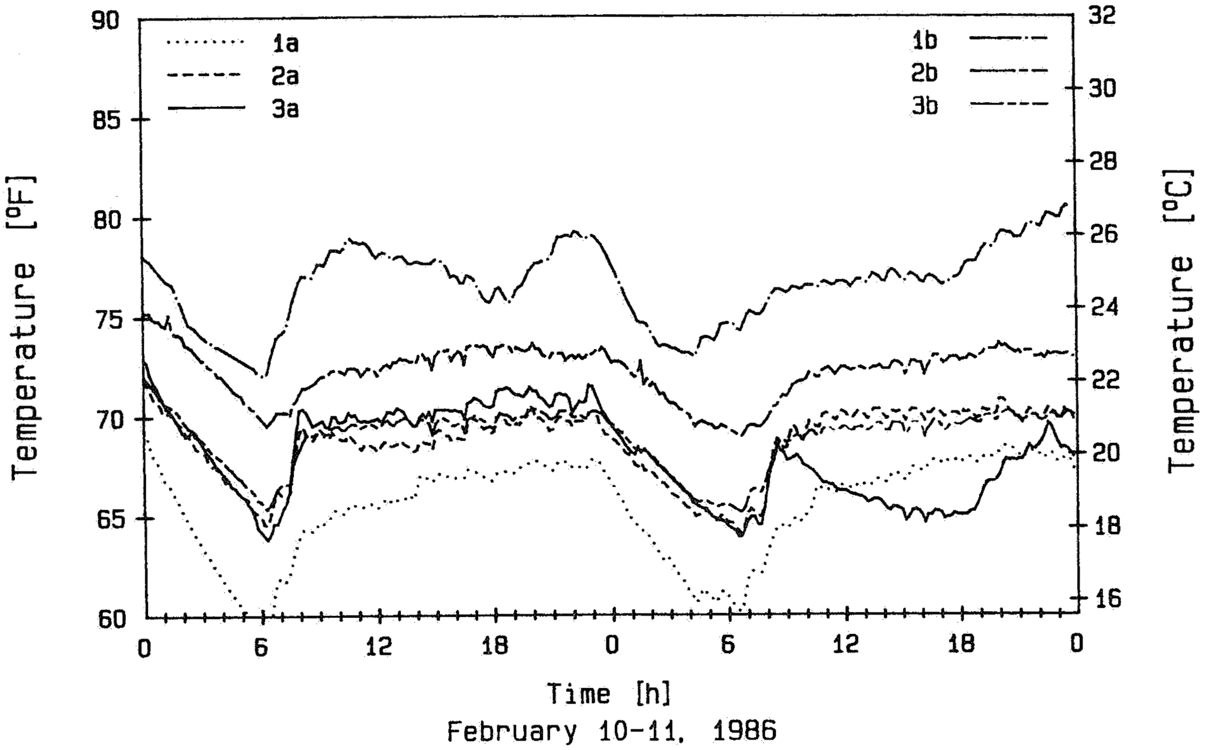

Figure 3. Apartment temperatures for Bosworth, February 10-11, 1986.

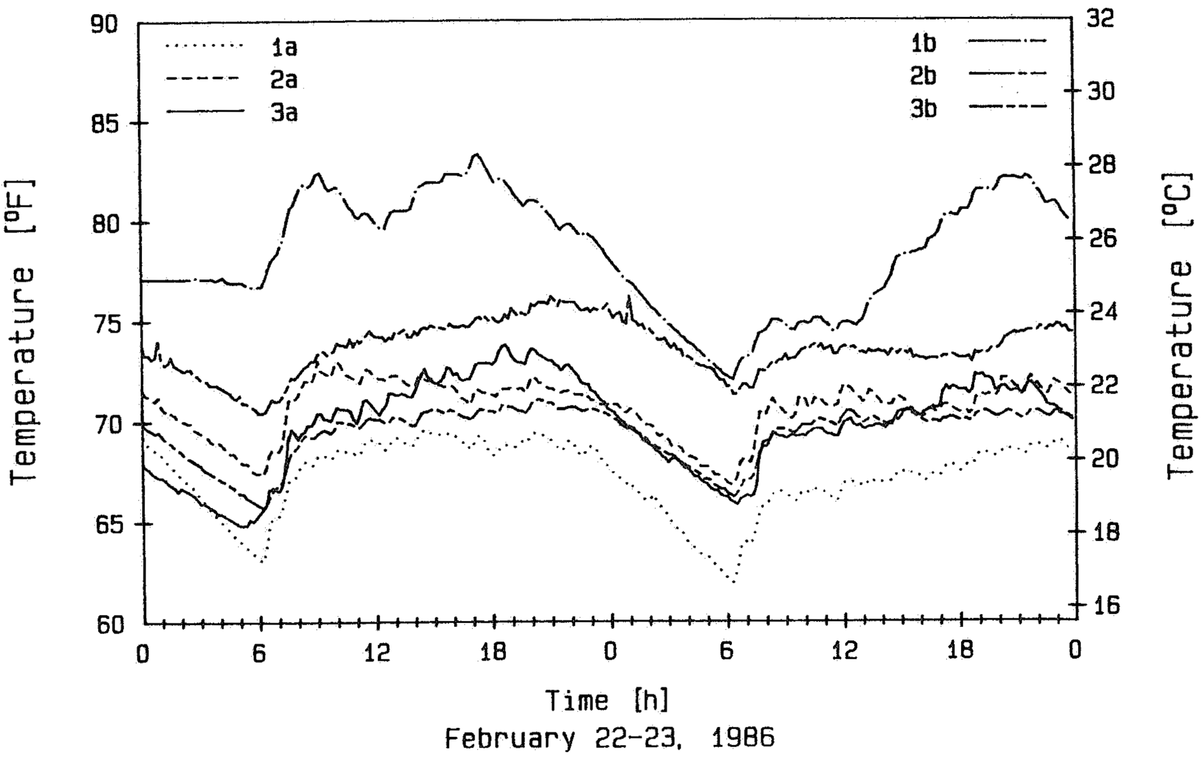

Figure 4. Apartment temperatures for Bosworth, February 22-23, 1986.

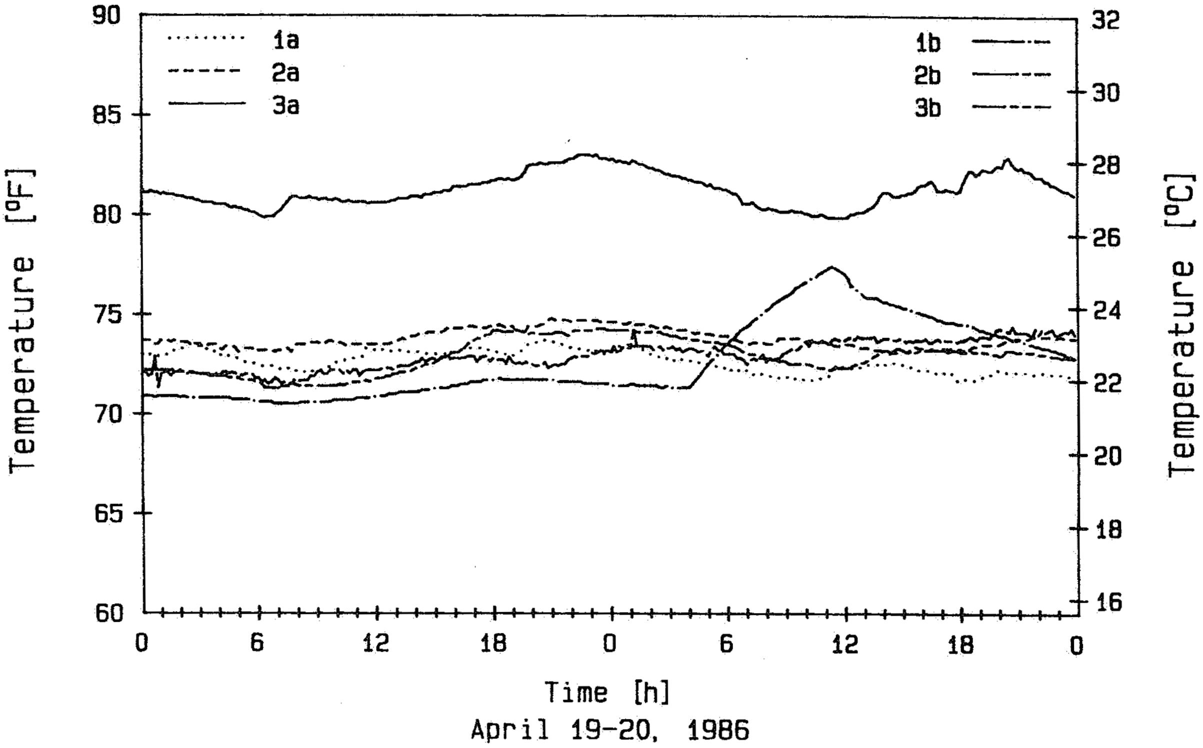

Figure 5. Apartment temperatures for Bosworth, April 19-20, 1986.

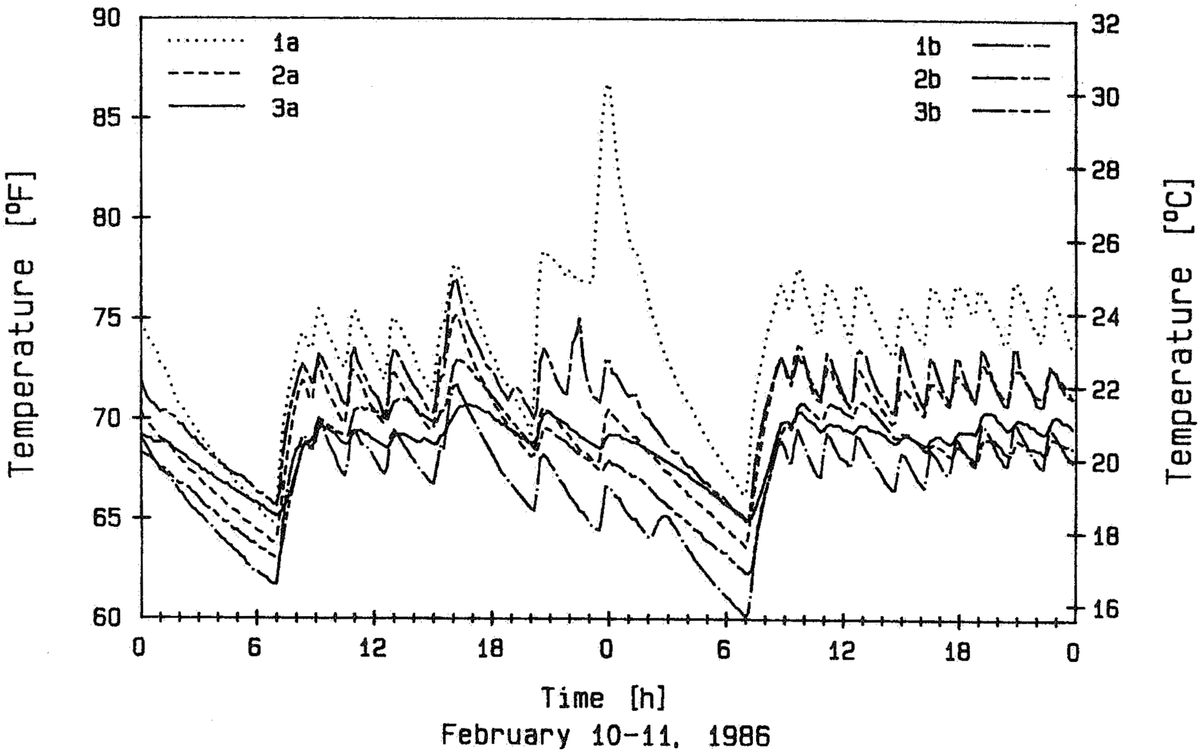

Figure 6. Apartment temperatures for Albany, February 10-11, 1986.

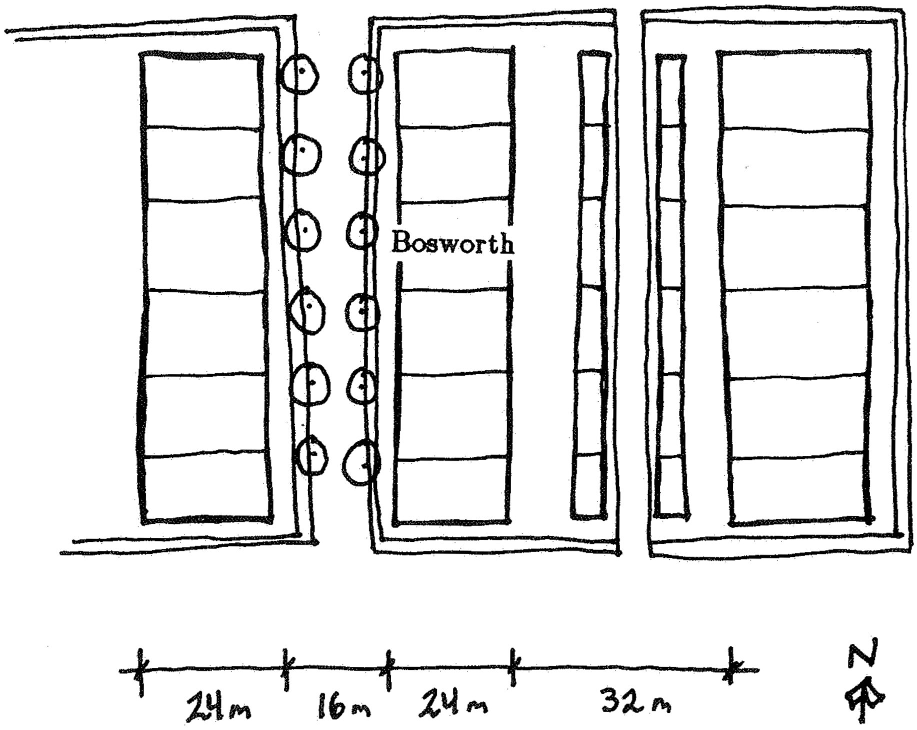

Figure 7. Site plan for Bosworth showing surrounding buildings.

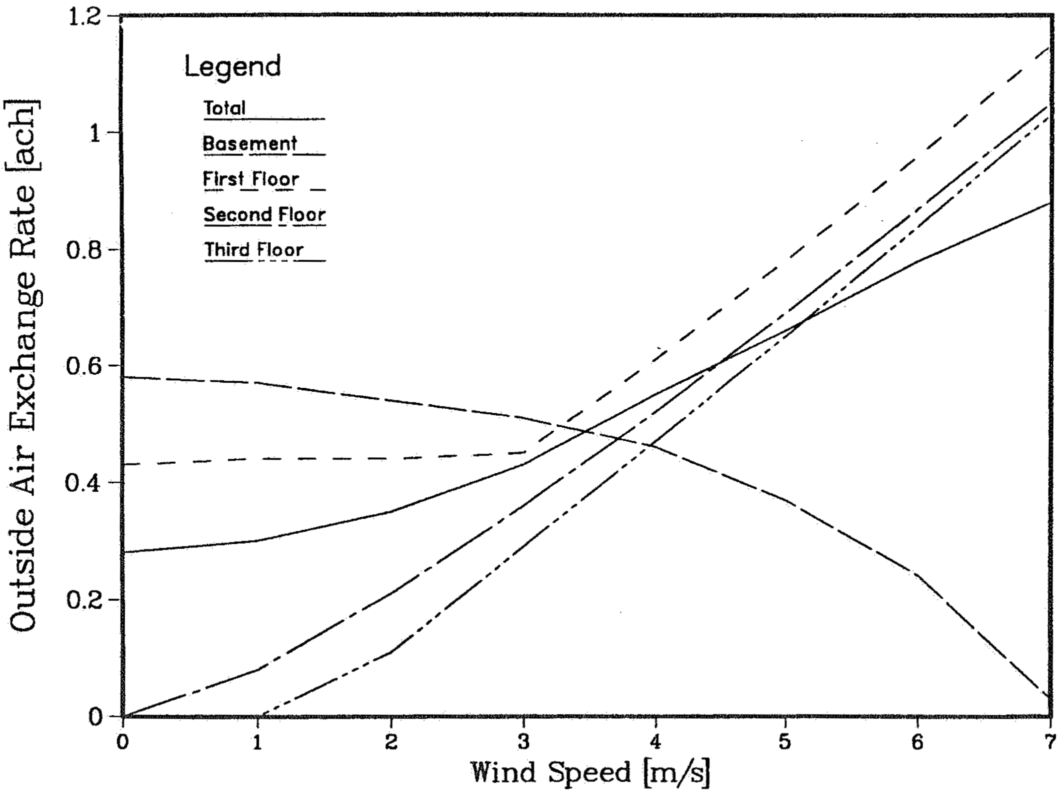

Figure 8. Outside airflow into each apartment at Bosworth as a function of windspeed for wind from the west.

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
29 September - 2 October 1986

PAPER 7

INHABITANT BEHAVIOUR WITH REGARD TO MECHANICAL VENTILATION IN FRANCE

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SYNOPSIS

In France, most of the ventilation systems in dwellings now consist of exhaust vents linked up with a fan, and air inlets.

A survey conducted by the CSTB shows that actual ventilation rates are frequently different from prescribed values and that a lot of problems encountered are related to occupant behaviour.

- The duration of exhaust flowrate peak value was measured ; it was shown that this duration was dependent on the kind of command and its location in the room.

- draughts through air inlets were a major concern.

- a lots of air vents did not operate correctly because of fouling. Reasons were that the inhabitants had not always a high consciousness of the necessity of cleaning, and that, moreover, a lot of air vents were not easily dismountable.

Among conclusions of the survey, are the following :

- air vents should be easily dismountable for cleaning and recommendations for it should be given to the inhabitants.

- air inlets, exhaust vents and fan command should be correctly located.

1 CHARACTERISTICS OF MECHANICAL VENTILATION SYSTEMS

Mechanical ventilation of dwellings has been brought in France during the sixties.

This technique is now quite widespread since (although accurate data are lacking) nearly all new multifamily houses have now mechanical ventilation, as well as, at least in the north part of France, most of single family houses.

The operating way of mechanical ventilation is illustrated on the fig. n° 1.

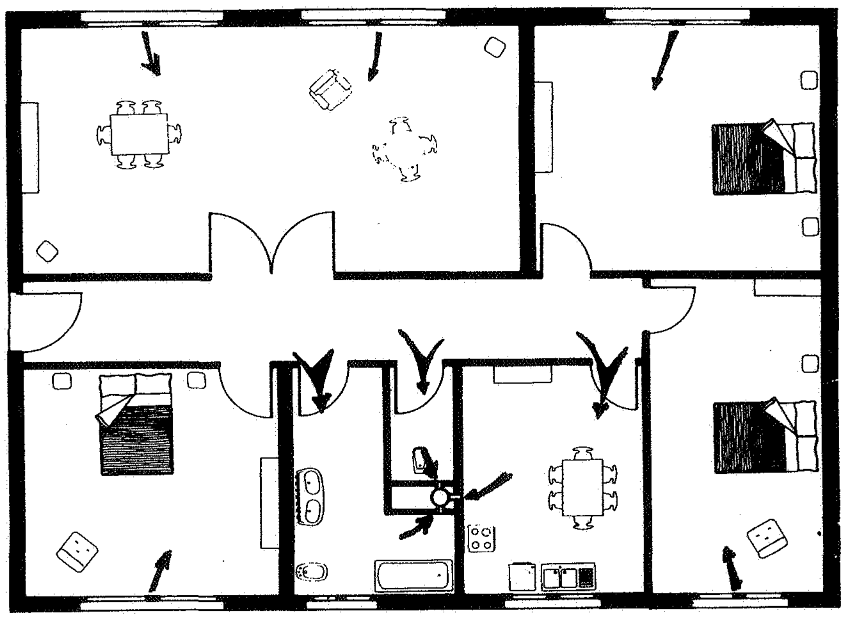


Fig. 1 Scheme of air flow in a typical dwelling with mechanical ventilation (doc ALDES)

1.1 Air inlets

Fresh air enters dwelling main rooms through specific air inlets which are usually located near the ceiling (for instance in the upper part of the window frame) in order to prevent discomfort due to draughts.

Usually the occupant has no means to adjust the air flow whose values under 10 Pa are generally 15 m^3/h or 30 m^3/h. However, most often, these air inlets are self - regulated with respect to pressure difference ; it means (fig. n° 2) that the air flow remains constant whatever the pressure difference value in a specified range (for instance 10 Pa to 100 Pa).

An important advantage of these air inlets is that they help to prevent uncomfortable draughts as the wind speed increases.

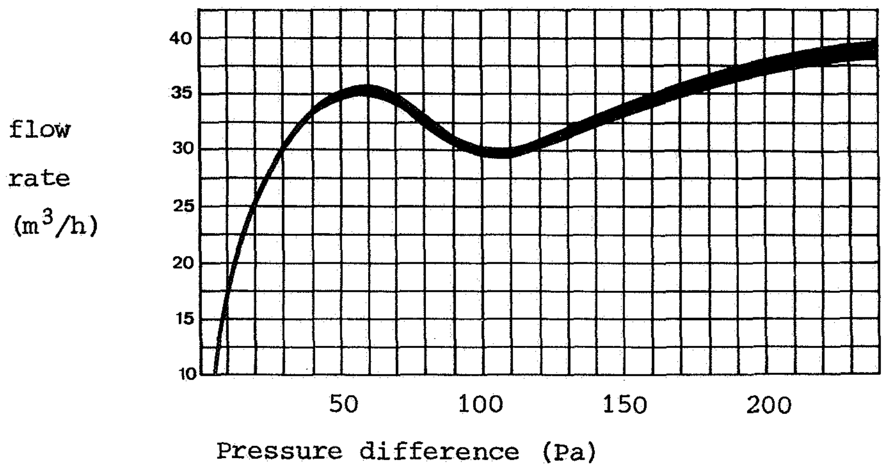


Fig. 2 : Typical pressure flowrate curve of a self-regulated air inlet

1.2 Fan

In multifamily houses the fan is common to the whole block of flats. It is usually installed on the terraced roof and bound to the exhaust valves through vertical air ducts ; the fan is operating under a contant speed and is usually powered by a separate electric engine to which it is coupled through a driving belt.

In single family houses the fan is usually located (fig. 3) inside the attic (whose access in modern dwellings is unfortunately not always possible). Most often, the fan may operate under two different speeds according to the householder command.

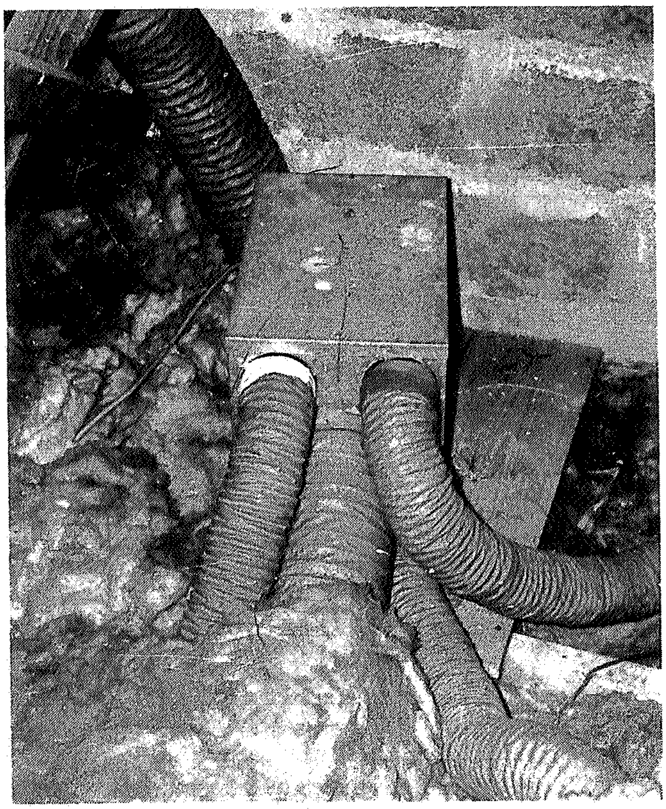


Fig. 3 : Fan in the attic of a single family house - maintenance is not made easy.

1.3 Exhaust valves

The exhaust valves are located in the kitchen, the bathroom and the closet. Their flowrates lower limits are set by the prevailing Regulation :

According to this Regulation, the ventilation system must be capable to achieve the following flowrates in a four room dwelling :

bathroom	:	30 m^3/h
closet	:	30 m^3/h
kitchen	:	120 m^3/h

Due to energy conservation policy, it is allowed that the exhaust flowrates may be reduced beyond these values when the occupants do not require high ventilation rates :

The reduced value of the kitchen exhaust valve is 45 m^3/h. No limit has been stated for the bathroom or the closet ; however a minimum value has been set for the whole dwelling : the sum of exhaust flowrates must always keep in excess of 90 m^3/h (figure given for a four room dwelling). This implies, according to prevailing Regulation, that the ventilation systems cannot be stopped by the householder.

A consequence of this Regulation is that, in nearly all the houses, exhaust flowrates in kitchens take two values : a lower value (45 m^3/h or more) and a peak value (90 m^3/h or more).

The flowrate value is controlled by the householder. The control system is different according to the kind of dwelling :

In multifamily dwellings, the flowrate reduction is usually achieved by a mechanical device ; the peak value is obtained by pulling (fig. 4) a cord which is bound to the exhaust valve and, when pulled, makes its aperture become greater. The lower value is obtained by pulling a second cord.

In single family dwellings, an electric command is most often preferred ; the kitchen exhaust flowrate is controlled by an electric switch located in the kitchen :

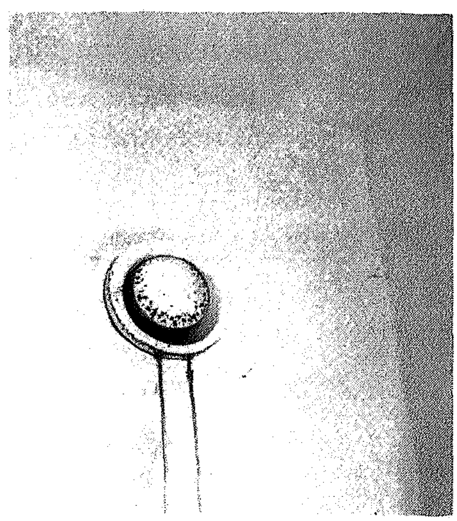


Fig. 4 : Exhaust vent in a kitchen - fouling of the vent and command cord may be noticed.

Flowrate variation is usually achieved by controlling the fan speed. It is worth noting at this stage that, according to prevailing Regulation, there should be no possibility for the householder to stop the ventilation : theoretically the choice is only between low flowrate and peak flowrate. As a matter of fact, it appears (see hereafter) that a lot of occupants did, however, manage to stop the fan.

An important limitation is that the exhaust valves must operate under a given range of pressure difference in order to meet acoustic requirements : If the pressure difference happens to become too high, the air valve itself becomes noisy. On the other hand, when pressure difference is too low, the aperture area must be greater, which increase the noise transmission between flats through the air duct.

Another important feature of the exhaust valves is their high sensitivity to fouling : exhaust valves, particularly those located in the kitchen have to be cleaned at least twice a year in order to prevent excessive flowrate drop.

1.4 Sizing

Air inlets, exhaust valves and fan are sized so that the relative pressure inside the dwelling is negative and equal to about 10 Pa when there is no wind effect.

An important limitation is that the pressure drop between rooms must not be too significant;usually an air gap of up to 1cm height is provided between the doors and the floor.

2 FIELD INVESTIGATION

Between 1980 and 1983, the CSTB (Centre Scientifique et Technique du Bâtiment) conducted a survey intended to yield a field evaluation of mechanical ventilation systems :

118 flats among 8 different buildings and 80 single-family houses*
all of them near Paris and less than ten years old, were investigated.

Results of the survey showed that there was a marked deviation between expectated and actual behaviour of the occupants :

2.1 Window opening and air inlets

2.1.1 window opening

Window opening has not been monitored but estimated through answers to a questionnaire.

Question	Answer	Percentage of answers	
		multi-family houses	single-family dwellings
Do you open windows during winter time?	no	14 %	32 %
	yes, heating being cut off during window opening	31 %	62 %
	yes, heating is not cut off	55 %	6 %

Windows are usually opened during housekeeping work and the mean opening daily duration is in the range of one hour [4].

The above table shows that the airing needs appear to be more important in collective buildings. This can be explained in two ways : On one hand, occupants of flats (most of them are tenants) seem to be less concerned with energy savings ; on the other hand, the higher air

* most of single-family houses were occupied by house owner ; most of multi-family dwellings were occupied by tenants.

renewal in single family houses (because of high air leakage value) may cause the occupants to reduce windows opening.

It should also be observed, and this last explanation is likely to be the most meaningful, that energy expenses in single family houses are directly controlled by the occupant, which may explain a greater inclination to reduce window opening.

The above remarks lead yet to an unanswered question : "what is the effect of air renewal value on windows opening ?"

Accurate answer, through field measurement, could lead to a better appreciation of the actual heat losses related to the different kind of ventilation systems.

2.1.2 Sociological point of view

As well as the above considerations, it should not be forgotten that window opening rate relies as well upon complex psychological grounds as upon a kind of implicit compromise between energy expenditure and air quality :

In a sociological analysis conducted by C.S.T.B., Ph. DARD [6] defends, among other points, the assumption that window opening is strongly related to an indoor space extension desire and also, sometimes, to some purification trend independent of the air quality itself.

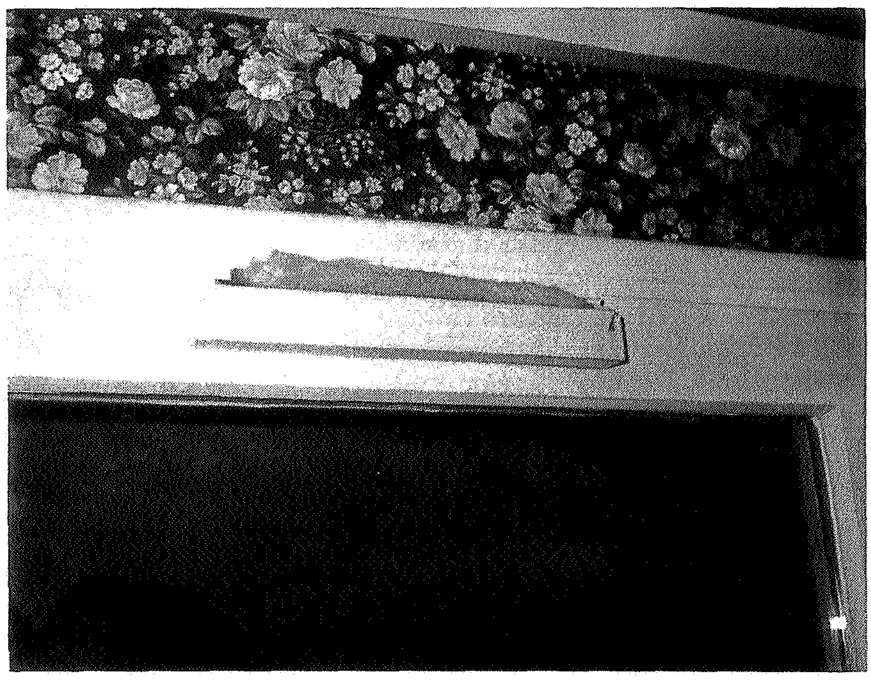
2.1.3 Air inlets

The survey on air inlet use has led to findings quite comparable with window opening : 22 % of single-family houses have at least one air inlet sealed, for instance with cotton wool (fig. n° 5). This figure is higher (33%)

in multi-family dwellings, probably because draughts due to wind pressure are more important there.

Reasons given by occupants for sealing are, by order of importance : draught prevention, energy savings*, prevention of soiling around the wall paper, and noise reduction.

It is worth noting that in some flats, air inlet sealing caused condensation to occur in winter. The sealants were then removed by the occupants.



<u>Fig. 5</u> : <u>Air inlet on the window frame</u> - The air inlet has been sealed by the occupants using cotton - wool.

* It has been observed[2] that low income occupants had a higher trend to seal air inlets.

2.2 Flowrate control by occupants

As discussed before, there is usually no means for the occupants to control the air flow through air inlets. However the flowrate through the exhaust vent located in the kitchen may be controlled (*) either by a cord (multi-family dwellings) or by a switch (single-family dwellings).

93 % of occupants in single-family dwellings[1], and as low as 63 % in multi-family dwellings[2] actually use this command. Difficult access of the cord in some flats (Fig. 7) as well as collective invoicing of heating may account for the difference.

Fig. 6 depicts the distribution of kitchen peak flowrate daily duration considering a sample of 64 single family houses that have been monitored during a one year period. The mean value of the observed daily duration is 1,5 hour ; this duration is rather scattered since the highest value is equal to twelve hours and that as many as twenty occupants never use the flowrate command.

No measurements have been done in muti-family buildings. It can however be expected, taking into account some partial observations, that the mean flowrate daily duration is likely to be in the range of four hours, being observed that this value is equal to nought or (less frequently) twenty four hours when the command cord is not of easy access (fig. 7).

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* 22 % of single-family houses, however, complain about the absence of flowrate control in the bathroom. A flowrate superior to the usual value (30 m^3/h) is often desired in order to ease clothes drying and vapour evacuation.

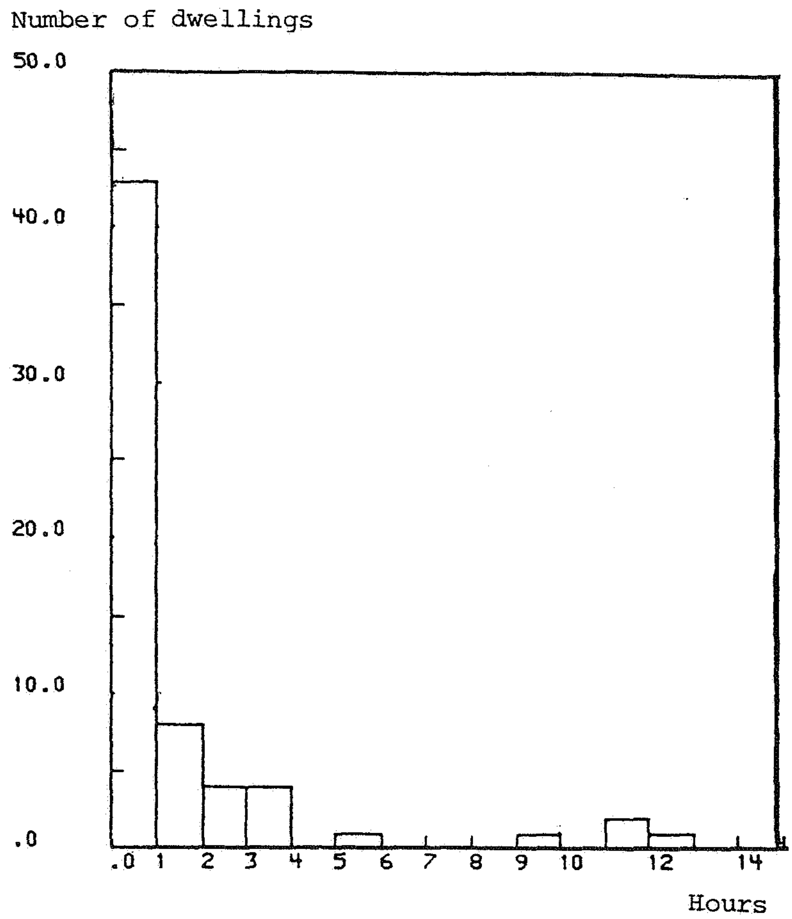
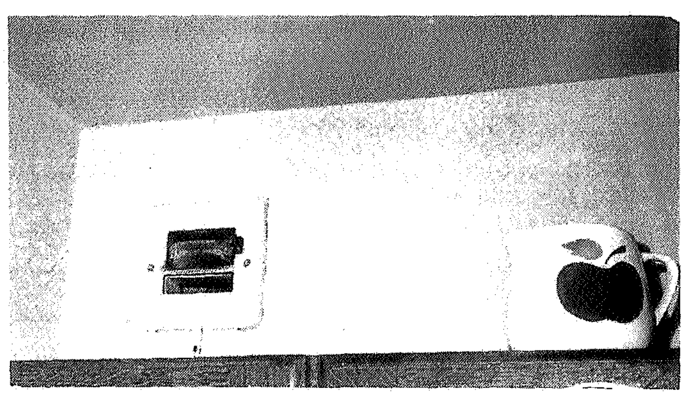


Fig. n° 6 : 64 single-family houses - Mean daily duration of peak flowrate in kitchen

The peak flowrate value seems to be highly dependent on the efficiency of the air evacuation. Although no precise data is available, it is felt that a kitchen hood, provided it is adequately located above the gas cooker leads to an important reduction in peak flowrate duration.

Fig. n° 7 : Inadequate location of exhaust vent in the kitchen - the command cord is not handy.



Reciprocally, if the valve, as it happens sometimes, is inadequately located (for instance near the door separating the kitchen from other rooms), the peak flowrate is rarely used[2].

2.3 Air valves cleaning

Air inlets and exhaust valves should be cleaned at regular intervals in order to remove dust, grease, etc.

Actually air inlets are rarely cleaned for the simple reason that dirt is not visible and that they are not always easily removed for cleaning. Exhaust valves are more frequently cleaned: According to occupants statements, the percentages (*) of occupants who do some cleaning are the following :

95 % of dwellings occupied by house owner
75 % of dwellings occupied by tenants

Problems related to valves cleaning are the following :

- some valves are adjustable, for instance, by means of a screwed rod : A great deal proved to be disadjusted by the occupants.
- After removal for cleaning, some other valves were difficult to reinstall, which caused a noisy air gap between the valve and the wall.

Fig. 8 depicts flowrate values as they have been measured in single and multi-family dwellings:

The scatter around the standard value (30 m^3/h) may be accounted for by inadequate sizing, fouling or disadjusted exhaust valve.

(*) The actual proportion is likely to be lower because of possible inaccuracies in occupants responses.

An important outcome of this scatter occurs when a gas appliance is fitted to the exhaust valve. When the flowrate happens to decrease beyond the security limit, then gas supply is automatically cut off, which may cause some occupants to remove the regulating valve in order to increase the flowrate.

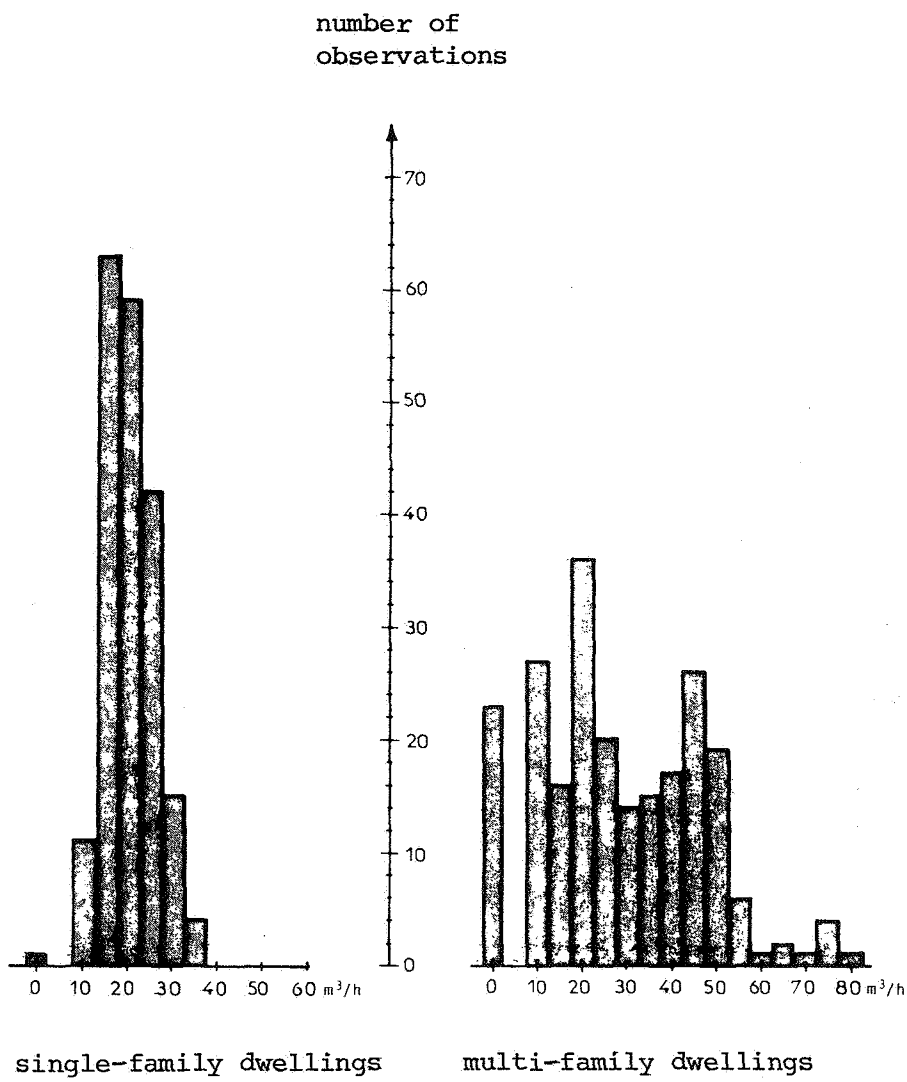


Fig. 8 : Histogramme of flowrates measured at closet or bathroom exhaust valves

2.4 Maintenance of installation

With a few exceptions, no occupant has received appropriate technical information on the ventilation installation and the way it works. This can explain some of the following observations :

- cleaning of air inlets is rarely done
- cleaning of the exhaust vent is usually limited to its visible part : in extreme circumstances, vents may become inoperable because of fouling in spite of exterior cleaning.
- Thick carpeting may be installed, which can block the air passage in the doorway and strongly reduce the room air renewal.
- Maintenance of single-family houses fan unit is rarely done : Three fan failures (out of eighty dwellings) have been ascertained during CSTB survey without the occupants being aware of it!

Similarly, the CSTB investigator found that the fan belt in one of the eight multi-family buildingswas broken without any effective alarm transmission to the building keeper.

Lack of information to occupants seems therefore to be responsible for insufficient maintenance. It is felt that better information could be provided by technical documentation and guidance for maintenance marked on the exhaust vent itself. An encouraging observation (1) is that, in a group of single-family houses, maintenance was correctly carried on because of the presence of an active co-owners association.

In other respects, as much as 25 %* of single-family dwellings managed** to stop unduly the fan unit from time to time, mainly during the night!

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* An other 30% cut off the fan during summer and holidays.

** For instance electric fuses may be removed.

The alleged reasons were : discomfort due to noise, energy saving concern* , necessity to cut the ventilation before lighting a wood fire in a fireplace, and also security concern during absence.

2.5 Noise

Noise is an important limitation of mechanical ventilation. It can be produced in different ways :

- by the exhaust vent itself whenever the pressure difference is greater than about 140 Pa
- by the fan unit (vibrations and noise)
- by noise transmission through riser duct between two adjoining flats.

This last ground is the less frequent since only[2] one occupant out of fifty complains about it in multi-family dwellings.

However, as a whole, 57 % of occupants in multi-family dwellings against 49 % in single-family houses consider that the installation is noisy, which may cause some of occupants to seal the valves.

On the other hand, in one of the multi-family buildings three air inlets were sealed because of fluttering of the plastic regulation valve under windy conditions.

3 CONCLUSIONS

The survey has put into evidence three main points :

Occupant behaviour is dependent on their social position and the kind of dwelling : ventilation needs are not exactly the same in single-family houses as in flats ; home owners are

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* In some dwellings, the radiators were right under the exhaust valve!

generally more cautious about maintenance than tenants ; occupants are more concerned with energy savings and air renewal reduction when the heating installation is individual.

Obviously, a lot of occupants wish to enjoy a greater possibility to manage themselves the ventilation installation. Presently, the single possibility afforded to occupants is to adjust the flowrate in the kitchen. It is to be hoped that in the future, more control possibilities will be afforded as well for air inlets as for exhaust valve flowrates.

Some defaults (noise, draughts, insufficient flowrates,...) are still encountered, they should be avoided through better application of simple guide lines, for instance : valves should be easily dismountable for cleaning ; air inlets, exhaust valves and fan command should be correctly located ; in order to prevent draughts and improve ventilation efficiency, recommendations for cleaning should be marked on the valves ; better sizing,especially in order do reduce noise,is expected.

As a whole, mechanical ventilation must therefore be still improved in order to better comply with occupants wishes. Nevertheless, it should be outlined that, the way it is now installed in France,mechanical ventilation succeeds in both preventing completely condensation annoyance and controlling effectively the heat losses through air renewal.

ACKNOWLEDGMENTS

This work was undertaken by the Division "Thermique et Aeraulique des Systemes et Enveloppes" of "Centre Scientifique et Technique du Bâtiment" in Champs sur Marne. The authors wish to thank Electricité de France and the Housing and Transport Minister for their support.

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
29 September - 2 October 1986

PAPER 8

VENTILATION HEATING SYSTEM OF SMALL HOUSES

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SYNOPSIS

The buildings built according to the latest construction technology aiming at energy saving are as tight as possible. The ventilation of a tight building has to be completely mechanical (supply and exhaust air system). The heating of the building can also be included in the mechanical ventilation system with small additions. The new warm air heating system developed at the Laboratory of Heating and Ventilating of the Technical Research Centre of Finland is therefore called ventilation heating system.

The ventilation heating system has several properties that can be achieved only when the heating effects needed by both heating and ventilation are completely adjustable on a room by room basis. Then the factors influencing room climate can be controlled with only one system.

The ventilation heating system has sufficient sound insulation and sound attenuation due to the structure of the central unit and right selection of air terminal devices. The exhaust air flows are controlled by the inhabitant according to his local and temporal needs. The pressure ratios of the building, and the outdoor and exhaust air flows, are under control in the different fan operation conditions. The temperature of each room can be controlled with one adjusting knob accordin to the needs of the inhabitant. The heating system is suitable for upper-distribution (blowing of warm air from the wall or ceiling). The room-based air flows do not have to be controlled accurately according to the heating need. The supply air ducts need not be heat insulated.

The ventilation heating system particularly gives better changes to meet the inhabitants' expectations on the heating and ventilation systems, and gives bases for industrial production of a new generation of warm air heating and ventilation systems.

1 INTRODUCTION AND BACKGROUND

1.1 Need for development in warm air heating

As a heat distribution system for small houses warm air heating came to the markets in its present form in Finland in 1976. It soon became more popular and reached the top of its success in 1981. Since then the proportion of warm air heating has considerably decreased in small house production due to failed system applications and strong increase in direct electric heating.

The investigation /1/ has evaluated the need for development of warm air heating systems on the basis of field tests on the existing warm air heating systems. Much need for development has also been found in the laboratory tests of warm air heating central units.

Future ventilation and heating systems must take particularly into account the inhabitants' expectations on flexible heating and ventilation systems /5/: stable room-controlled ideal temperature, silent and effective demand-controlled ventilation.

In building of new ventilation heating systems special attention was paid to the development and experiments of the following: the tightness and acoustics of ventilation heating system, room-based temperature control, the special properties of high sidewall supply outlets, control of the outdoor air and exhaust air flows in the different fan operation conditions, local and temporal control of exhaust air ventilation.

The operation of the ventilation heating system developed on the basis of laboratory tests has been studied in the tight (1,1 air changes per hour at 50 Pa) 1,5-story experimental house (88 W/K thermal conductance of building envelope) of the Technical Research Centre of Finland.

1.2 Why ventilation heating?

According to the latest construction technology the buildings have been made as tight as possible. The ventilation of a tight building has to be completely mechanical (mechanical supply and exhaust air system). With small additions heating of the building can also be included in mechanical ventilation.

If outdoor air is not supplied into the building mechanically, sufficient supply air openings for outdoor air have to be arranged in the building envelope, mostly by leaving supply air openings without weather strip in the upper sashes. Thus, in order to guarantee sufficient ventilation the building has deliberately been made leaky.

The sound insulation of a tight building equipped with mechanical ventilation is significantly better than that of a deliberately leaky building. Tightness is one of the most important properties of a building when we try to reach good sound insulation.

2 OPERATION OF THE VENTILATION HEATING SYSTEM

Figure 1 shows the air technical operation diagram of ventilation heating system. When water heated room-based warm air heating coils and boiler plants are used a suitable operation diagram for heating is presented in Figure 2.

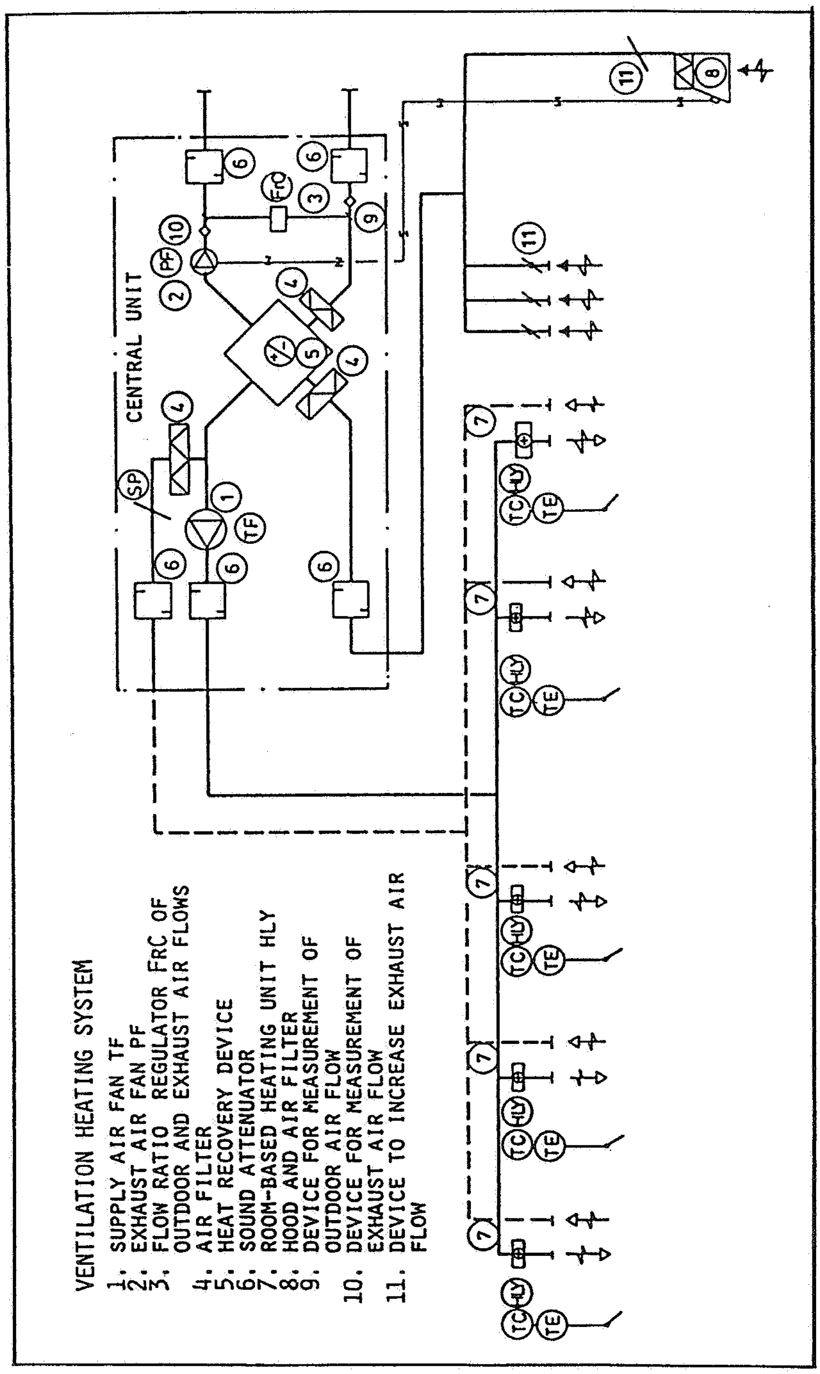

Figure 1. Air technical diagram of the ventilation heating system /3/.

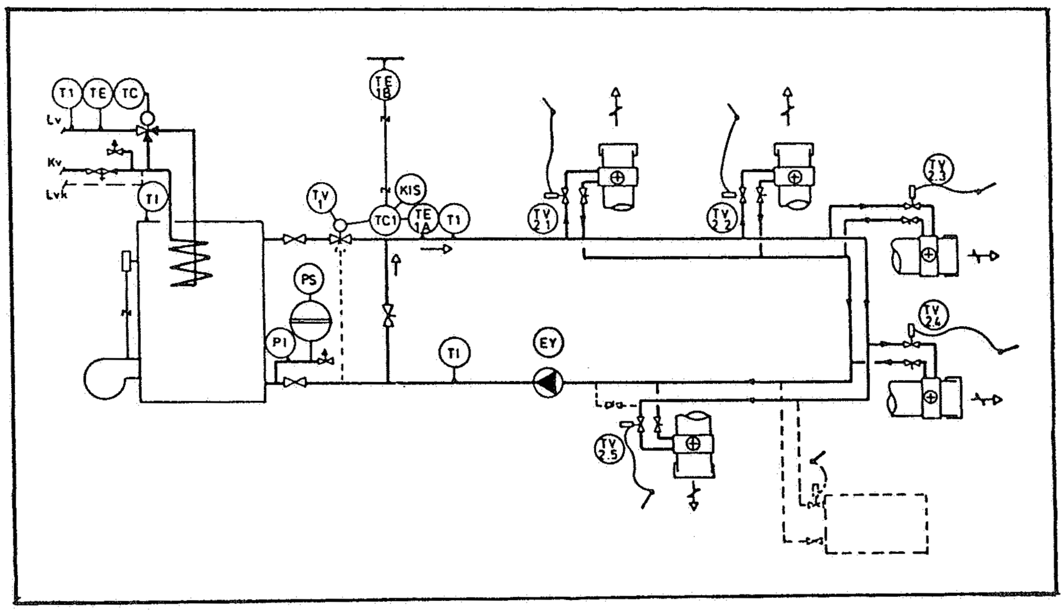

Figure 2. Operational diagram of the warm water heating network of the ventilation heating system. Boiler plant, two-pipe reverse-return system /3/.

2.1 Air technical operation

Supply air fan (heating air and outdoor air fan) TF operates in two different positions (rotation speed or voltage control), of which the control position with higher air flow is used under the heating season and the saving position with smaller air flow at other times. The minimum air flow needed by the supply air fan at other times is adjusted with the aid of recirculation air damper SP thus that the maximum outdoor air flow is reached when the supply air fan is at its minimum when the exhaust air fan operates at its maximum.

The flow ratio regulator FrC of the outdoor air and exhaust air flows keeps the difference between the exhaust and outdoor air flow constant, even though the air filters get dirty, and protects the heat recovery device from freezing. The regulator FrC controls the outdoor air flow according to the exhaust air flow and keeps negative pressure in the house. The flow ratio regulator is adjusted so that the maximum outdoor air flow is about 70 - 80 % of the maximum exhaust air flow. The difference between exhaust air flow and outdoor air flow remains almost constant within the whole flow range.

The exhaust air fan PF operates continuously with an air flow corresponding to minimum ventilation rate. The exhaust air terminal devices of moist rooms (e.g. toilet and bathroom) are silent devices equipped with a possibility of increasing air flow. Their dampers enable easy spatiotemporal control of exhaust air ventilation. Kitchen ventilation can be increased with the damper of the hood. Total ventilation can be increased with the control knob in the hood by increasing the rotation speed of the exhaust air fan. When the exhaust air fan stops the tight damper of the outdoor air duct closes.

The room-based air flows of an air ductwork are adjusted with the aid of sufficiently high pressure (> 50 Pa) and silent air terminal devices. The recirculation air is circulated on a room by room basis (sound insulation) or led centrally through individual room transfer openings under the doors and hallways to the central unit.

Outdoor air is preheated primarily in the heat recovery device and when mixed with the recirculation air. In addition, air is heated 1 - 2 K in the supply air fan. The recirculation air flow is adjusted with the aid of recirculation damper SP thus that at maximum outdoor air flow the temperature of the air blown into the ductwork does not with design outdoor temperature sink below the dew point temperature of the air surrounding the not thermally insulated ductwork. A practical design value for the recirculation air flow could be twice the outdoor air flow.

In the tight 1,5-story experimental house the total warm supply air flow was 119 dm^3/s, mechanically supplied outdoor air flow was 34 dm^3/s and the exhaust air flow was 52 dm^3/s. The warm supply air flows of the different rooms were 15 - 21 dm^3/s.

A room-based terminal heat transfer unit HLY heats the low temperature (> 10^oC) air in the supply air duct and the room. The rooms can be heated with warm water or electrical heating coils. The terminal heat transfer unit comprises room temperature sensor TE and control unit TC.

The structure of the central unit of the ventilation heating system is simple. After the preadjustments of the air flows the system works automatically. The desired room temperature can be adjusted with the control knob in the heating unit in each room.

2.2 Heat technical operation

Control centre TC 1 of the heating water network controls the regulating valve (e.g. two- or three-way valve) on the basis of the measurement values of supply water temperature sensor TE 1A and heat need sensor (e.g. outdoor air sensor) TE 1B and keeps the supply water temperature according to the set points of TC 1. The set points of the temperature of the water going to the terminal heat transfer units are selected thus that in normal loadings each room can always have enough heating effect for heating and ventilation. A bypass pipe equipped with flow control valve is installed in the water heating network for a small bypass flow in order that there is always fast enough heat available for each heating coil and at the same time the disadvantageous pressure conditions of coil regulator valve are avoided. The water flows of the heating coils are limited according to the design conditions. The room-wise temperature controlled valves TV 2.1 - TV 2.5 throttle, when needed, the water flow of the heating coils according to the need for heating.

Even water radiators can be installed in the heating, network, e.g. for the kitchen, garage and wind chamber.

The heating water network according to two-pipe reverse-return system presented in Figure 2 should technically be dimensioned thus that the pressure loss of the pipe is lower than 100 Pa/m and the pressure losses of the coil or radiator valves are higher than 2 kPa /2/.

3 ADJUSTMENT OF ROOM TEMPERATURE

In the ventilation heating system there is during the heating season for each room simultaneously available both heating and cooling effect and room temperature can simply be selected with a control knob in the wall. Figure 3 shows a typical control situation of a room temperature in the experimental house on a spring day.

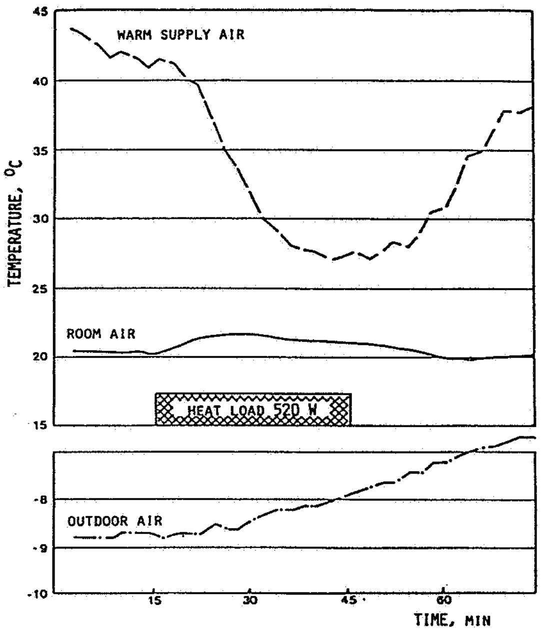

Figure 3. Properties of room-based temperature control in the ventilation heating system on a sunny spring day.

4 PREADJUSTMENT OF AIR FLOWS

In the ventilation heating system the central unit is placed in the middle of the building. The sound attenuated and low temperature air from the central unit is supplied and distributed at high level along short uninsulated air ducts at a high enough pressure to the silent air terminal device on the back or side wall of each room. No other sound generating dampers are needed in the ducts. The heating coil in each room can be in the air duct right outside the room or in the air terminal device.

At an air flow corresponding to maximum heating effect or maximum exhaust air ventilation rate the sufficiently high pressure and silent supply and exhaust air terminal devices should meet the following requirements:

- total pressure loss > 50 Pa
- highest accepted sound pressure level in a room (10 m^2 sound absorption) 25 dB(A).

A small air temperature gradient is reached in the room when the throw corresponding to the terminal velocity 0,2 m/s of the supply air device's warm air flow is at least the free length of the room and the supply air terminal device has good air mixing properties, figure 4.

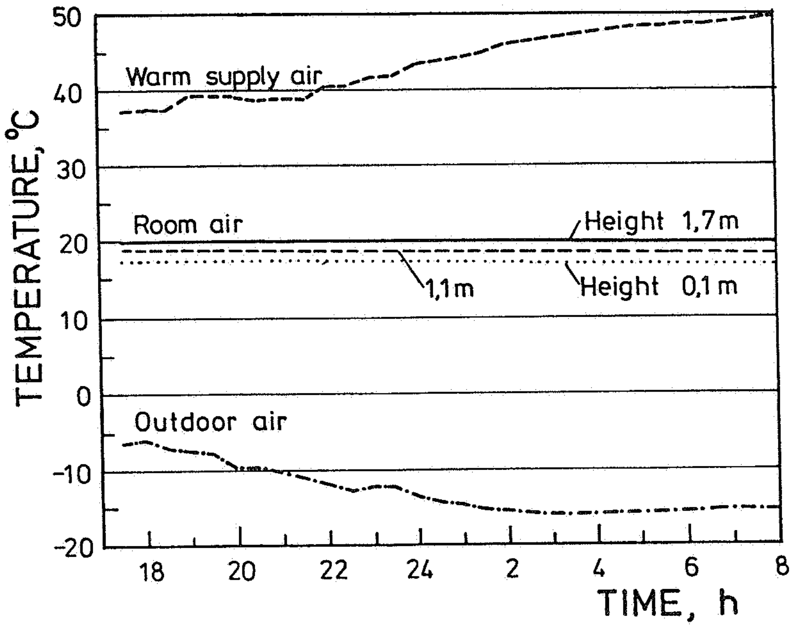

Figure 4. Indoor air temperature gradient in a bedroom heated by the ventilation heating system on a winter night.

The preadjustment and sound technical properties required of the air terminal devices combined with good air distributing properties make a great part of the marketed supply air devices, e.g. grilles and registers, unsuitable for the ventilation heating systems.

In the ventilation heating system the room-based warm air flows do not have to be exactly according to the heat losses of the rooms, because the heating effects needed by the rooms are transferred to the air from separate heating coils. The heating air flow in the room shall be sufficient in order that the heating effect corresponding to the design situation can be transferred to the room from the heating coil. The warm air flows of the rooms shall be limited thus that the sound levels of the air terminal devices are low enough.

Figure 5 /4/ shows the interactions between the supply air temperature and warm air flow rate in an upper distributed warm air heating system. By selecting the right supply air temperatures and air flows we can obtain good room climate.

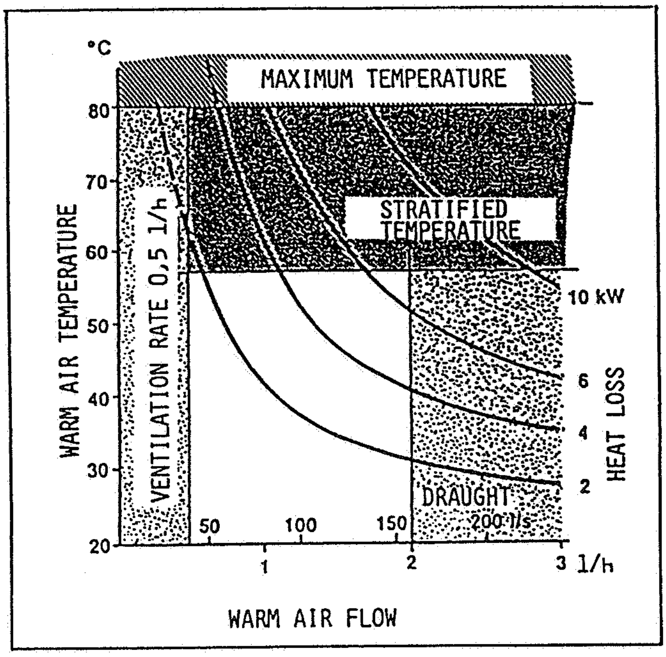

Figure 5. Interactions between supply air temperature and warm air flow rate in an upper distributed warm air heating system /4/.

5 NOISE CONTROL

At maximum air flow the total sound power levels are about 79 - 87 dB at the inlets and outlets of the fans of the ventilation heating system. This means use of very effective noise control in order to reach the noise levels accepted in rooms, 25 - 30 dB(A). In bedrooms the sound level should be 25 dB(A) at most.

In the ventilation heating system all the noise control (vibration isolation and sound attenuation of fans and sound insulation of the casing) have been made in the central unit. In addition, the right type of sufficiently high pressure and silent air terminal devices are selected for preadjusment of the air flows in the rooms and max 3 - 4 m/s flow velocities are used in the air ducts.

6 AIR FILTRATION

The need of filtering the outdoor, recirculation and exhaust air used in the ventilation heating system can be esitmated on the basis of both equipment and room soiling and sanitary viewpoints.

In the ventilation heating system the efficiency and structure of the air filters can freely be selected according to need of filtering. Bypass flows of the air filters must be prevented.

6.1 Outdoor air filters

At least the largest dust particles have to be filtered from the outdoor air to keep the heat recovery device clean. A good prefilter is sufficient. If the outdoor air has high dust content and plenty of small particles at least a fine filter of Eurovent air filter class EU4 has to be used.

6.2 Recirculation air filters

The development of dust in the apartment is decisive for the dust content of the recirculation air. The dust and textile fibres developed due to friction are relatively large. A good prefilter should be sufficient for filtering them. The particles of cigarette smoke are < 1 µm while the average particle size is about 0,1 µm. Efficient filtering of these particles as well as other small particles hazardous to health requires very good fine filters (at least EU7).

6.3 Exhaust air filters

Exhaust air contains in addition to recirculation air dust also grease from the kitchen. A kitchen grease filter protecting the ducts and a good prefilter protecting the heat recovery device should be sufficient for exhaust air filtering.

7 CONCLUSIONS

7.1 The advantages of the ventilation heating system

The ventilation heating system has several properites that can be achieved only when the heating effects needed by both heating and ventilation are completely adjustable on a room by room basis. Then the factors influencing room climate can be controlled with only one system.

The special advantages of ventilation heating systems are:

- The ventilation heating system has sufficient sound insulation and sound attenuation due to the structure of the central unit and right selection of air terminal devices.

- The exhaust air flows are controlled by the inhabitant according to his local and temporal needs.

- The pressure ratios of the building, and the outdoor and exhaust air flows, are under control in the different fan operation conditions.

- Each room can be both heated and cooled.

- The temperature of each room can be controlled with one adjusting knob according to the needs of the inhabitant.

- The room-based air flows do not have to be controlled accurately according to the heating need.

- The heating system is suitable both for a high and low temperature system.

- The heating system is suitable for a so-called mixed system (it is not profitable to heat all the rooms with air).

- The heating system is suitable for upper-distribution (blowing of warm air from the wall or ceiling).

- The supply air ducts need not be thermally insulated.

- The air filters can be selected according to need.

7.2 Needs for further development

Several needs for development of single devices have emerged during the development of the ventilation heating system. The small air heating coils with room thermostats and suitable flow ratio regulator for outdoor and exhaust air flows needed are not on sale. The cost of the prototypes developed have, however, been small, Figure 6 /6/. The industry should develop, for instance, the following sufficiently cheap components suitable for the ventilation heating system:

- flow ratio regulator of outdoor and exhaust air flows,
- tight dampers for air flow,
- small air heaters for each room,
- sufficiently high pressure and silent air terminal devices,
- vibration isolators for small fans.

The development of ventilation heating system gives bases for industrial production of a new generation of warm air heating and ventilation systems.

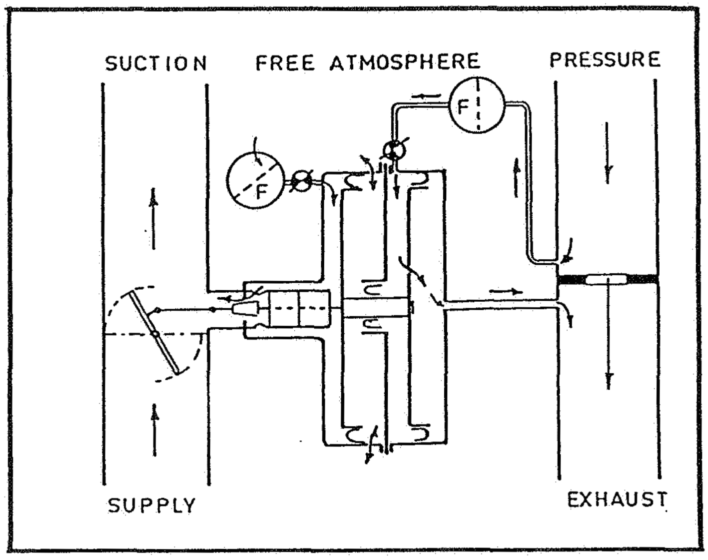

Figure 6. Flow ratio regulator of outdoor and exhaust air flows in the ventilation heating system, principle of selfcontained cascade control /6/.

The ventilation heating system particularly gives better changes to meet the inhabitants' expectations on the heating and ventilation systems.

Acknowledgements

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
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PAPER 9

USER CONTROLLED EXHAUST FAN VENTILATION IN ONE-FAMILY HOUSES

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SYNOPSIS

A group of 18 identical well-insulated experimental houses in Sweden, utilizing a user controlled exhaust fan ventilation system, was monitored during 1985-1986.

The ventilation rate can be controlled by the user by adjusting the fan speed with a conveniently located three-way switch. No heat recovery is provided for, the idea being that the average ventilation rate will be low, thereby saving energy.

The houses are described. The results from measurements of ventilation efficiency, ventilation rates, run time of fan speeds and energy consumption are presented.

The investigation has shown that a simplified exhaust fan ventilation system can lead to a comfortable indoor climate.

The results so far indicate that the average yearly consumption of electricity for space heating, hot water heating and household use will be as predicted i.e. 12,000 kWh, compared with approximately 20,000 kWh for a well-built house that meets the current Swedish National Building Code. This energy saving was achieved by insulating and tightening the houses very well and installing a user controlled ventilation system.

1. INTRODUCTION

A group of 18 identical well-insulated experimental houses in Stockholm, Sweden, utilizing a user controlled exhaust fan ventilation system, have been built during 1984.

The main principles behind the design of the houses were:

- energy efficient and inexpensive design
- well-insulated and tight building envelope
- resource efficient lightweight construction technique
- simple foundation
- simple heating system with individual thermostats
- energy and water efficient appliances
- instructive owner's manual
- a simple ventilation system

The ventilation rate can be controlled by the user by adjusting a conveniently located three-way switch. No heat recovery is provided for, the idea being that the average ventilation rate will be low, thereby saving energy. The houses were monitored during 1985 and 1986, to assess both thermal performance and comfort conditions.

2. DESCRIPTION OF THE HOUSES

2.1 General Description

All 18 houses are modern wood frame constructions. They are heated with electric baseboard heaters. The houses are 119 m^2, with three bedrooms upstairs, a kitchen, and a living room downstairs (see figure 1).

The houses have an exhaust ventilation system, mechanically controlling the exhaust air. There are exhaust vents in bathrooms, laundry, and kitchen. Nine of the houses have additional exhaust vents in the bedrooms. Every house has special vents to the outside for supplying fresh air. The ventilation rate can be controlled by the user by adjusting a conveniently located three-way switch: 1 (no one at home) = 0.1 air changes per hour, 2 (the whole family at home) = 0.3 air changes per hour, 3 (maximum) = 0.5 air changes per hour. When the stove is used the ventilation rate can be increased by further opening the outlet device located above the stove. The total air flow through the exhaust fan will remain the same. If this isn't enough the fan speed can be increased with the switch mentioned above.

2.2 Energy Conservation

Insulation: Mineralwool insulation was installed in walls, ceilings, and floors (above a crawl space) in all houses. Thermal resistance of the building envelope is much better than in most conventional Swedish houses. Walls have U-values of 0.13 W/m^2K, roofs of 0.10 W/m^2K, floors of 0.18 W/m^2K. For windows quadruple-glazing (U-values below 1.6 w/m^2K) was used.

Tightness: As a moisture and air barrier, a continuous polyethylene sheet was employed between the insulation and the interior finish of walls, ceiling and floor. This was done for all houses except one. The number of penetrations through the continuous polyethylene sheet was limited. The building enevelope of all houses meets Sweden's National Building Code requirement for airtightness, 3.0 air changes per hour at 50 Pa (excluding vents). The average tightness is 1.6 air changes per hour, excluding the house without polyethylene sheet, which has a value of 3.1. Traditional modern Swedish construction (those buildings erected prior to Sweden's 1975 introduction of airtightness standards) commonly evidence 5.5 air changes per hour.

Heat recovery: No heat is recovered. Instead of recovering heat from the exhaust air substantial energy savings are achieved if the occupants lower the ventilation rate e.g. when they aren't at home. The average ventilation rate will then be low.

3. DESCRIPTION OF MONITORING PROGRAM

The houses were monitored continuously for 2.0 years, to assess both thermal performance and comfort conditions (1,2). Short unoccupied periods were used for special measurements and one-time tests which included the following:

- pressurization (airtightness) (3)
- tracer gas measurements (ventilation efficiency and ventilation rates including mechanical ventilation and air infiltration) (4,5,6)
- infrared photography scans (airtightness and thermal insulation)
- air flow mesurements in ducts
- indoor temperature measurements.

During the long-term monitoring the following factors were recorded:

- electric energy use, measured separately for space heating, hot water, and household
- indoor and outdoor temperature
- run time for different exhaust fan speeds etc.

4. RESULTS

4.1 Ventilation Rates

The ventilation rates i.e. the supply of fresh air from the outside was monitored using the constant concentration tracer gas technique. The measurements show that the ventilation rate for the whole house was as planned, 0.25 air changes per hour (70 m^3/h) when the exhaust fan is set on the "at home" position and 0.15 air changes per hour (50 m^3/h) when set on the "no one at home" position. Some variation with time can be noticed (see figure 2 and 3). This variation shouldn't have any practical significance. The above results weren't obtained the first time the measurements were made. More than half a year of changing and adjusting the ventilation system was required by the contractor to obtain the desired ventilation.

The measured mechanical ventilation rate is somewhat higher then the measured total ventilation rate i.e. the sum of mechanical ventilation and air infiltration. The difference is within the inaccuracy of the two measurements. A definite conclusion which can be drawn is that the air infiltration is usually very small i.e. all the air is leaving the house through the exhaust fan. When the fan is turned off the air infiltration will be approximately 0.10 air changes per hour.

The amount of fresh air supplied to individual rooms varies with the outdoor temperature and the wind. The total ventilation rate for the whole house is almost constant. When the temperature sank drastically the supply of fresh air directly from the outside increased on the first floor and decreased on the second floor (see figure 4,5,6 and 7). This can be explained by the change in pressure distribution caused by the temperature drop. There was a shift in the pressures caused by the exhaust fan. Then the air flow from the first floor to the second floor was probably increased.

If the house had been tighter the shift in ventilation would have been less drastic. The actual airtightness for this particular house was 2.4 air changes per hour (excluding the vents). In a previous report (7) it was estimated that the airtightness for a house with an exhaust fan ventilation system should be better than 3.0 air changes per hour (including vents).

All individual rooms get fresh air directly from the outside. There doesn't seem to be any difference in the bedroom ventilation rates between houses where the used air is removed directly out of the bedrooms (parallell flow) as opposed to indirectly (serial flow) (see table 1). By indirectly is meant that the outgoing air has to pass through an adjoining room, i.e. the upstairs hall, before leaving the house, through the exhaust vent in the bathroom.

Table 1. Average ventilation rate i.e. fresh air coming directly from the outside into the individual rooms.

	Serial flow	Parallel flow
Outdoor temp.	1 °C	0.6 °C
Wind speed	0.6 m/s	0.6 m/s
Duration of measurements	17 h	12 h
Living room	5 m^3/h	14 m^3/h
Hall downstairs	28 m^3/h	10 m^3/h
Laundry	7 m^3/h	6 m^3/h
Kitchen	1 m^3/h	3 m^3/h
Entrancehall	6 m^3/h	18 m^3/h
Master bedroom	9 m^3/h	10 m^3/h
Bedroom	4 m^3/h	5 m^3/h
Bedroom	4 m^3/h	4 m^3/h
Total	64 m^3/h	70 m^3/h

The average mechanical ventilation rate during the heating season (November through March) is 0.3 air changes per hour, which is as predicted. This value is based on recorded values of run times (see table 2) for the different settings of the fan speed and one-time tests of the ventilation rates.

Table 2. Recorded values of run times (hours) for different settings of the exhaust fan speed for the period November through March. All 18 houses are included.

Fan setting, air changes per hour	0.1	0.3	0.5
Lowest	0.0 h	1,390 h	12 h
Average	875 h	2,700 h	200 h
Highest	2,620 h	3,575 h	600 h

4.2 Ventilation Efficiency

The ventilation efficiency was measured using the tracer gas decay technique. The decay was monitored in 17 different points.

The distribution of fresh air within the individual rooms seems to be satisfactory (see figure 8 and 9). The ventilation in the bedrooms upstairs is not affected by the fact whether the door is closed or not.

4.3 Energy Consumption

During one year (April 1985 - March 1986) the houses consumed 12,800 kWh (± 2250) of electricity. This is an actual measured consumption, where the indoor temperature for the different houses varied between + 19 and + 22 °C during the heating season. The mechanical ventilation system didn't work properly until December. The actual ventilation rate before December is therefore uncertain. The results seem to be close to the predicted yearly energy consumption rate of 12,000 kWh.

Of the total consumption of electricity, space heating consumed 7,200 kWh (± 1000), domestic hot water heating 2,450 kWh (± 1350) and household electrical use (lights, washer, dryer, range, and miscellaneous) 3,200 kWh (± 1150).

With a conventional mechanical ventilation system the energy losses due to ventilation would have been 4,050 kWh during the heating season or 6,500 kWh in a year. In the experimental houses the same losses are lowered to 2,250 kWh resp. 3,600 kWh due to the reduced average ventilation. This is assuming an average value of 0.5 air changes per hour for a conventional ventilation system and that the average ventilation rate for the experimental houses are the same for the heating season as for the whole year.

5. CONCLUSIONS

The investigation has shown that the simplified exhaust fan ventilation system can lead to a comfortable indoor climate, with fresh air and comfortable temperatures. The results up to now indicate that without any heat recovery the average yearly consumption of electricity for space heating, hot water heating and household use will be close to the predicted value i.e. 12 000 kWh. A well-built house, that meets the current Swedish National Building Code, uses approximately 20,000 kWh. This energy saving was achieved by insulating and tightening the houses very well and installing a user controlled exhaust fan ventilation system. The houses will be evaluated in greater detail once the monitoring is finished by the end of 1986 and presented in a final report.

6. ACKNOWLEDGEMENTS

The performance monitoring and evaluation was funded by the Swedish Council for Building Research. Per-Olof Carlson, Arne Johnson Ingenjorsbyra, was in charge of designing and building the houses in Stockholm. The author appreciates the assistance of Leif Lundin, who aided in the measurements, Christer Karlsson, who aided in the evaluation, and Nancy Shoiry, who edited this paper.

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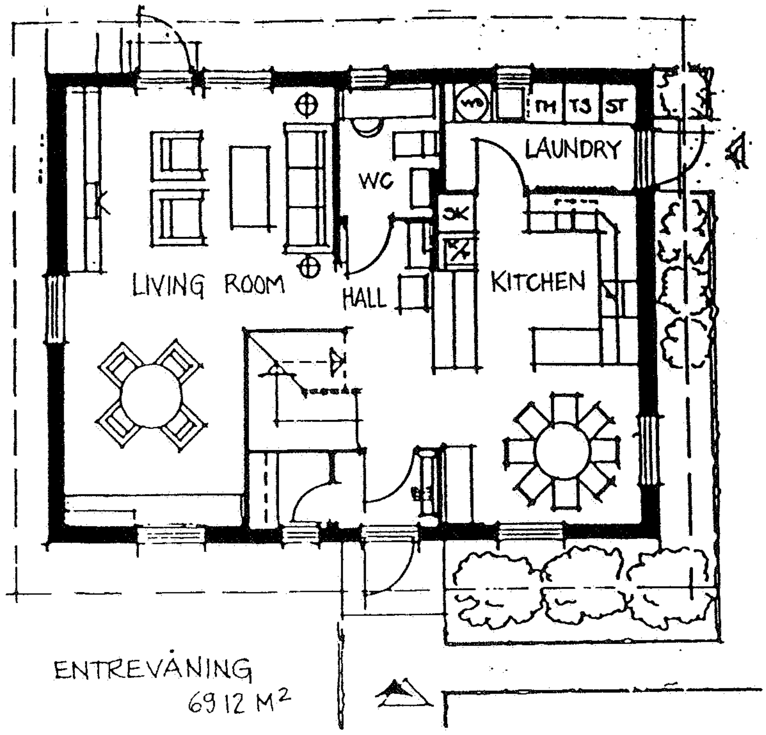


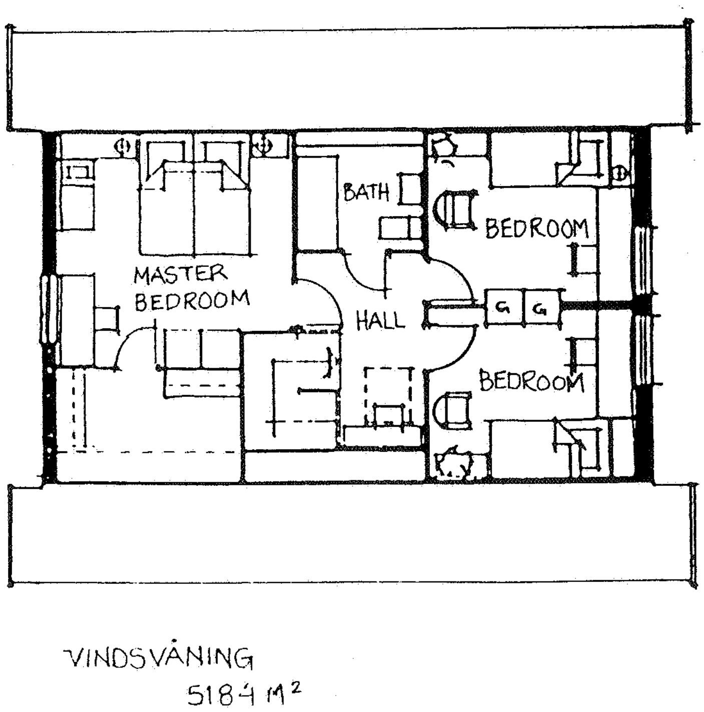


Figure 1   Plan of the experimental houses.

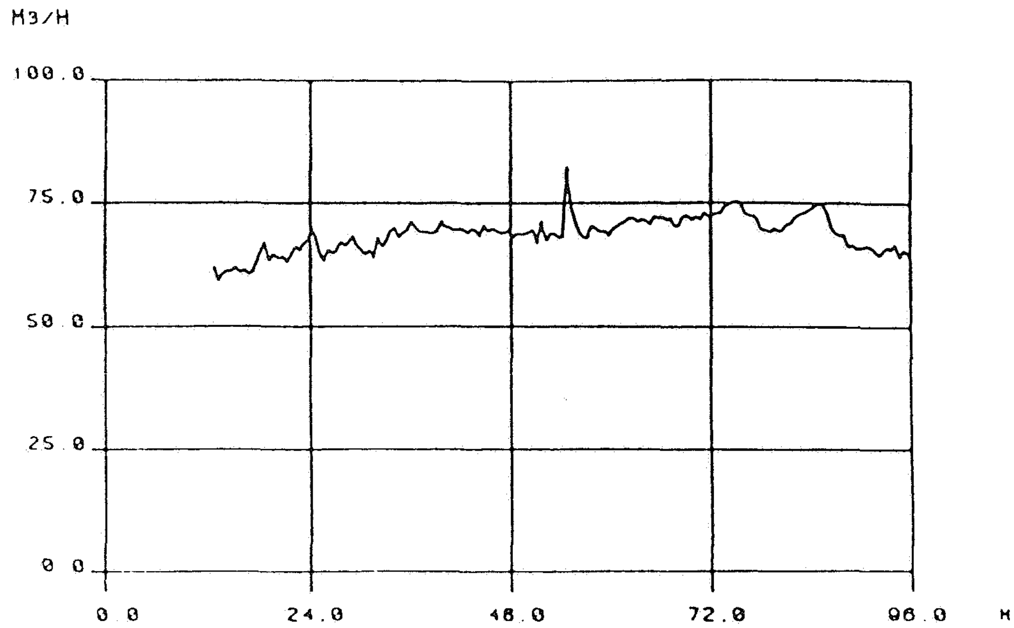


Figure 2 Measured ventilation rate (mechanical ventilation + air infiltration) when the exhaust fan is set on the "at home" position. The average wind speed was 0.3 m/s and the average outdoor temperature was -14 °C (see figure 4).

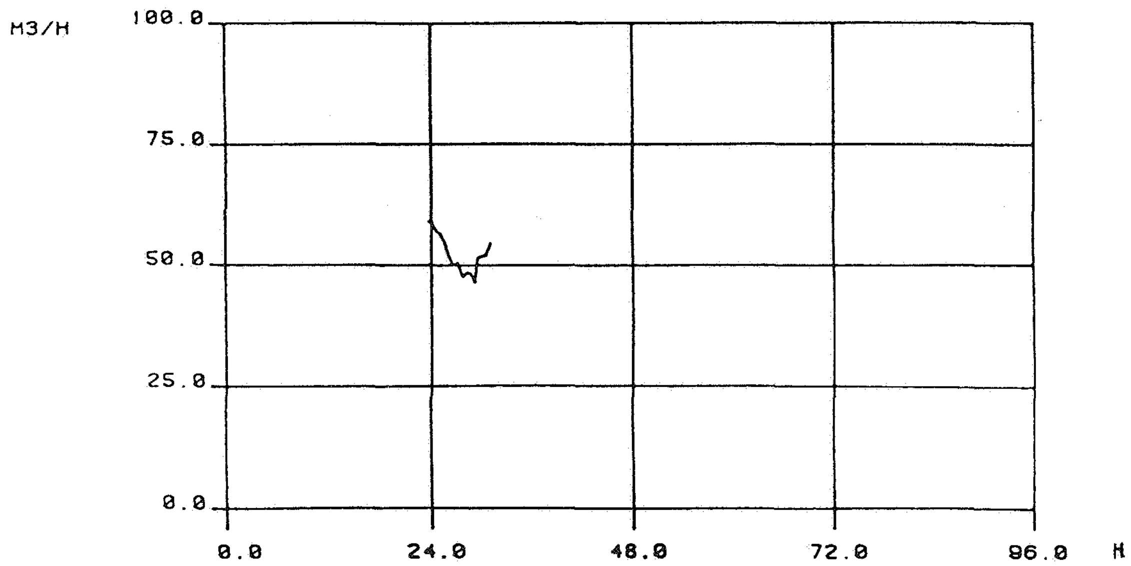


Figure 3 Measured ventilation rate (mechanical ventilation + air infiltration), when the exhaust fan is set on the "no one at home" position. The average wind speed was 0.8 m/s and the average outdoor temperature was -0.9 °C.

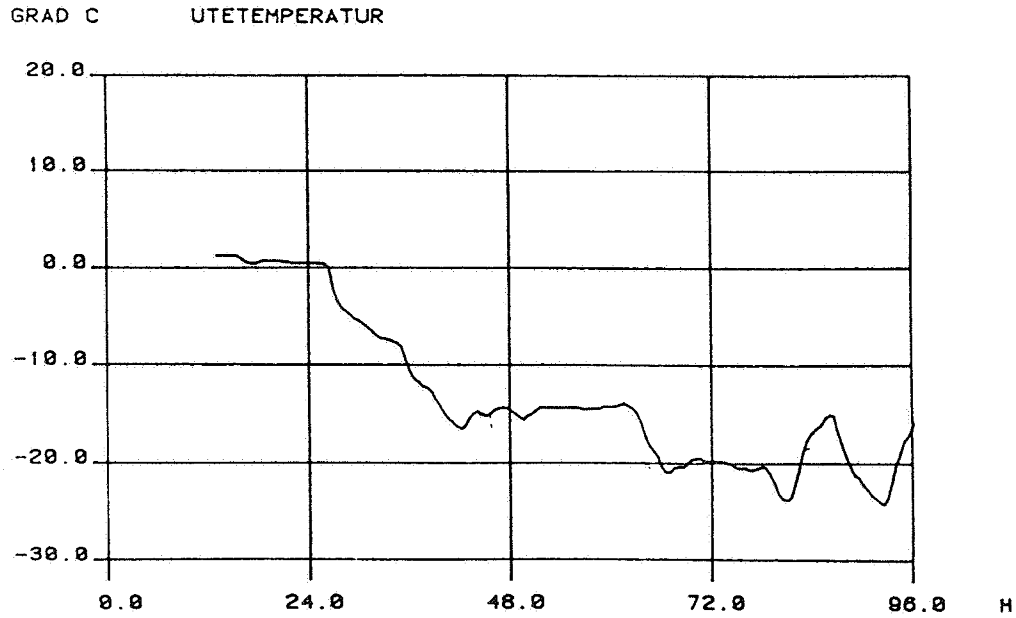


Figure 4 Outdoor temperature.

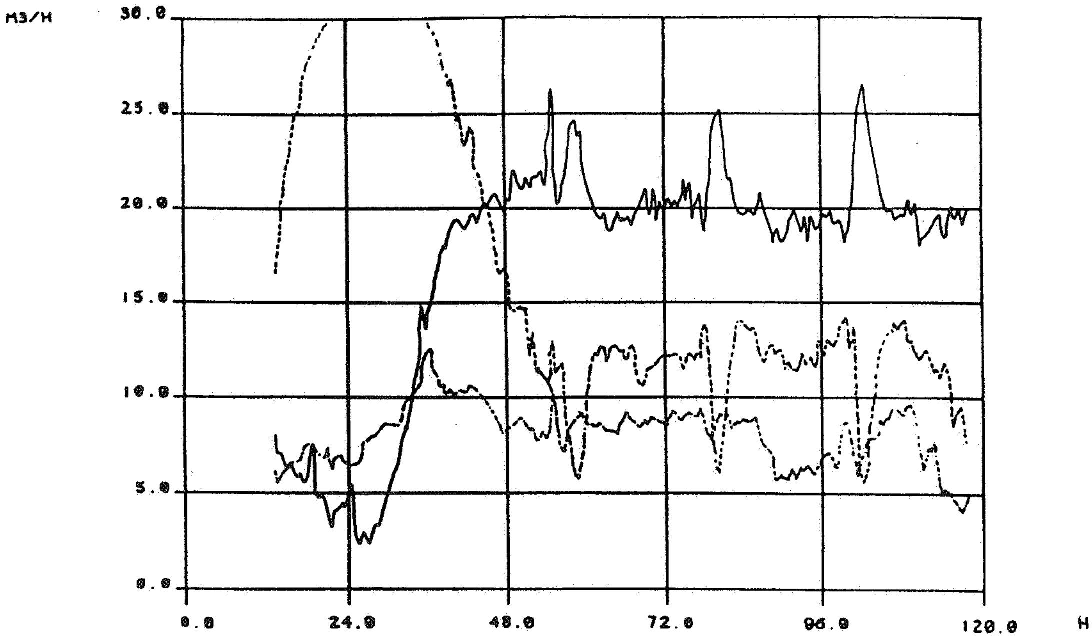
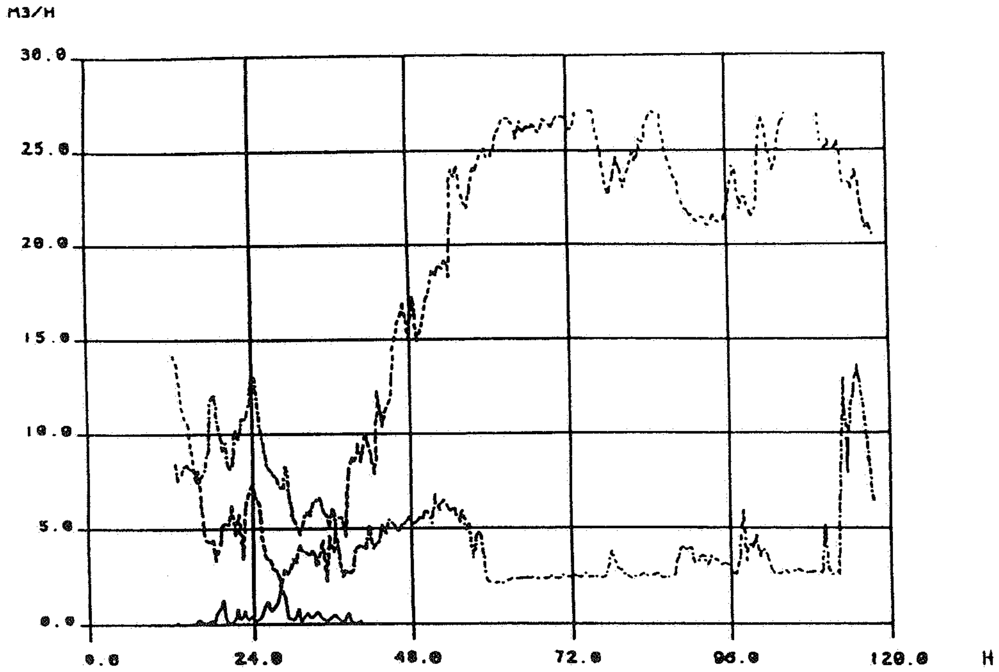


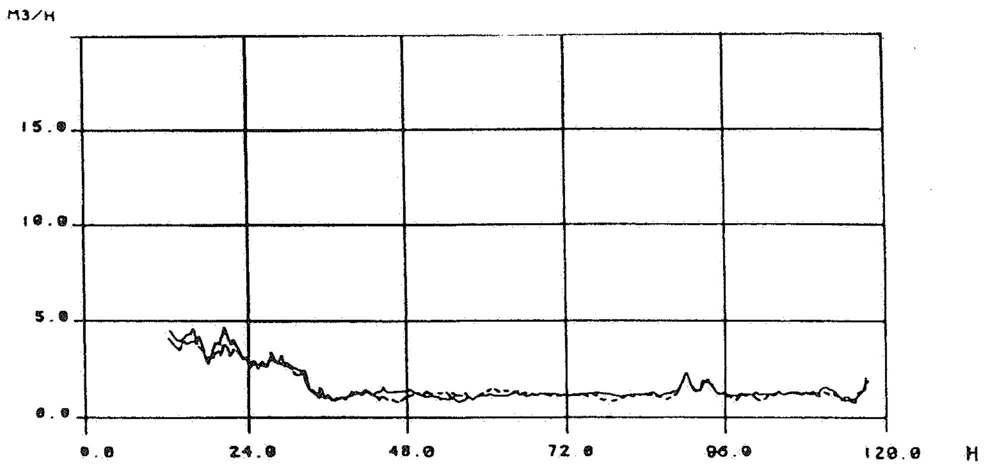
Figure 5 Measured ventilation rates (mechanical ventilation + air infiltration), when the exhaust fan is set on the "at home" position.

___________	living room
----------	hall downstairs
-·-·-·-·-	laundry



<u>Figure 6</u> Measured ventilation rates (mechanical ventilation + air infiltration), when the exhaust fan is set on the "at home" position.

――――――――	kitchen
---------	entrance hall
-·-·-·-·-	master bedroom



<u>Figure 7</u> Measured ventilation rates (mechanical ventilation + air infiltration), when the exhaust fan is set on the "at home" position.

――――――――	bedroom
---------	bedroom

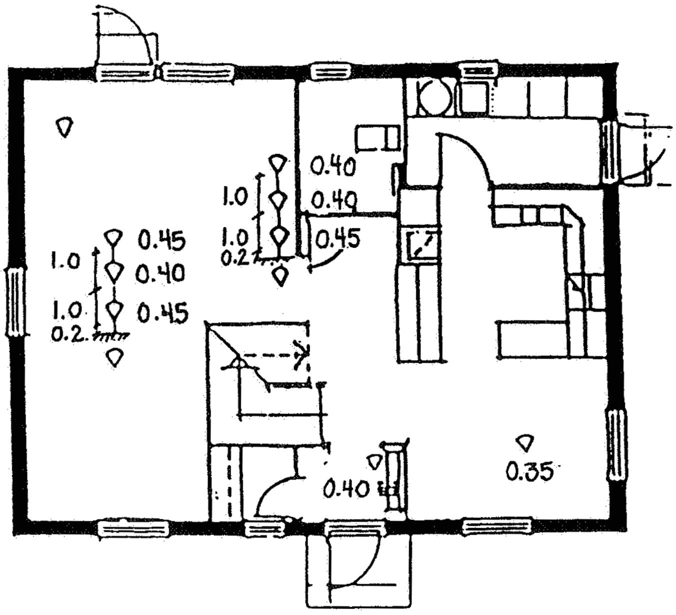


Figure 8 Ventilation efficiency downstairs in air changes per hour at 0.2 m, 1.2 m and 2.2 m above the floor. The exhaust fan was set on the "at home" position. The wind speed was 0.2 m/s and the outdoor temperature was -5 °C.

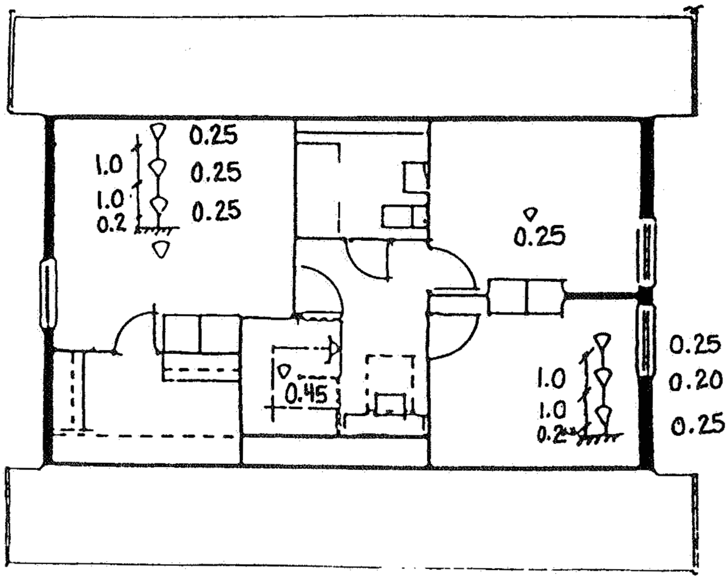


Figure 9 Ventilation efficiency upstairs in air changes per hour at 0.2 m, 1.2 m and 2.2 m above the floor. The exhaust fan was set on the "at home" position. The wind speed was 0.2 m/s and the outdoor temperature was -5 °C.

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
29 September - 2 October 1986

PAPER 10

VENTILATION AND INDOOR AIR QUALITY IN NEW NORWEGIAN DWELLINGS

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SYNOPSIS

SINTEF, The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, has monitored a number of experimental low-energy houses, and also undertaken measurements in some other houses to establish the energy consumption, air tightness, ventilation rates etc. Some of the experimental houses are extremely air tight.

In connection with these measurements we have made some observations on the occupants behavior related to ventilation, and their satisfaction with the ventilation system.

<u>Ordinary built houses</u>

In 10 detached houses built in 1980 according to the present air tightness requirements ($n_{50} \leq 4$), we studied the use of ventilation during wintertime with outdoor temperatures -10 °C to -20 °C. The houses were equipped with exhaust ventilation system and vents in the windows. The use of vent inlets in the upper frame of the windows varied from 0 to 10 out of total 15 vent inlets. The mechanical ventilation was used only in 3 houses, in the rest it was blocked or switched off by the occupants. The occupants have made it possible themselves to switch the fan off. This together with changes in temperature and wind made the air change rate vary between 0.2 and 0.7 air changes per hour with an average 0.45. The n_{50} test gave an average of 3.9 for these houses.

<u>Experimental, extremely air tight houses</u>

The project consists of 11 low energy houses, with an average air change rate 0.85 h^{-1} according to the n_{50} test. The infiltration rates measured under normal winter conditions were lower than 0.1 h^{-1}. The houses have different ventilation systems. The best comfort conditions were observed in the houses with mechanical balanced ventilation system. In 3 houses with natural (buoyant) ventilation with outlet ducts over roof from kitchen and bathrooms and inlet vents in windows according to traditional practice problems with comfort, and condensation were observed. The measured ventilation rate, even in cold weather with all vents open, was very low. This was partly compensated by the occupants through opening of windows. These houses were prepared for mechanical exhaust which was installed after 2 years. The occupants noted a very considerable improvement in comfort after this modification.

<u>Energy saving in households</u>

In an interview investigation in 112 similar row houses in Trondheim (by Steinar Ilstad) a strong relationship between air infiltration/ventilation rates based upon different indicators, and annual energy consumption was established. The energy consumption varied from (average) 15600 kWh for "low ventilation index" to 19450 kWh/ for the winter period for "high ventilation index".

Our projects confirm that occupants behavior in relation to ventilation varies considerably. Many Norwegians sleep with open windows year round. Others shut down the ventilation by closing all vents or stopping the fans during cold periods. The habits are influenced by new building technology. More knowledge is needed for a complete picture of the users behavior, satisfaction and need for ventilation, and the efficiency and economy of different systems.

1. INTRODUCTION

In Norway today ventilation, indoor climate and air quality is one of the major subjects in research work related to environmental engineering. This concerns both commercial buildings, schools and dwellings. These subjects and problems are related to our work with energy conservation in buildings.

At SINTEF, The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology, we have monitored a number of experimental low-energy houses, and also undertaken measurements in some other houses to establish the energy consumption, air tightness, ventilation rates etc.

In connection with these measurements we have made some observations on the occupants behavior related to ventilation, and their satisfaction with the ventilation system. In some houses we have also measured the indoor air pollution caused by building materials.

This paper describes two specific research projects. One project concerns ordinary built houses and another deals with experimental, extremely air tight houses. We focus on the results concerning air change rate, ventilation control, behaviour, comfort and air quality.

We also present some results from an interview investigation in 112 similar row houses concerning energy savings in households, and give some comments on Norwegian behaviour regarding window opening and ventilation control in general.

2. ORDINARY BUILT HOUSES

In January 1984 we measured the air change rate and heat loss factor in 10 identical detached dwellings. The main purpose of the project was to establish the relationships between the measured transmission heat loss factor, and the heat loss factor calculated according to Norwegian standard methods.

The houses were built in 1980 with a 100 m2 living area in detached 1 1/2 storey buildings. The houses are insulated with 150 mm mineral wool in walls and roof, and double glazed windows, figure 1. The houses are equipped with exhaust ventilation system and vents in the upper frame of the windows.

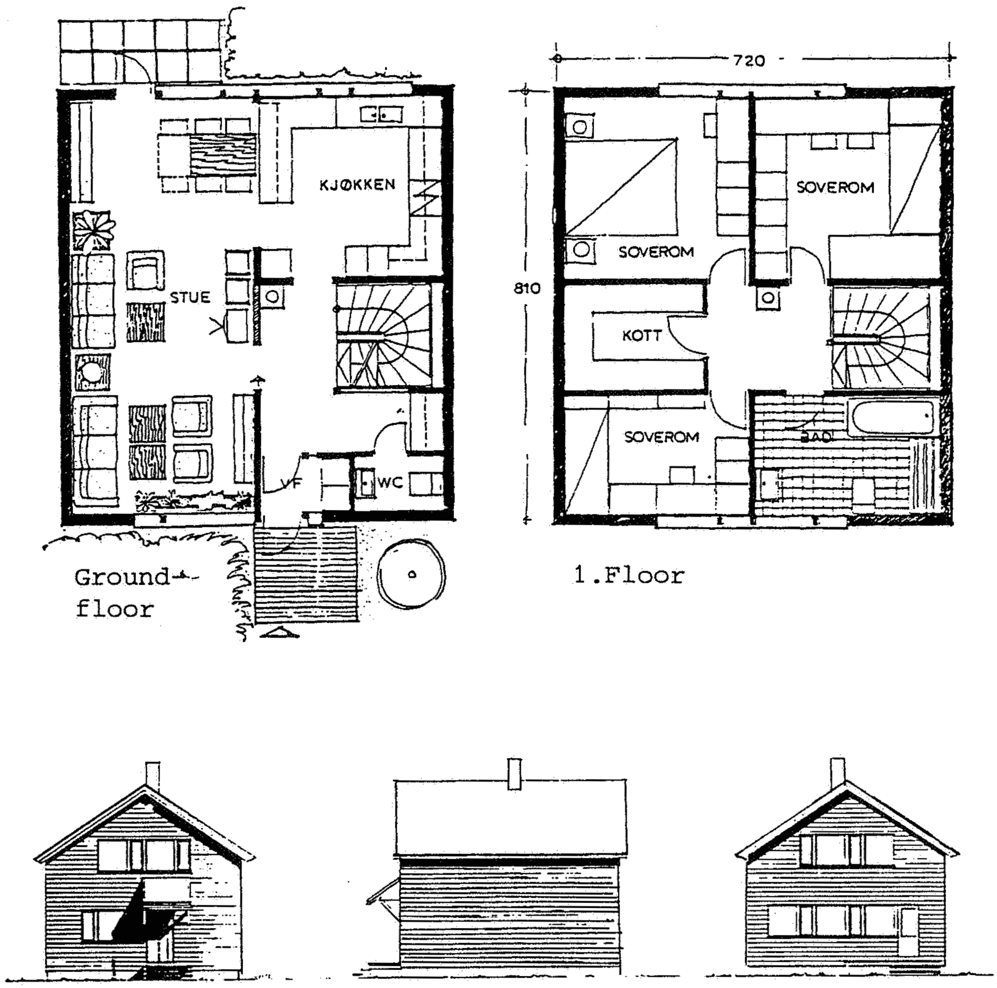

Fig 1 Ordinary built house (~100 m2)

We rented each house one day and measured
- temperatures (out- and indoor)
- wind speed
- energy consumption
- use of ventilation
- air change rate
- n_{50}-test

The air change rate was measured with N_2O (dinitrogen-oxyd) tracer gas with falling concentration.

During the measurement period the outside temperature and average wind speed varied considerably. The temperature varied from +4 °C to -20 °C.

Fig 2 Outdoor temperature during the measurements period

Each house was equipped with in all 15 vents in upper frames of the windows. The outlets are installed in kitchen, bathroom and WC, and are equipped with adjustable control vents.

Table 1 shows the connection between the use of the ventilation system, air change rate, outdoor temperature and windspeed, together with the n50 test-result for each house.

House	Open vents	Exhaust ventilation	Air change rate h^{-1}	Outdoor temp. °C	Wind speed m/s	n50 h^{-1}
1	2	on	0.6	4.6	6.0	4.8
2	5	off	0.3	1.5	4.2	3.3
3	1	off	0.2	0	4	3.8
4	0	off	0.3	-3.4	2.4	3.8
5	10	off	0.6	-7.2	2.3	4.5
6	1	off	0.2	-3.5	2	4.0
7	3	off	0.5	-2.5	3	3.4
8	6	off	0.6	-10.4	3	5.4
9	0	on	0.7	-18.2	0.2	3.8
10	0	on	0.5	-20.1	0.2	3.6

Tab 1 Relation between ventilation, air change and and outdoor climate

The use of vent inlets in the windows varied from 0 to 10 out of a total of 15 vent inlets. The ventilation fan was in the period actually running only in 3 houses. In the others it was blocked or switched off by the cccupants. The occupants had made it possible themselves to switch the fan off. (According to the code of practice this should not be possible). The windows were not opened during the measurements.

The air change rate varied between 0.2 and 0.7 air changes per hour with an average 0.45. This is caused by different use of ventilation together with changes in temperature and wind. The results from 3 houses (No. 4, 5 and 7) indicates an infiltration rate from 0.2 to 0.3 air changes per hour. We conclude that the occupants are satisfied with this low air change rate.

In the houses with the exhaust ventilation in use, none or only a few vents were open.

The n_{50} -test gave an average of 3.9 for these houses. Seven out of ten houses satisfies the present air tightness reguirements ($n_{50} \leqq 4$) for detached dwellings.

3. EXPERIMENTAL, EXTREMELY AIR TIGHT HOUSES

Description:

The "Heimdal-project" consists altogether of 14 low energy houses built 1980-81 as detached dwellings. The houses were planned and built in order to gain experience with different energy conservation systems. Three of the houses are passive solar houses with identical form and plan. The other 11 houses have the same form with about 120 m2 living area in 2 storeys. The houses are all occupied in a normal way.

The houses (not the solar houses) have different ventilation systems:

- 3 houses with natural (buoyant) ventilation with outlet ducts over roof from kitchen and bathroom and inlet vents in windows.
- 3 houses with exhaust ventilation from kitchen/bath and inlet vents in windows.
- 5 houses with different balanced mechanical ventilation systems combined with heat recovery systems.

Measurements of ventilation and air quality:

* We have measured the air tightness (n_{50}) in the houses twice. First time immediately before occupation and then one year after.

* The air change rate was measured with closed inlet vents, windows and doors and no use of mechanical ventilation. This was done in order to determine the infiltration rate under different windspeed and outdoor climate. In the 3 houses with natural ventilation measurements was also done with open inlet vents. We used N_2O tracer gas with falling concentration.

* Chemical pollutants (organic gasses, dust, formaldehyde and radon) are measured in unoccupied houseswith normal ventilation conditions.

* Use of window-ventilation is not systematically registred, but stipulated from interviewing the occupants.

Results:

The average air tightness for the 11 houses were 0.85 h^{-1}, with variations from 0.6 to 1.5 h^{-1}.

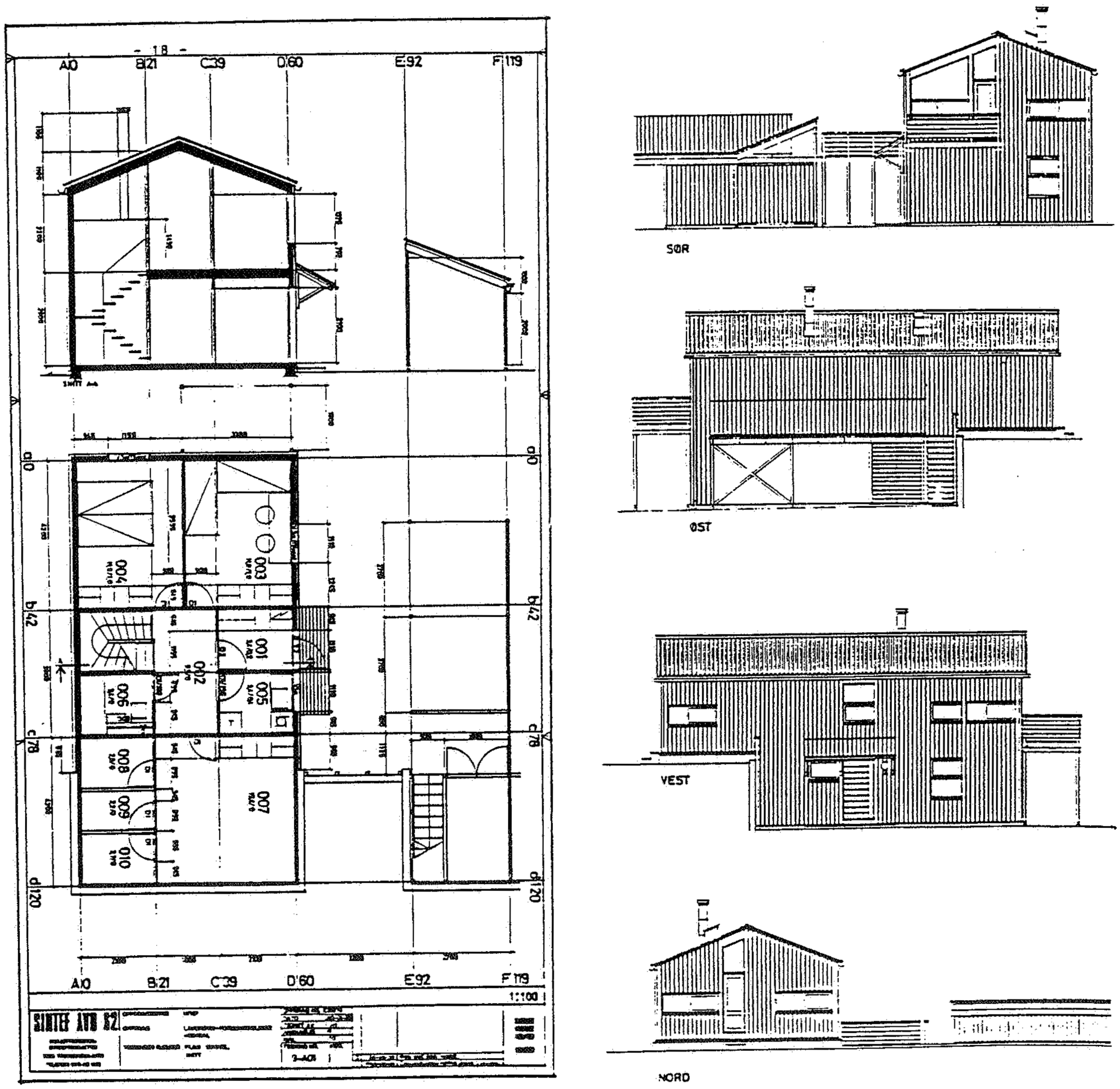

Fig 3 Low energy house

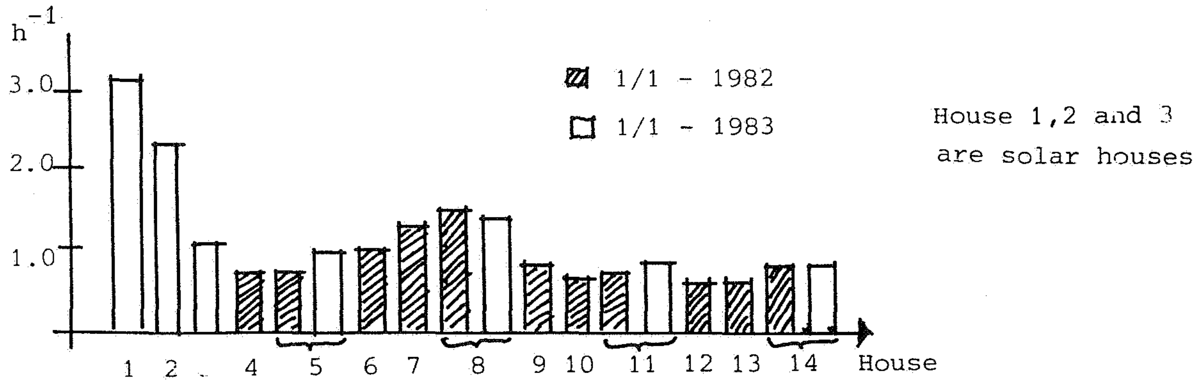

Fig 4 Air change rate n_{50}-test

The infiltration rates measured under normal winter conditions varied from 0.03 to 0.11 h^{-1} with an average of 0.05 h^{-1} for 7 houses.

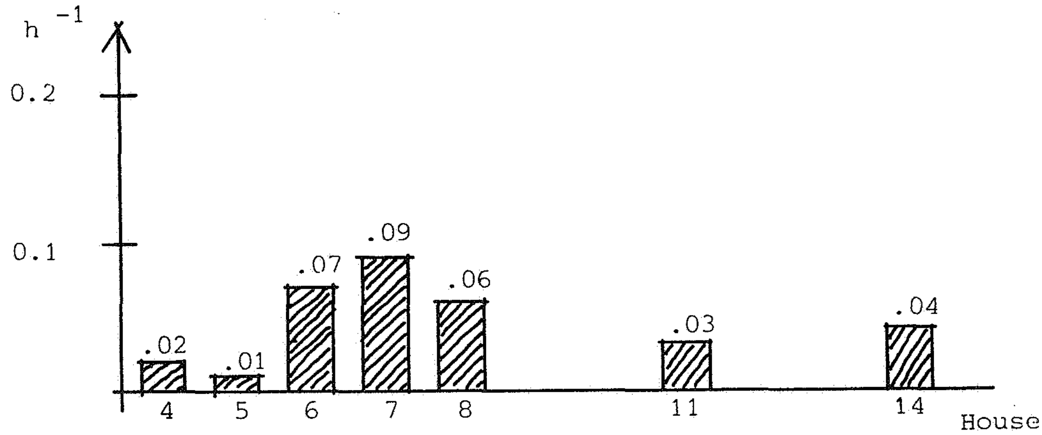

Fig 5 Infiltration rate

For one house we measured the infiltration rate under different climatic conditions. We had only small variations with different outdoor temperature and wind.

By use of natural ventilation and open inlet vents we measured a total ventilation rate of 0.2 h^{-1} in average. The low rate was partly compensated by the occupants by opening windows at irregular intervals.

In the 3 houses with natural ventilation we observed problems with comfort and condensation. These houses were prepared for mechanical exhaust which was installed after 2 years. The occupants noted a very considerable improvment in comfort after this modification.

The analysis of chemical pollutants showed:
- the presence of organic gasses to be inversely proproportional to the air change rate
- high airchange rate gives high dust concentration, i.e. the outdoor concentration is higher than indoor concentration

- low concentration of formaldehyde < 0.1 mg/m3 (mostly used plasterboard inside)
- radon concentration indoor similar to outdoor concentration

The ventilation rate (total) varied between 0.2 and 0.7 h^{-1} during these measurements.

Interviews with the occupants showed that ventilation through open windows is used during wintertime even in houses with excellent ventilation systems. The variations between occupants are considerable.

4. ENERGY SAVINGS IN HOUSEHOLDS

This was an interview investigation carried out by Steinar Ilstad, ORAL, University of Trondheim. The purpose of the study was to investigate how differences in total energy consumption between apartments can be explained by differences in the occupants behaviour (habits, attitude, social control).

The study comprised 112 similar row houses with 100 m2 living area heated by electricity. The data collection procedure included reading the electric meters in September and April, and systematic interviews with each family, on habits concerning indoor temperature, ventilation, hot water use, use of electric appliances etc. In relation to ventilation they were asked about use of inlet vents, air humidity, open windows during night and during day.

The relationship between air infiltration/ventilation rates and different indicators on ventilation habits was established. The energy consumption varied for the heating period from (average) 15600 kWh for "low ventilation index" to 19450 kWh for "high ventilation index". This means 25% higher energy consumption caused by different use of ventilation.

Some details from the interview investigation:

- 30% close all inlet vents during wintertime, 20% keeps all open
- 40% sleep with no open windows at night, 55% open 1 or 2 windows
- 35% open 1 or 2 windows during a part of daytime, 20% open 3-4 windows

In a similar investigation in 97 apartments it was found less use of open windows.

5. CONCLUSIONS

* Our projects confirm that occupants behavior in relation to ventilation varies considerably. Many Norwegians sleep with open windows year round, others shut down the ventilation by closing all vents or stopping the fans during cold periods.

* We have no problem with condensation in normal new dwellings with only simple ventilation systems. According to interviews condensation problems only exist in older not sufficient insulated houses.

* In extremely air tight houses mechanical exhaust ventilation is needed to give satisfactory comfort.

* Chemical pollution seems, even in extremely air tight houses, not to be a problem in houses with normal use of building materials and low ground radiation as in the Trondheim area.

* More knowledge is needed for a complete picture of the users behavior, satisfaction and need for ventilation, and the efficiency and economy of different systems.

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
29 September - 2 October 1986

PAPER 11

INFLUENCE OF THE METEOROLOGICAL CONDITIONS ON THE INHABITANTS' BEHAVIOUR IN DWELLINGS WITH MECHANICAL VENTILATION

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List of Symbols

ϑ_{La}	Exterior air temperature	[^{0}C]
ϑ_{Li}	Indoor air temperature	[^{0}C]
W	Exterior air velocity	[m/s]
t_{open} (w)	Temperature selected window ventilation periods	[%]

1. Introduction

Within the framework of the national research project "Ventilation in housing construction", studies on occupants' window opening behaviour[1] were conducted in a demonstration building in Duisburg (West-Germany) which also formed part of the project. This demonstration building which was raised in 1983 is a row-house composed of 3 blocks. In each block there are four floor levels with two flats each. Fig. 1 shows the plan of a block floor with 2 apartments, each covering a flat floor space of 80 m^2. The storeys have an east/west orientation. All apartments are equipped with a central ventilation system. In the dining room, the parents' bedroom and the children's room, there is a double-sash window, with one side/bottom sash fitting and one casement hung respectively. The sitting room window is a fixed window, the balcony door has side/bottom sash fittings.

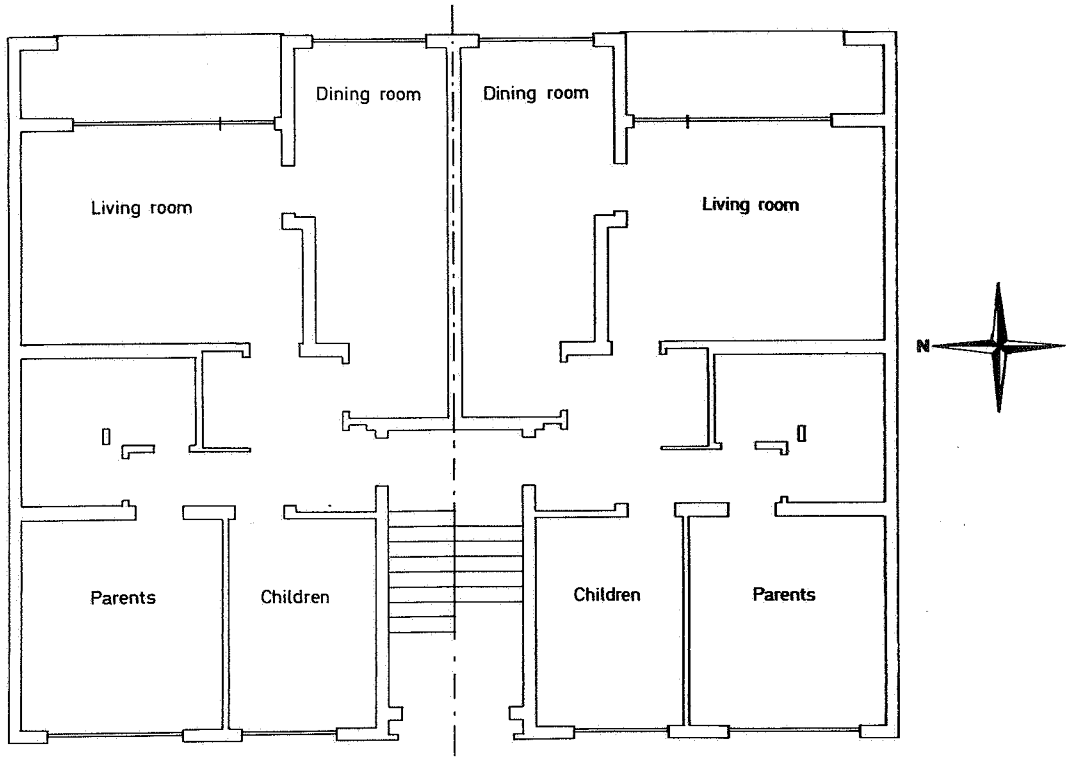

Fig. 1 Ground plan of a block floor with two flats. Ground plan and size of flat are equal for all the 24 apartments included in the survey.

2. Measured Values and Plausibility Testing

In order to allow the continuous recording of varying opening positions, every window sash and door leaf is furnished with contact sensors. Accordingly, eleven window contact sensors were installed in each flat. Every 30 minutes, the data provided by these contacts are recorded by the central data logger. The present analysis is based on data compiled between Jan. 1st - Dec. 31, 1984. No less than 4.6 million values out of the data recorded in this period are related to window opening. Additionally, all relevant weather data, (such as air temperature, wind velocity, global irradiation etc.), were continuously recorded as well as temperatures, humidity, and energy consumptions for room heating and domestic appliances[2,3].

Prior to processing this complex data material, it was considered necessary to have all measured values checked for their plausibility. When checked, some measurement contacts were found to be faulty (both temporarily and throughout the entire measuring period). In a further plausibility test, both opening periods and opening positions of any side/bottom hung sash were checked in detail. Due to design and positioning of the measurement contacts, the side/bottom hung sash window will be registered to be open in the side-hung position by both the side and the bottom contact. If the same window is open in the bottom hung position, however, this is recorded <u>only</u> by the bottom contact. Consequently, faulty recording must be assumed, whenever the opening times recorded (for one and the same sash) by the bottom contact are shorter than those recorded by the side contact. In the final analysis, only those rooms with 100 % reliable measurement contacts were considered, i. e. all of a room's eleven window contacts had to pass both plausibility tests in order to be eligibile for evaluation. The respective plausibility test results are compiled in **Table 1.** While approx. 70 % out of the li-

<u>Table 1</u>: Plausibility test results for window contacts in the rooms under observation
(Measurement period: Jan. 1 - Dec. 31, 1984)

Room		Living room			Dining room			Parents			Children		
Flat	Block	A1	A2	A3	A1	A2	A3	A1	A2	A3	A1	A2	A3
Ground floor	left	X	▽	▽	●	●	●	X	X	▽	▽	●	▽
	right	▽	X	X	●	●	●	●	X	●	● ▽	X	●
1st floor	left	X	X	X	●	●	▽	X	X	X	X	X	X
	right	X	X	X	●	●	●	X	X	X	X	●	X
2nd floor	left	X	▽	X	●	▽	●	● ▽	▽	X	▽	▽	X
	right	●	●	X	●	●	▽	▽	X	X	▽	X	●
3rd floor	left	X	X	X	▽	●	●	X	X	X	X	▽	X
	right	X	▽	▽	●	X	▽	X			X	X	X

▽ measurement contact temporarily faulty (no values measured) [first plausibility test]

● measured values partially unaccounted for (total opening time recorded in bottom-hung position < total opening time recorded in side-hung position) [second plausibility test]

X all window contacts functioning correctly over the whole measurement period [data included in analysis] ving rooms, parents' bedrooms, and childrens' rooms have passed the plausibility tests, there is only one dining room providing correct data. Since this one dining room is not representative for statistical evaluations, it is excluded from the analysis.

3. Frequency and Duration of Open Windows- and Meteorological Conditions during Observation

For the rooms included in the evaluation, the mean monthly opening time is investigated for all rooms as a whole and with respect to the various types of rooms. However, the results presented in this context are not the absolute duration of opening. Rather, the opening time recorded is related to the maximum possible duration of opening (hours per month) and thus normalized. The results are presented in Fig. 2. Here, a distruction is made between side-hung and bottom hung position; analysis covers the entire window (i. e. both window sashs). With a result of approx. 10 % in side-hung positions, this implies that all sashs were opened on average for 6 minutes per hour in side-hung position.

As it may be gathered from Fig. 2, windows are open longest in summer and shortest in winter. While in August the overall opening time for all windows amounts to about 25 % on average - i. e. 15 minutes per hour - it decreases to about 5 % in winter. In the first 6 months of the year, windows are preferably opened in side-hung position, while in the last 6 months of the year the proportion of window being kept open in the bottom-hung position is at about 50 %. This phenomenon may possibly be amounted for by the higher degree of trapped moisture (sweating), which necessitates an increased air change at the beginning of first occupation.

Comparing the results for the different types of rooms with the overall figures, bedrooms are found to be the rooms most usually ventilated. Here, too, at the beginning of occupation the side-hung position is prefered, while at the end of the measuring period the bottom-hung position prevails. Even in extreme winter-weather, bedrooms are ventilated distinctly more frequently than all of the rooms on average. During the entire measuring period the window opening time recorded for bedrooms exceeds the average for all rooms by some 50 %.

Values measured for living rooms are comparable to the average of all rooms. In living room ventilation, the bottom-hung window opening position is predominant. This may be explained by the balcony door providing the only openable unit. It has a side/bottom sash fitting, with the bottom-hunged position obviously being preferred by users.

In childrens' rooms, windows are open least of all rooms. Here, too, in the first 6 months of the year the side-hung position is preferred, while in the last 6 months the bottom-hunged position is more frequent. In terms of ventilation habits, the childrens' rooms are among all rooms those ventilated most regularly. Here, it is only in extreme seasons, that the average overall-opening times distinctly deviate from the mean value of approx. 10 %. As illustrated by Fig. 2, the window opening behaviour strongly

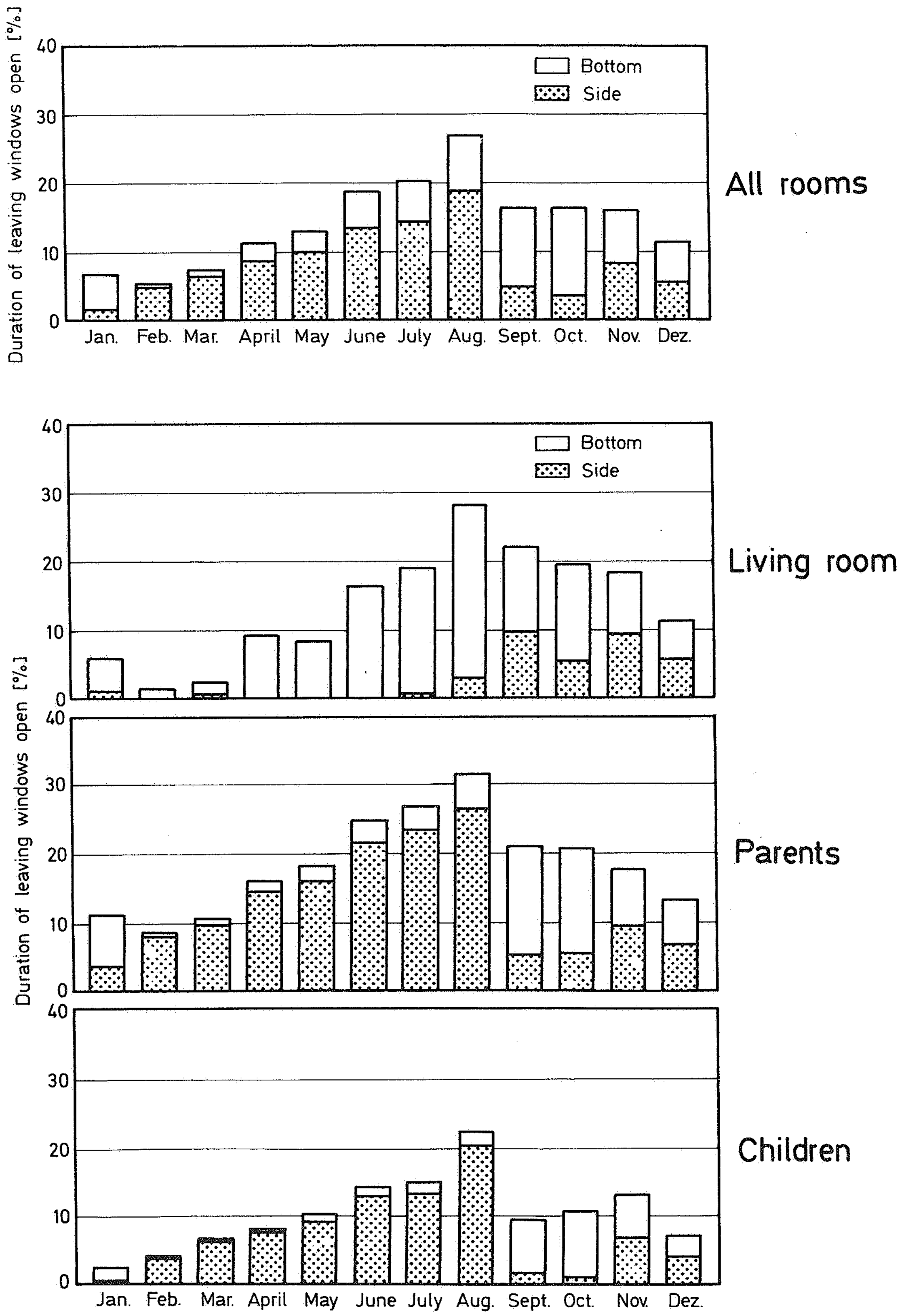

Fig. 2 Mean monthly duration of leaving windows open.
Values for all rooms and for different types of rooms (expressend in percentages).
Analysis covers the entire window, i.e. both window sashs.

correlates with seasonal influences. Due to this correlation, the most important weather parameters were investigated in addition to the users' opening habits.

In Fig. 3 annual mean daily outdoor air temperatures are presented. They range from -2 °C to 28 °C. Until mid-April, relatively low temperatures clearly below the heating line were recorded, and even in June mean daily temperatures were seldom recorded to exceed 15 °C. In autumn, the mild weather with mean daily temperatures around 15 °C lasted until the end of October, before temperatures dropped below the heating line.

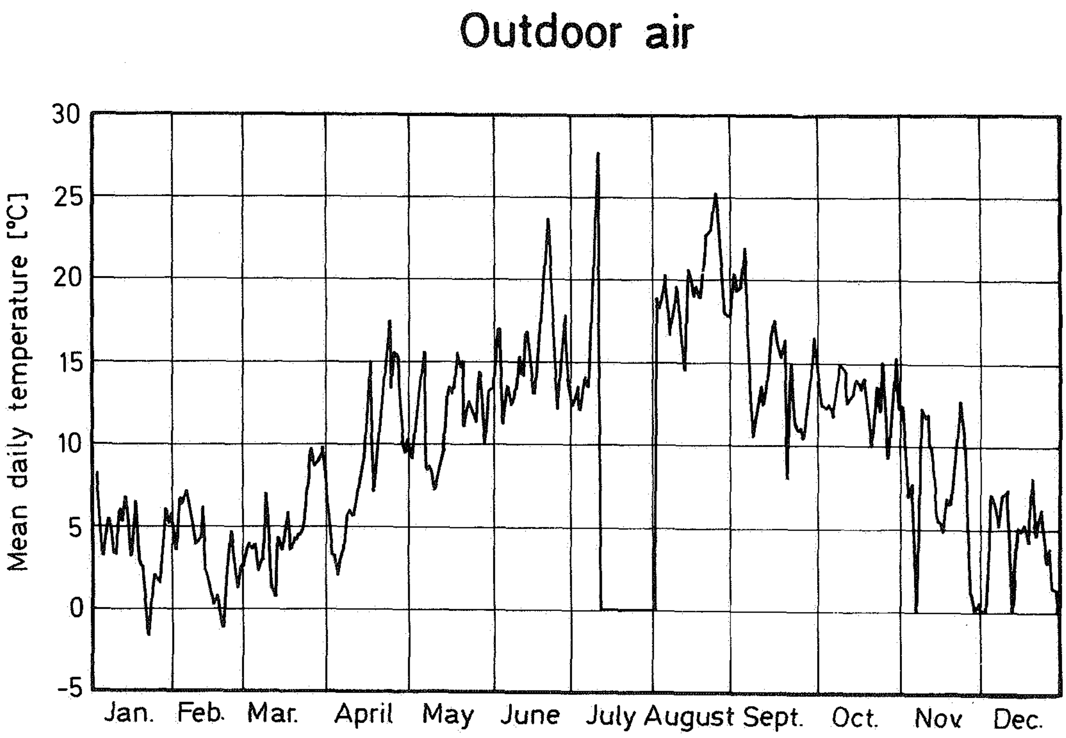

Fig. 3 Mean daily outdoor air temperatures recorded from Jan. 1 - Dec. 31, 1984. (The July gap is due to a blackout in the data recording system.)

The annual curve of the daily totals of global irradiation incident on a horizontal area is plotted in Fig. 4. Ideal conditions (cloudless skies) would produce a bell-shaped curve with its maximum on June 21 (sun at highest point) and its minimum on Dec. 21 (sun at lowest point). Due to cloudcover or overcasting, deviations from the bell-shaped function occur. At the beginning of April, in May, and in September there are pronounced radiation minima to be observed.

In Fig. 5, the annual curve of the mean wind speed is plotted. Maximum and minimum values range between 0 and 7.5 m/s. On average, windvelocities fluctuate around 2 - 4 m/s; in the cold days of January and February, wind speeds were, however, slightly higher than in the other months.

Global irradiance

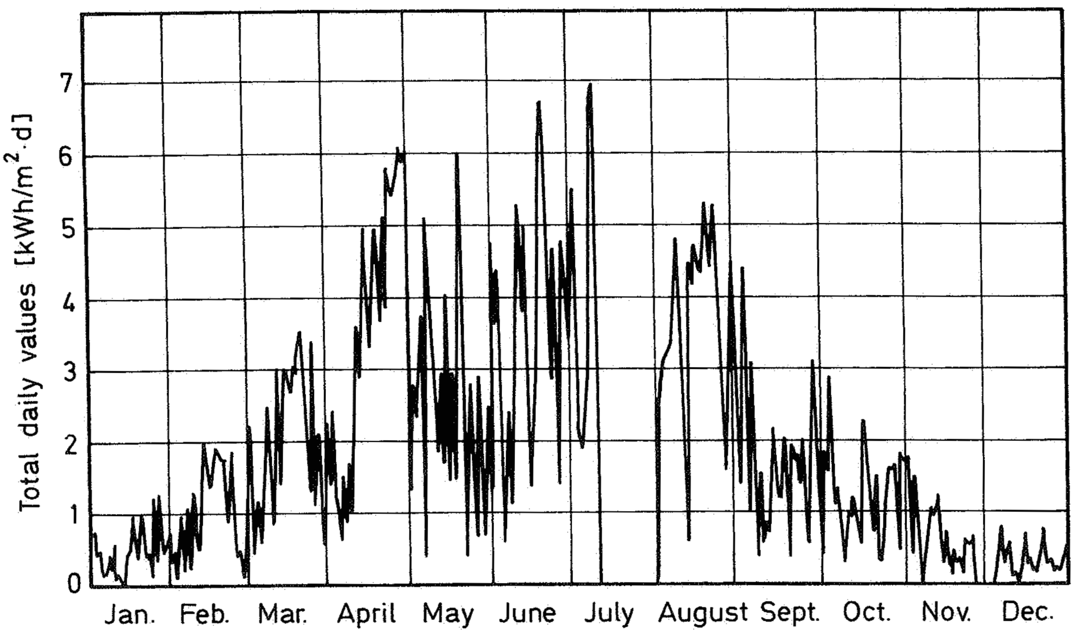

Fig. 4 Total daily values measured for the global irradiance incident on a horizontal surface. (The July gap is due to a blackout in the data recording system.)

Wind velocity

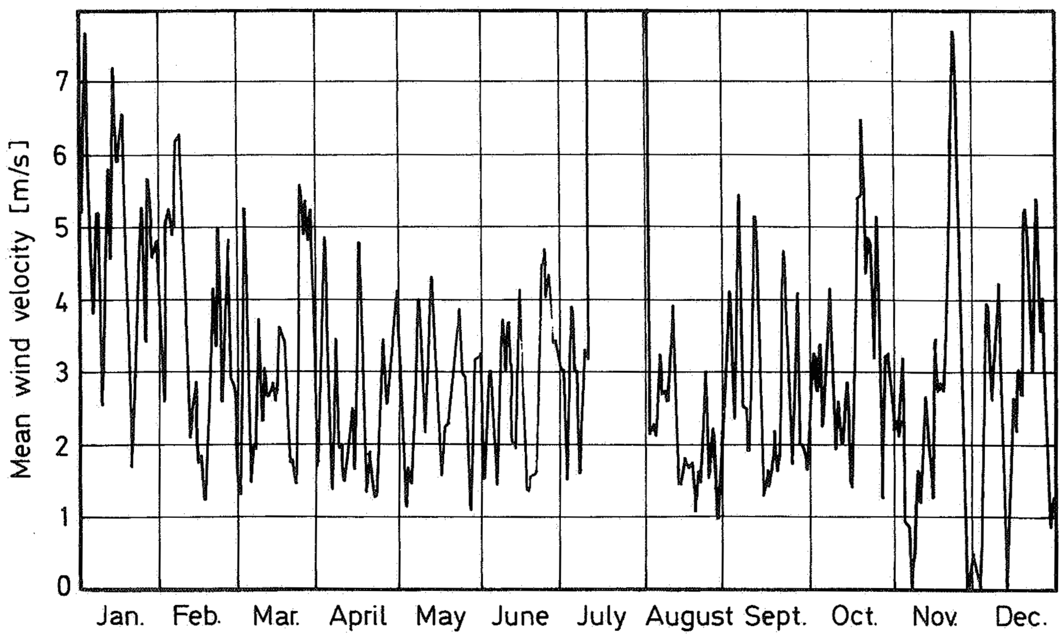

Fig. 5 Mean daily wind velocities measured between Jan. 1 and Dec. 31, 1984. (The July gap is due to a blackout in the data recording system.)

All annual curves show a gap between July 11 and 31, 1984, which is obviously due to a black out in the data recording system. This data gap has however no influence on the determination of the mean monthly values, because July data were used only from days 1 - 10.

4. Variations in Users' Behaviour

In order to demonstrate to what extent users may vary in their window opening habits, one occupant with extremely long ventilation periods and one with extraordinarily short ventilation periods were compared to the average value of all occupants, classified according to the different types of rooms. The deviations are illustrated by mean monthly values in **Fig. 6.** As for the liv-

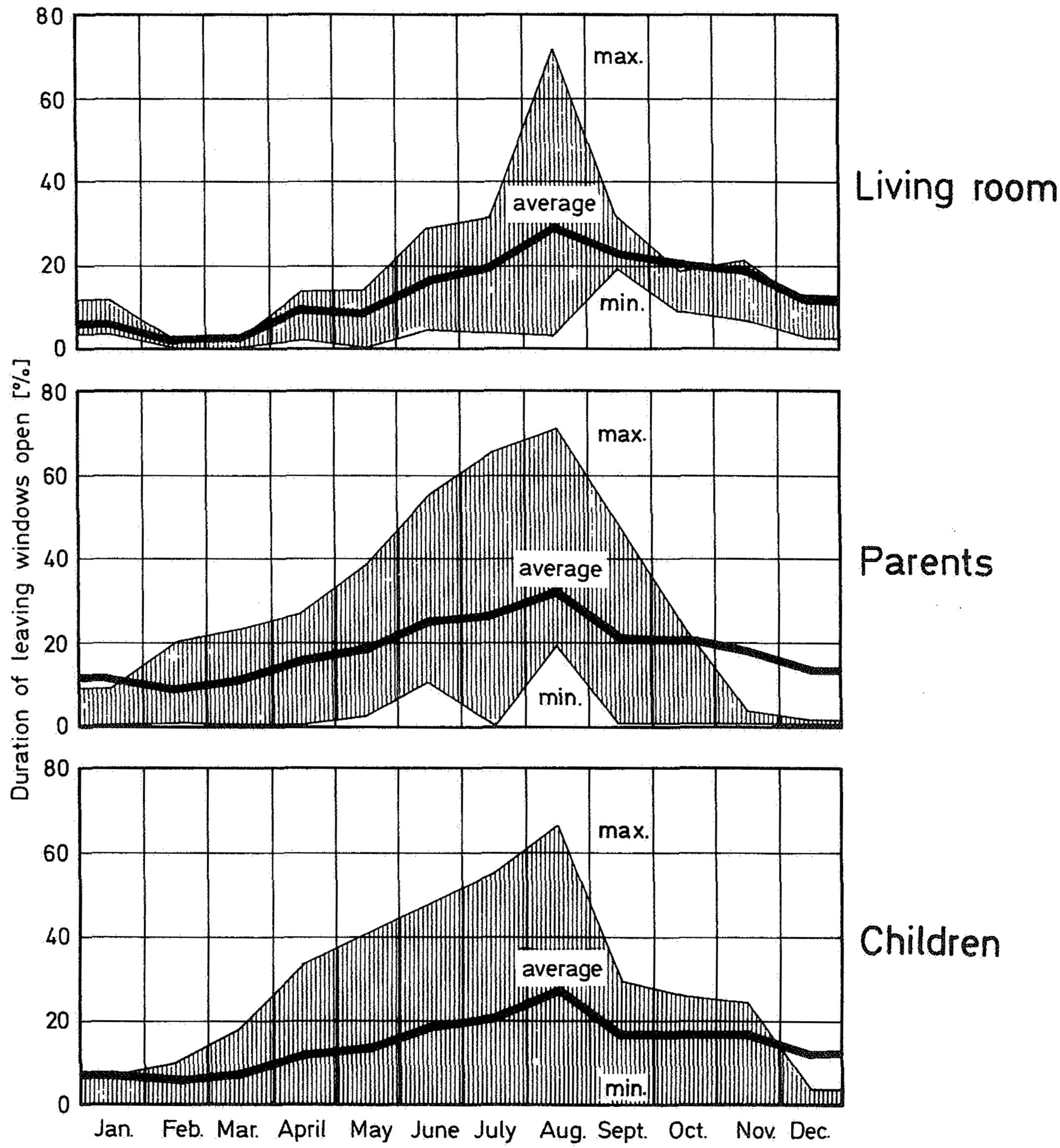

Fig. 6 Variations in occupants' ventilation behaviour in different rooms given as mean monthly duration of leaving windows open (mean monthly overall occupants' values as compared with values measured for a single occupant with untypically short ventilation periods).

ing room, there are hardly any significant deviations from average. They range within a margin of ± 10 %. In bedrooms and childrens' rooms, however, deviations are much more marked, with a variance of up to ± 20 %. If - instead of viewing all of the values - only 90 % are taken into account, discarding the extremely untypical users' values, the margin of deviation is reduced to less than ± 5 %. Accordingly, the elaborated relations describe a representative part of the whole complex under investigation.

5. Users' Behaviour in Correlation with Meteorological Conditions

In the following it is to be investigated whether there is a relevant correlation between duration of window opening and weather parameters. Accordingly, window opening times were correlated with meteorological data. Since these analyses are based on 1.5 million twin values, it is impossible to give an adequate and clear diagrammatic presentation. Instead, the respective mean values are superimposed to the weather parameters. Diagrams are given for overall values (all rooms) and values differentiated between living rooms, parents' rooms, children's rooms.

5.1 Outdoor Air Temperature

Investigating outdoor air temperature influences on users' window opening behaviour, a distinction is made between daytime and nighttime ventilating. Daytime ventilating is further subdivided into days with high and low solar radiation intensities. The diagram in Fig. 7 illustrates outdoor air temperature influences. Evidently, the influence of global irratiation is only a relatively weak one. Daytime values vary in a moderate margin. In general, night time ventilation occurs less frequently than daytime ventilation. The correlation between ventilation habits and outdoor air temperature may be approximately described by 2 straight lines. Below 12 ^{0}C, daytime ventilating increases by some 0.75 % per K temperature difference; above 12 ^{0}C by some 1.1 % per K; in terms of ventilating frequency, this represents an increase of about 50 %. At night temperatures below 12 ^{0}C, ventilation duration is raised by about 0.5 % per K, and at night temperatures exceeding 12 ^{0}C by some 1.1 % per K, which corresponds to a 100 % increase in ventilation frequency. These results allow the mean overall ventilation behaviour to be described as a function of outdoor air temperature. In Table 2, the individual functions for temperatures <12 ^{0}C and ≥ 12 ^{0}C are compiled.

The temperature dependence was partially found to vary from the overall room values according to the type of room. In living rooms, a change in ventilation behaviour is to be stated at temperatures above 12 ^{0}C. This shows good agreement with the average value for all rooms. Here, increases in ventilation frequency amount to some 0.71 % per K for temperatures below 12 ^{0}C and to some 1.4 % per K for temperatures above 12 ^{0}C, which again indicates a doubling of ventilation frequency. In spite of the nighttime ventilation curve deviating from the daytime curve, here, too, two different sectors (below and above 12 ^{0}C) are to be observed. For temperatures below 12 ^{0}C, increases amount to some 0.33 % per K, and for temperatures exceeding 12 ^{0}C to some 0.83 %

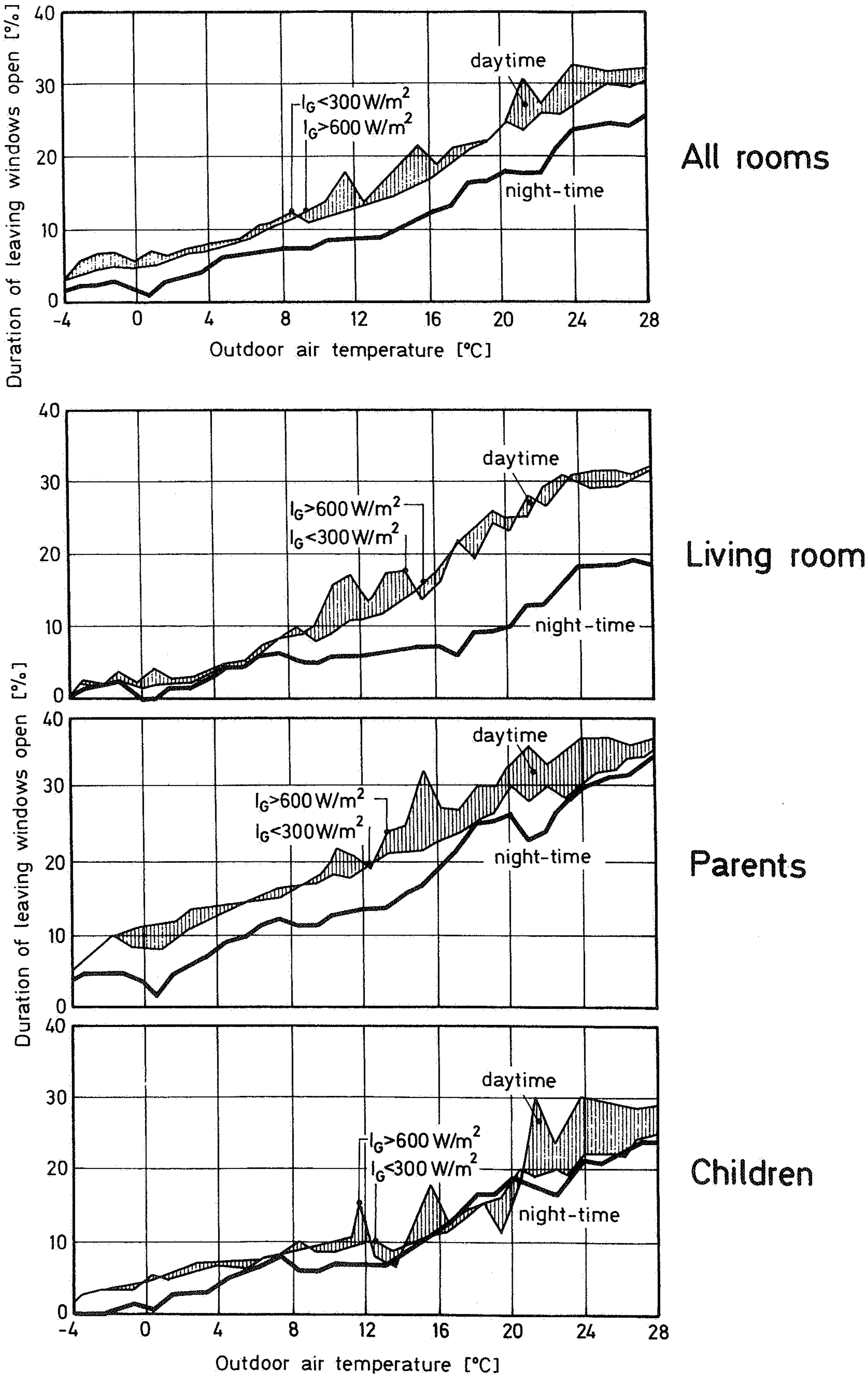

Fig. 7 Overall duration of leaving windows open as a function of daytime and night-time outdoor air temperatures for all rooms and for various types of rooms (expressed as percentages).

per K. In **Table 2**, the average living-room ventilation behaviour is presented as a function of outdoor airtemperatures.

Table 2: Correlation between window ventilation duration and outdoor air temperature (analysis results)

Room		Unit	Outdoor air temperature $\vartheta_{La} < 12^{\circ}C$	$\vartheta_{La} \geq 12^{\circ}C$
Living room	daytime	%	$4 + 0,71\ \vartheta_{La}$	$12.5+1.4(\vartheta_{La} - 12)$
	night-time	%	$2 + 0.33\ \vartheta_{La}$	$6 + 0.83(\vartheta_{La} - 12)$
Parents	daytime	%	$9 + \vartheta_{La}$	$21 + (\vartheta_{La} - 12)$
	night-time	%	$5 + 0,63\vartheta_{La}$	$12.5+1,2(\vartheta_{La} - 12)$
Children	daytime	%	$4 + 0,5\vartheta_{La}$	$10 + (\vartheta_{La} - 12)$
	night-time	%	$2 + 0,5\vartheta_{La}$	$8 + (\vartheta_{La} - 12)$
All rooms	daytime	%	$6 + 0,75\vartheta_{La}$	$15 + 1,1(\vartheta_{La} - 12)$
	night-time	%	$3 + 0,5\vartheta_{La}$	$9 + 1,1(\vartheta_{La} - 12)$

Daytime ventilation behaviour in parents' bedrooms is not characterized by the significant change of habits recorded for temperatures above 12 °C. Rather, it can be approximately described by a straight curve with a gradient of 1 % per K over the entire temu erature scale. The corresponding nighttime curve, however, again records a comparatively distinct change in ventilation behaviour at 12 °C outdoor air temperature. For temperatures below 12 °C the gradients amount to approx. 0.63 % per K, for temperatures above 12 °C to approx. 1.2 % per K, which signifies once more a 100 % increase in ventilation frequency. Hence, the average ventilation behaviour in parents' bedrooms may accordingly be described as a function of outdoor temperatures as compiled in Table **2**.

Though ventilation behaviour in children's rooms is quite similar to the average ventilation habits recorded for all rooms, gradients are slightly lower here. For temperatures below 12 °C, the gradient is about 5 % per K, for temperatures above 12 °C it is about 1 % per K. Night-time values range below daytime values by about 2 % of opening times. This difference is almost independent of temperature influences. The average temperature dependent average ventilation behaviour in children's bedrooms is also outlined in Table 2.

5.2 Horizontal Global Irradiance

Another meteorological parameter to be investigated is the solar irradiance. In **Fig. 8**, durations of leaving windows open are plotted for summer and winter months as a function of the horizontal global irradiance. Although there seems to develop a manifest influence, a distinct dependence on solar irradiance cannot be confirmed, as the influences of outdoor air temperature and global irradiance are superimposed in **Fig. 7**. As clearly shown in **Fig. 6**, the global irradiance varies only in a narrow and hence negligible margin.

5.3 Wind Velocity

It may be supposed that ventilation periods are also affected by wind velocities. In **Fig. 9**, influences of wind velocities are illustrated. The relationship may be expressed almost linearly, while the ventilation behaviour is found to be almost independent of any type of room. Based on an average wind velocity of 3 m/s, wind influences can be introduced as a correction term for temperature-related window ventilation periods by way of:

$$t_{open\ (w)} = \frac{10 - W}{7} \cdot t_{open\ (3\ m/s)} \qquad [\%]$$

5.4 Comparison with Previous Studies

To evaluate the results obtained in this study, they are compared to findings presented in previous investigations. In an extensive series of studies conducted by Austrian researchers[4] and in earlier British Observations[5] values recorded during heating periods in solely window-ventilated flats with various heating systems are presented, resulting in the following functional relations for mean window ventilation duration:

Panzhauser et al.[4]: $t_{open} = 100 \cdot (2.6 \pm 0.6\ K)/(\vartheta_{Li} - \vartheta_{La}) \qquad [\%]$

Brundett[5] : $t_{open} = 100 \cdot 2.6\ /\ (\vartheta_{Li} - \vartheta_{La}) \qquad [\%]$

In **Fig. 10** the above-mentioned relations established for window-ventilated flats are compared with the results obtained in the present study (in accordance with Table 2). It is found that in flats without mechanical ventilation systems windows are open about 4 times as long as in mechanically ventilated flats. Accordingly, energy losses due to "uncontrolled" ventilation are drastically reduced, but not - as frequently assumed - prevented.

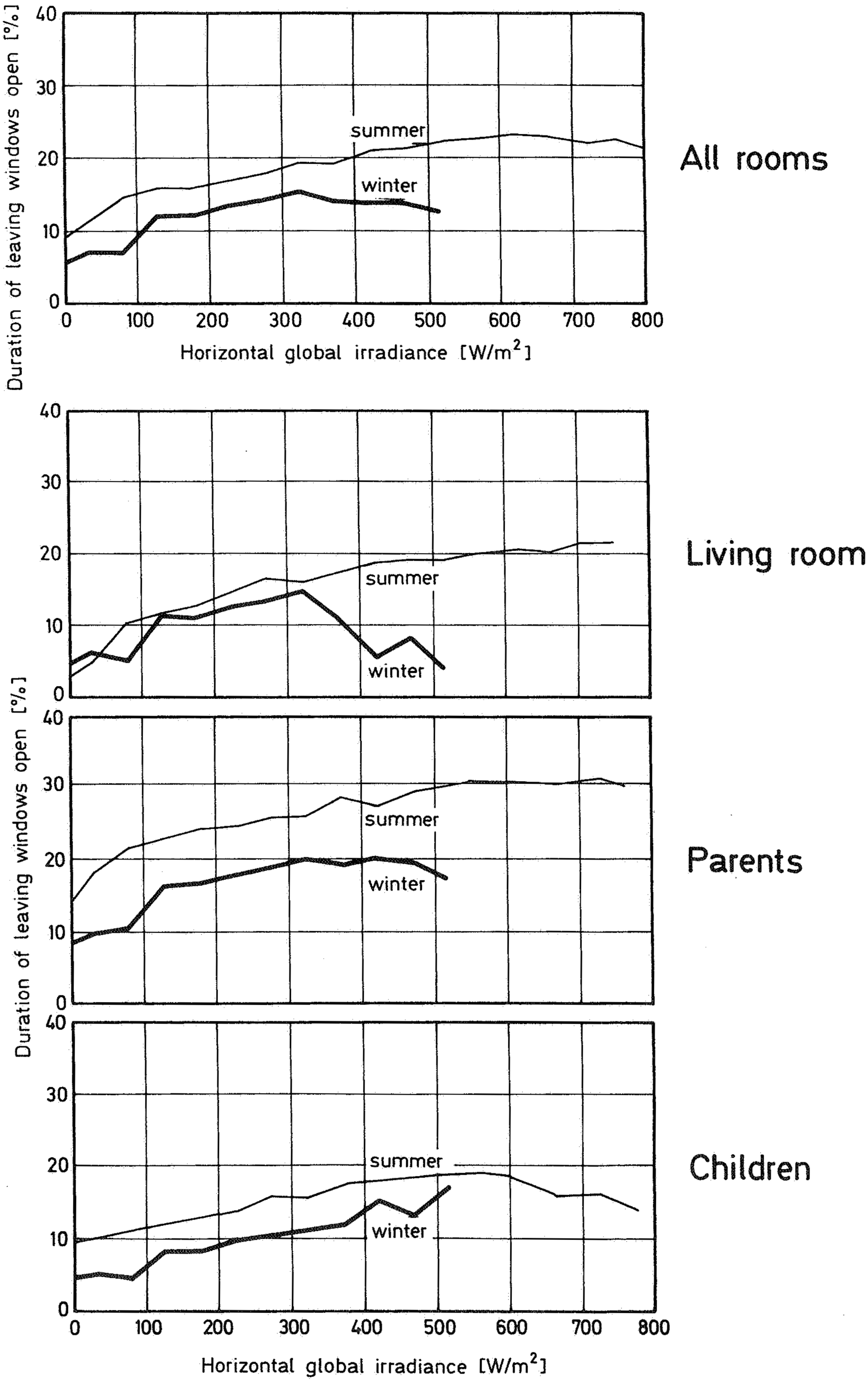

Fig. 8 Overall duration of leaving windows open as a function of the horizontal global irradiance in summer and winter months (for all rooms and for various types of rooms; expressed as percentages).

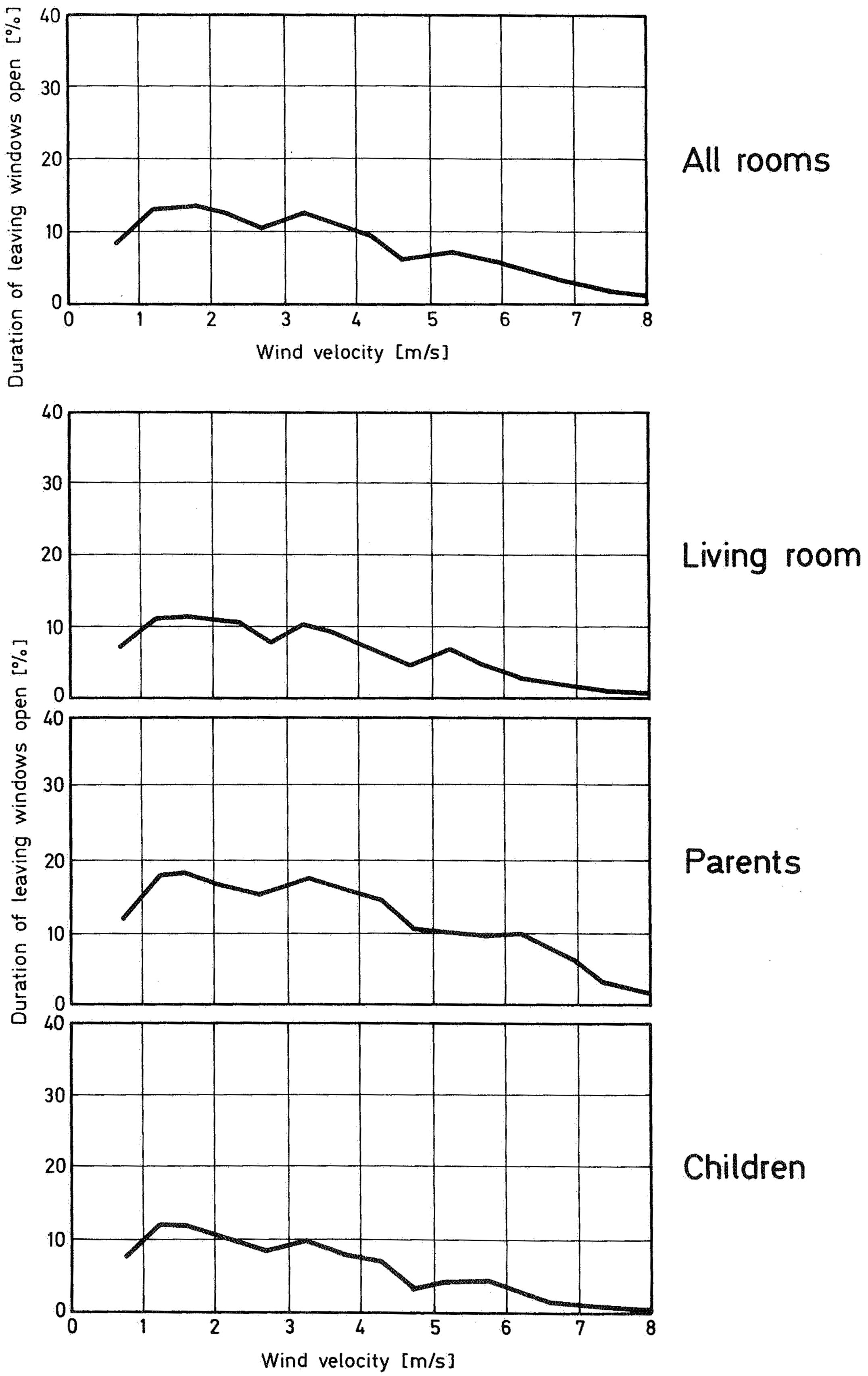

Fig. 9 Overall duration of leaving windows open as a function of wind velocity, given for all rooms and for various types of rooms; expressed as percentages).

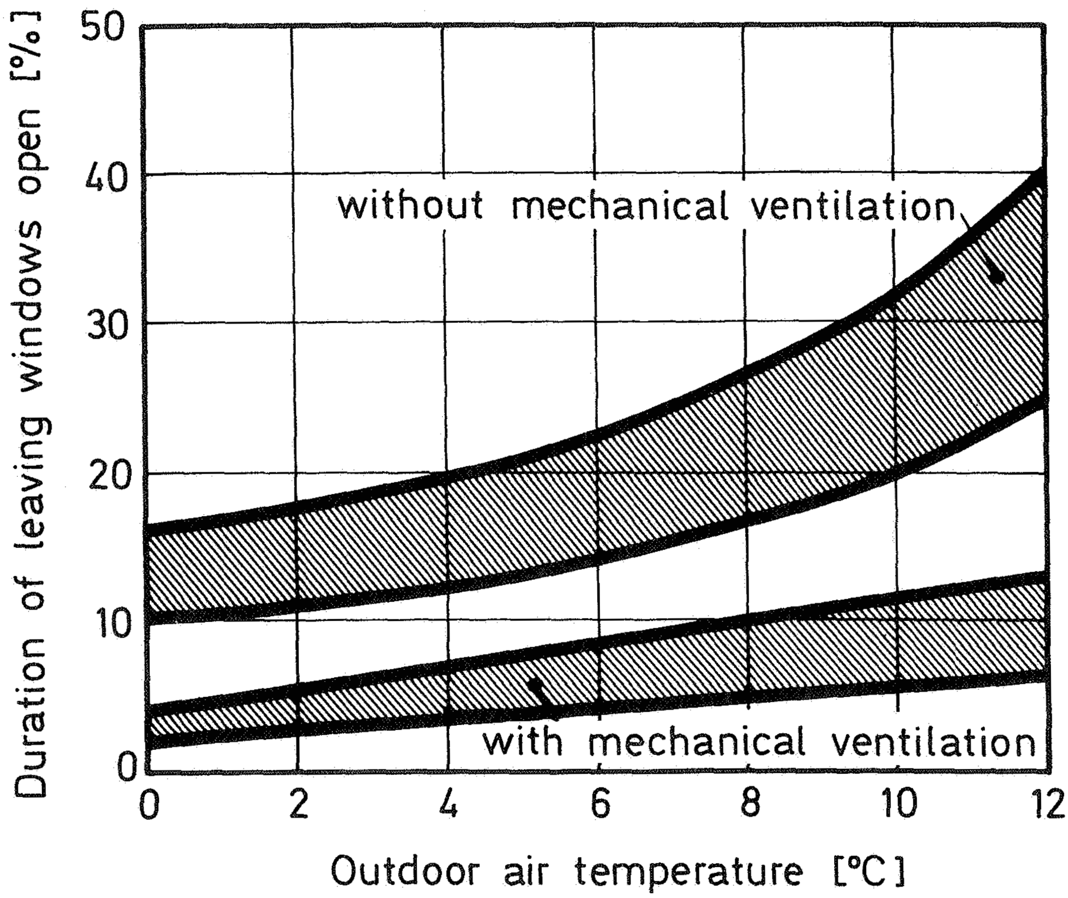

Fig. 10 Comparison of durations of leaving windows open in window-ventilated flats with natural ventilation (acc. to PANZHAUSER[4] and BRUNDRETT[5]) and flats with mechanical ventilation as a function of outdoor air temperature (based on an indoor air temperature of 20°C).

6. Synopsis and Outlook

Within the framework of the national research project "Ventilation in Housing Construction", studies on occupants' ventilation behaviour were conducted in a demonstration building in Duisburg-Neumühl (Federal Rep. of Germany) which also formed part of the project. Analyses were based on values measured from Jan. 1 - Dec. 31, 1984 in 24 flats with identical ground plans, all of which were equipped with mechanical ventilation systems. Data on all opening positions of all openable window sashs and door leaves were continuously recorded, thus providing exact time data for all opening positions to be stored on data carriers. All available data had to pass two plausibility tests, which resulted in 70 % of the main room data considered eligible for analysis.

In evaluating the occupants' behaviour with regard to the different types of rooms, natural ventilation was found to be most frequent in bedrooms, followed, in decreasing frequency, by children's rooms and living rooms. For all rooms, ventilation habits distinctly correlated with outdoor air temperature and wind velocity. A function suited to describe these relations was derived. An alteration in occupants' behaviour recorded during the period of measurements is probably accounted for by the initially higher content of trapped moisture (sweating) at the beginning of first occupation. When finally comparing the present results with studies on users' ventilation behaviour in flats with conventional window ventilation, it was found that in buildings with mechanical ventilation systems window ventilation duration is reduced to a quarter of the corresponding values recorded for buildings with traditional ventilation.

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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PAPER 12

A SOCIOLOGICAL PERSPECTIVE ON TENANT BEHAVIOUR WITH REGARD TO DOMESTIC VENTILATION - AN EXAMPLE AT LAUSANNE, SWITZERLAND

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Synopsis

Airing is a simple and daily action. However, it is difficult to define - within the complex relationship of the architectural and technical data of an apartment building - the thresholds of personal comfort of each tenant and the general attitude towards energy-saving and environment pollution.

This research attempts to offer partial answers as to "how" and "why" inhabitants of a rented apartment building behave as they do in aeration. In order to do this, the authors adopted a two-fold approach: first, by using computerized data recording of outdoor and indoor temperatures per room, the number of hours of sunshine, the surface temperature of radiators and the opening of the windows in each room; second, through interviews with the tenants, sometimes filmed, in order to ascertain their behaviour patterns and underlying motivations in ventilation.

The results of this study point to the importance of the diversity of interactions, taking into account the existing infrastructure and a person's awareness of energy problems, his technical knowledge, his "thermal" background, his needs and expectations of comfort. Combining with all these elements are the different types of motivations for window opening: domestic, ecological or environmental, communicational and social, those concerned with health and hygiene and of a physiopsychological nature.

Among the explanatory reasons for this plurality of motivations and ways of interaction are: the problem of the flow of information and contradictory orders between heating specialists and hygienists, the lack of understanding about the effects on energy an open window can have, the desire to safeguard the individual freedom of action in domestic situations, the tendency to leave necessary measures to the "specialists".

A Sociological Perspective On Tenant Behaviour with regard to Domestic Ventilation - an example at Lausanne, Switzerland.

1. Introductory

Concern about energy-saving has led engineers to design increasingly more personalized and efficient heating processes. However, this technology often comes up against one basic and paradoxically unpredictable variable: the behaviour of occupants. Consequently, we call upon the social sciences to serve as interface and link between the "users" and the external "deciders".

Individual behaviour in relation to heating problems intervenes on two levels:

1) heat emission - in the choice of temperature, i.e. turning radiators on and off or requesting individual preferences to those in charge of the household heating
2) Heat regulation - through air ventilation or airing (kitchen and bathroom ventilators, opening and closing of windows).

This potential for individual action creates a series of presuppositions relatively independent of technical constraints (referred to later), but also leads to engineering, concerns for hygienic housing: if there is insufficient ventilation, the physical deterioration of the building increases on a medium or long term basis.

"If uncontrolled ventilation is acceptable in temperate regions or on our latitude during a temperate period, in cold regions and during winter it accounts for approximately 20% of all energy costs for heating. Since the energy crisis, some measures have been taken: weatherstripping window joints, limiting of window openings, reducing the air flow or the duration of mechanical ventilation. These measures have proved effective for heating conservation but disastrous for housing hygiene, both for the health-giving qualities of air and the dryness of walls." (Iselin and Guillemin, 1984:49, on Occupant Behaviour in Ventilation - A Sociological Perspective).

Ventilation is therefore a complex problem that, among other things, depends largely on its users. There are certain exceptional and rare cases such as mechanical ventilation of certain rooms, particularly W.C.s and bathrooms.

Studying occupants'behaviour in relation to their habitation gives us a thorough understanding of what is happening and the underlying motivations. We should then be able to create suitable technically innovative improvements.

For several years, a certain amount of social science research has been devoted to this particular problem of energy control. Two recent studies deal specifically with ventilation and are worth mentioning here: Vezin's synthesis of various studies that focuses directly or indirectly on the psychosociological dimensions of domestic ventilation (Vezin, Lorimy, 1985); and Dard's study that examines mechanical ventilation, among other aspects of energy consumption. Many other studies approach ventilation as a practice of household energy consumption (cf. especially the studies of E. Monnier, 1985 and IREC-IES on "Energy Cultures" to be published in 1986).

In this context we adopt a double strategy for our research: firstly, the psychosociological and cultural dimensions of the ventilation of a rented urban habitat; secondly, the combination of a qualitative approach (concentrated interviews recorded on video) and a quantitative one (recorded indoor and outdoor temperatures of the housing under study and the recording of window manipulations).

2. Research objectives and description of the survey's "terrain"

Our work is part of the task of Annex VIII ("Occupant behaviour towards ventilation systems") on the conservation of energy in buildings, studied by the member countries (e.g. Switzerland) of the International Energy Agency. Its purpose is to answer the following two questions:

1) How do the occupants of rented flats in apartment buildings react to ventilation?

2) Why do they behave in such ways?

The final objective is to make information available that can motivate housing designers and occupants and make them more aware of ventilation problems within the habitat.

The survey was made in an apartment building of 24 rented flats located in the northern suburb of

Lausanne near two busy roads. Monitored for six years by an acquisition data device with 600 measure points recorded automatically every five minutes, this building has already been the object of much research. The recordings were indeed various, the most important for our survey being the outdoor temperature and the number of hours of sunshine, the indoor temperature, the surface temperature of the radiators, the opening of the windows of each room (15 hooked-up apartments) and the electricity consumption of each household. Moreover, from the start, we used relevant previous information accumulated from studies on the behaviour of the tenants in relation to their building environment and boiler heating system. Our procedure took these various quantitative elements into account and compared them as closely as possible. The survey itself consisted of a series of detailed, focused interviews with the building's tenants about their reactions to ventilation and the different practical and symbolic aspects that correspond to them. Video filming - in order to include an audiovisual document - completed our approach.

Several of the most informative graphs used as references are included in the appendices (can be referred to when measuring is mentioned in the text).

3. Findings: first reflections

Owing to the strong social homogeneity of the building's inhabitants or more exactly to the (quantitative) non-representativeness of the disparities observed in relation to the social norm, we had to give up one of our original objectives: the pinpointing of average behaviour profiles from sociological variables such as age, training or the socio-professional status. Our statistical analyses refer instead to thermal data created by the practice of opening windows. These are linked to variables that are infrastructural (residential location according to floor levels), functional (assignment of functions to the different rooms in the flat), and environmental (geographical position of the apartment).

These analyses have taken into account the climate criteria, especially outdoor temperatures. Thus, within our survey's target period, we singled out the two weeks that recorded the most important disparities: the week of 18th to 24th January 1986, with an average outdoor temperature of 3.2°C, and the week from the 8th to 14th February 1986 with an average outdoor temperature of minus 7°C, i.e., a "warm" week and a "cold" week for the season. The comparison of the indoor temperatures and the number of times windows were opened helped verification of the influence of the climate factor.

4. Observations

The average number of times that windows are opened clearly decreases when the outdoor temperature drops, creating a homogeneous indoor thermal situation.

The radiators in the various rooms of the flats are the object of differentiated manipulations: the bedroom radiator is probably adjusted whatever the outdoor temperatures and tends to be closed at night. The living-room radiator is left open, unlike the kitchen radiator which is closed.

Opening the living-room windows seldom varies when the outdoor temperature drops; on the other hand, tenant behaviour is very different in the bedrooms. Window opening duration is more important here than in the living-room and clearly affected by the outdoor temperature.

We can already draw two intermediate conclusions:
a) A flat's aeration/ventilation in winter is primarily done through the bedroom;
b) Maintaining a constant indoor temperature in the bedroom seems to come more from manipulation of the windows (which decreases when weather gets very cold) rather than from the radiators.

We have identified fluctuations in the opening of windows and in the use of radiators, according to floor levels. Although behaviour patterns and the radiator manipulation are quite similar, the fourth floor (the highest and best insulated at the top) constantly recorded indoor temperatures relatively high (over 25°C in the living-rooms, whatever the outdoor temperature is).

Paradoxically, whatever the outdoor temperature - especially when the weather is fine - the fourth floor tenants open the windows more often than those of the other floors (especially at night). The tenants on the first floor open their windows more during the day when the weather is not too cold. Here we enter head-on into the role of behaviour patterns and, at this stage, into the realm of suppositions.

Are the first floor tenants more often at home? This would explain the constant in the number of times that windows are opened. To put it another way, do the second and third floor tenants go out more during the day? Do all the fourth floor tenants at night have indentical behaviour towards aeration? Or rather, do these ventilation behaviour patterns depend on indoor temperatures? We could believe so since paradoxically it is those who open most often (fourth and first floors) who also benefit from the highest indoor temperatures. Finally, we wonder if each floor level hasn't its own culture of warmth and cold - as if neighbours communicate and share together norms of comfort and behaviour regarding the manipulation of radiators and windows. Two other factors also play an important role thermally: the flat's position in space and its orientation. The occupants who have a living-room facing south (the sunniest) have the highest indoor temperature. Paradoxically, they tend to open their windows more frequently at night.

By deduction and interpretation of the measurements, we could almost point out the biggest "ventilators": those who use ventilation sparingly; those who are "chilly", those who like the cold; those who manipulate the radiators and/or windows, or those who do not.

The interpretation of these quantitative data gives general indications of what is happening in the building concerning the appropriation and use of the rooms. They also suggest differences in behaviour according to floor levels and the orientation of the flats and the rooms.

We are thus able to describe, to observe situations or behaviour patterns generally, but we have no explanation. To explain and analyse we must go into further descriptive detail, focusing on the individual rather than the goup - in order to be better able to generalize again.

5. Qualitative approach of occupant interaction in ventilation

The information gathered from direct contact with our tenants enabled us to progress methodically through each nuance and complexity. It proved quite difficult to study the behaviour patterns of the interviewees and the concrete, specific findings as recorded by the measuring equipment. Nevertheless, it was this generality of daily actions (in domestic ventilation) that we wanted to explore. The work brought to light numerous an interesting dimensions: male-female ventilation responsability, the contrast of people's thermal sensitivities (those who are warm, those who are cold), the social behaviour and the period of socialization, the different national cultures, the reactions to the window-radiator relationship, the technical ignorance and lack of knowledge of energy problems, the personal hypotheses and preferences regarding the installation of heating systems and aeration. All these elements have their importance. As we cannot go into too much detail here we will merely point out two key fields observed with our inhabitants of the target building: the diversity of interactions and motivations in domestic ventilation.

6. The many facets of interaction

Contrary to what one might imagine, the action of airing is of considerable diversity. It depends first on an existing infrastucture, the type and number of windows, the position of the flat within the building, its noise environment, the number of hours of sunshine, the quality of the building's exterior, its heating installations, and many other elements that are "imposed", that the tenant-user has practically no control over.

However, further factors arise in the infrastructural context - factors concerning the tenants' personal taste in relation to the functional specialization of the different rooms of a flat. Thus, interactions in ventilation can differ according to the size of the household, the degree of occupancy of the flat and even in relation to its interior arrangement. Furthermore, it is clear that practices vary according to the type of room: one does not air in the same way a living-room, a kitchen, a bathroom or a bedroom.

Other variables, referring to the user himself, add to the great variety of these factors. Here are some of the points worth brief metion.

First, the level of awareness of energy problems. Is the individual interested in energy and especially, in what way does he feel concerned? Is he able to place ventilation within the energy context, does he see the mutual relationship and effects? These questions, among others, can locate the threshold awareness and responsibility with regard to energy consumption.

The following point, closely connected to the preceding one, concerns technical knowledge on the domestic use of energy. Does the user know the official rules recommended in ventilation? Does he adopt rational measures in his behaviour towards ventilation, particularly the window-radiator relationship and the duration of opening? Does he look for and is he capable of understanding the information offerted on energy and its domestic management?

Moreover, it seems to us important to report the role of particular behaviour and habits that have an effect on ventilation: smoking or living with smokers, cooking habits (Spanish cooking, frying), steam from the kitchen or the bathroom. These reasons create a need for air renewal and can have important thermal consequences. The same with habits: the occupant's "thermal history" must be considered through the succession of different apartments rented and their thermal functions, and through these people's work environments. As we observed in our apartment building example, heating and aeration demands are different for different people - a car mechanic exposed to draughts or someone working in an overheated laundry.

We must also mention people's different needs and expectations of comfort. Everyone or at least every household have their own notions of comfort. The quest for comfort and well-being is closely connected to everything about heating, its regulation and ventilation. There are those who like dry heat, those who prefer the cold, those who seek out draughts, or on the contrary, avoid them. There are people who appreciate a uniform temperature level in every room and others who adopt a thermal strategy specifically for each room of the flat. This search for comfort also includes using shutters or blinds and their indirect thermal effects, the bathroom and the kitchen; all behaviour/interactions orientated by the concern for comfort directly influence energy consumption through the heating-aeration relationship, or more precisely, the window-radiator dialectic.

Furthermore, another element deserves to be considered and linked with individual behaviour: how occupants open the windows. We are impressed by the number of ways there are. There is diversitiy first in the angle of opening: certain people open a window completely, others hardly leave it ajar, still others use only one side. Some people have their own ways of blocking the opening. The angle variable is naturally associated with the opening time. Three extreme cases are roughly presented: 1) large angle of opening during a short time, 2) limited angle of opening over long periods (3-36 hours), 3) limited angle of opening for short periods (5-20 minutes).

Furniture arrangement also often determines the angle of opening and particularly when there are indoor plants near windows. Other sources of opening determiners are tables, chairs, pedestal tables, bed position and even knick-knacks placed on window sills.

Choosing which window to open affords even more diversity: some households never open certain windows, other often. These differences are often explainable by reasons of domestic convenience and household maintenance: such and such an open window would get in the way, another is more accessible, still another, if it were open, could damage the furniture... or even a clock, as we ourselves have observed.

Such diversity of behaviour has multiple origins, shaped by the individual: his value system and awareness of energy problems, technical knowledge, concept of comfort, habits, idiosyncrasies, housing history and professional thermal background, domestic environment and activities, personal appropriation of interior spaces and interpersonal relations with neighbours.

7. Reasons for opening windows

We are not the first to point out the multiplicity of reasons that in a general way can lead to opening windows. There has already been mention of the variety of functions that windows can fill. However, we find it interesting to re-examine these two key elements of ventilation with the residents of the building studied, in relation to their sociocultural specificities and their location in the building.

Bearing in mind that each flat has a balcony (or for first floor tenants, direct access to the lawn surrounding the building), the various reasons for opening a window or window-door of the balcony fall into five main categories. Each of them includes a different number of motivations whose importance is not necessarily meaningful or revealing for the individual except perhaps for the quantitative loss of energy. It was not intended to take into account "emotional" or psychosocological factors.

For each of the five following types, we have again used the (nonexhaustive) list of the modifications.

1. Domestic motivations

The activities that involve the management and maintenance of the inhabited space - the satisfaction of needs called "elementary" - are the basic motivations given for airing. In fact, housekeeping, temperature regulation, the drive for optional comfort, meal preparation or the consumption of hot water all have effects on ventilation behaviour.

The persons questioned about their motivations for window opening gave the following reasons: steam and cooking smells, to hang out the wash, dry the freshly washed kitchen floor, air out after sweeping, clean and shake dusting cloths, to sweep the balcony, eat on the balcony, eliminate odours from entertaining, to hang out the floor cloth on the window sill.

It is obvious that "eating on the balcony" concerns only summertime or between-seasons. There could therefore be temporal overlapping and our intention is to give an overall view.

2. "Ecological" or environmental motivations

In our first chapter, we briefly made mention of the window's role as an extension of the inhabited space, as a true link with the surrounding environment, between public and private life. The use of the window also appears as a link with nature, as an ecological contact or relay, especially in our case study of tenants. Of course having a balcony no doubt contributes to reinforcing and making easier the natural liking for contact with the outdoors. Nevertheless, we are quite suprised to find this motivation type with such intensity and as such a constant.

The list of motives which were referred to are as follows: to check what the weather is like, enjoy the view, the greenery, look at the mountains, the trees, grow potted herbs and flowers, sunbath, feel the fresh air, look at the snow, feed the (winter) birds.

Here again, some of these motivations concern only summer or the fair-weather days of the other seasons.

3. The communicative and social motivations

The window is important for sociability even if this function is not recognized or referred to by everybody. In fact, certain people affirm that the window is useful for communication, even if briefly; others admit using it as a social control tool for the apartment building, or as an aid in watching over children.

The following reasons have been mentioned: to communicate, to say hello or talk to the neighbours, to talk with passers-by, to watch and check on the children - their comings an goings - when they are on a visit, leaving for school (girls, especially), coming home late.

Certain of these motivations are less frequent than others (such as talking from the window). Some are important, even part of the daily routine.

4. Motivations linked to health and hygiene

The tenants of our building all know to a certain degree that airing is indispensable to an organism's health and, for the most part, necessary for housing hygiene. Moreover, almost everyone questioned mentioned the need to freshen indoor air. A whole series of habits goes hand in hand with this explanation of hygiene. It is sometimes difficult to distinguish between a legitimate practice for health's sake or for comfort's sake. We can use the example of opening bedroom windows during the night: the majority of those who state explicitly that they "cannot sleep with the window closed" justify the habit to sleep cooler (or at a lower temperature from elsewhere in the flat) "because it is pleasant" rather than "because it is healthier"; a few tenants stated both reasons together.

The motivations that make up this type include: making the flat healthier, avoiding dampness and mildew, opening for sleeping, needing fresh air, going to the balcony to smoke (in order to avoid disturbing others).

5. Physiopsychological motivations

Sometimes the interviewees had trouble explaining and justifying the need to open a window. This behaviour appears instinctive, compulsive and hard to clarify. It is often expressed as a "need" or desire.

Among the motivations of this type: the need to just "go and see," the need to look outside, the desire to daydream at the window, the need to breathe in fresh air, to open when doing the dishes.

As we see from this brief description of motivations and summarized typology, the act of opening a window has multiple origins. Each has an importance within the residential microcosm of the Lausanne building's tenants. We do not attempt to organize them into a hierarchy or give greater importance or place to one over another.

Furthermore, if the interviews did help to describe and clarify the motives that triggered the opening of windows, they also pointed to reasons that accounted for closing them. For the most part, these were due to the surrounding environment, seasonal weather conditions and a number of cultural habits: various noises (cars, children playing in the yard, rain on the blinds); cold, or hot weather (sic); dust from polluted outdoor air from the immediate environment (re-sic); security reasons; keeping out cats.

8. Confusing communication

Our intention with regard to the users of heating and ventilation devices has never been to find fault with their lack of coherence. That would mean denying individual freedom and the irreducible sphere of individual needs and choices of expression. It would also imply that there is a "right way of doing things" - a behaviour pattern in ventilation that emerges as so rational that it is imperative in itself. This rational model should even in the last instance integrate the potential of individual freedom of action. There is no need to emphasize an absolute reference of this type: today we must bring together the plurality of viewpoints on domestic air regulation and its consequences. It is indeed clear that this situation has strong effects on the users'behaviour and state of mind.

Those in charge of applying rules and regulations often make distinct but contradictory speeches through the media - the town administrators, real estate promotors, the public services, the construction, scientific and heating milieux, the architects.

Here is an example: We all know the injunction "opening seldom but widely is better than opening a little and a long time." This idea springs from a desire for minimum energy loss and a probably more effective air change (it would be necessary to actually see the context of such a measure). However, there is another viewpoint partially opposed to this widespread and official diktat: the analysis made by Iselin and Guillemin (1984), experts in applied research in housing hygiene. Roughly speaking, they say that however windows are open, they do not provide a sufficiently effective air change; either for eliminating the excess steam accumulated in the construction material and which provokes a faster deterioration; or for getting rid of all kinds of pollutants inherent or introduced into the domestic environment. Therefore, according to this last viewpoint, the widely accepted practice can increase costs owing to the premature aging of an apartment building.

Another example: the gap between the individual user's sense of responsibility and industry's tendancy to waste, e.g., propriators buying combustibles who have little interest at stake in energy-saving. The remaining question: what is the importance of energy in relation to a person's manner of opening windows within the material framework of an apartment building - an apartment building within the context of a specific region or country. Although our case study at Lausanne used a specific boiler-heater during a normal winter, the effects of window opening on the indoor temperature were minimal: even the most conscientious tenants lived with rather high temperatures. The energy consequences of self-discipline are therefore hard to comprehend by the individuals concerned and involve a large reality of abstraction. All these elements came up during the interviews - directly or indirectly, explicitly or implicitly. The result: feelings of powerlessness, inadequacy; cynicism, insincerity; the absurd, a lack of confidence or interest, or a feeling of irresponsibility. Almost all persons interviewed were honest about their lack of knowledge and curiosity for information, their reliance on experts when problems arise; with a vague feeling of the somewhat magic idea of being able eventually to intervene in the process, in order to "pay for what we actually consume."

The technique is not their problem. They make do with what they have. Some are sure of themselves, others doubtful, still others wonder what they must do, none manifest any absolute coherence for a climate that doesn't allow for it. Everyone, however, does have his own coherence, to a certain extent. Over and above all material, technical or moral factors or rather, by integrating them in a personal way, each user expresses through his own manner and way of doing things, a certain domestic sovereignty, a potential for individual manoevring within an overal system hardly favorable for it.

We can note at best a reinterpretation of the relationships between the technical devices; most often an absence of relationship beyond the one generally perceived, or rather, based on "doing," between the window and radiator manipulation. The overal relationship with the energy problems is, for the most part, an abstraction. Through the estrangement of the meaning of things (absence of evident cause and effect, contradictions in the facts and discussions about "being able" and "knowing how"), the absence of significant perceptions in user-behaviour variations, create a vicious circle leading to more and more personal detachment. It is interesting to see the contrast here with the hypersensitivity of the exogenous and artificial temperature variations (modification of the boiler-heater's regulation curve).

Consequently, all communication with the user in energy matters should essentially take into account (and somewhat paradoxically) the following elements:

- technology and science still take more responsibility than the users are ready to assume (at least for now);
- the diversity of motivations and ways of doing things, which make up the sphere of individual domestic freedom, are respected as much as possible, even esteemed (the "symbolic" purification combines with the "rational" purification of the air);
- the message is compatible with (1) the general functioning and regulation of the building heating system (taking into account thermophile pressure groups within the building); (2) as much as possible, energy, construction, town and country planning/national and regional development policies.

More than a guilt-provoking message or one trying to build up personal involvement, the graphs analyses, and especially the interviews provide a means of communication with the user which aims at being a better integral part of the overall reality of energy.

9. Short provisory assessment

There is no "big" window opener, so to speak, in the entire apartment building. The tenants seem to be happy to open slightly, once or twice per day or less, but rarely "wide open." We have seen that this way of interaction hardly affects the indoor temperature insofar as the loss of heat during openings was largely and rapidly compensated for by the supply of heating, influenced by the outdoor temperature. In the end, the combination of window-radiator manipulation turns out to be an important indication of user behaviour; not so much step by step as, generally speaking, a strategy of indoor climate regulation or negotiation of various relationships with the outdoors worked out by the windows and the distribution of activities within the domestic time-space.

It is difficult to compare things that have no common basis for comparison. Nevertheless we will briefly summarize what seems to us to be the essence of our research:

- the concrete bringing into perspective of a qualitative survey with multiple, automatic measures with a view to getting a realistic and finely tuned picture of the behaviour and representations of users in domestic ventilation
- a somewhat strict or at least plausible methodology for raising verifiable issues
- partial "finds" on the diversity of interaction and their corresponding points of view
- correlations between significant traits of domestic ventilation and the users' environment, age, occupation, location in the building, state of health, education and native culture
- the bringing to light of a widespread technical ignorance and a feeling of non-responsibility with regard to people who have knowledge and know-how (the specialists)
- the highly confused and incomplete nature of relevant information from the mass media
- the relatively unconscious aspect of the activities of ventilation, sometimes - concerning theorizing - the potential for a wide gap between theories and practices
- the weak general effect of the strategies of window opening on the indoor climate as experienced in the Lausanne building
- the "energy-greedy" existance of a real pressure group of particularly thermophile tenants; through their demands on the landlord's agents, they force the entire building to live with excessive heat. At the same time they nullify the potential for individual strategy in domestic ventilation.

Need it be said that each point has some common basis and is interrelated? Each detail from this research must therefore be seen within the overall context.

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A N N E X

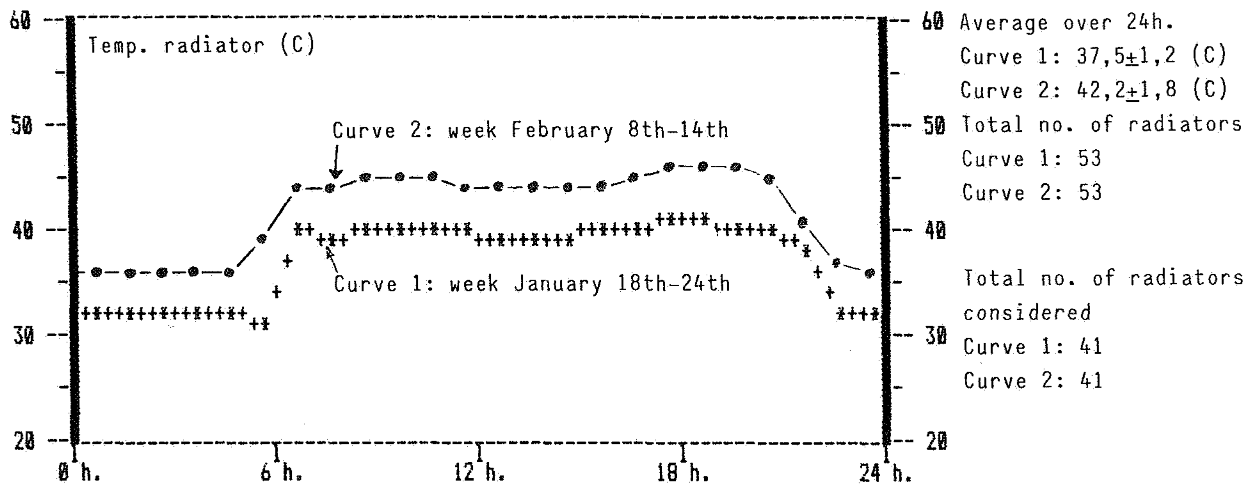

Fig. 1: Daily profile (hourly rate) of radiator surface temperatures over the "cold" week (Feb. 8th-14th) and "warm" week (Jan. 18th-24th) for all the rooms of the building

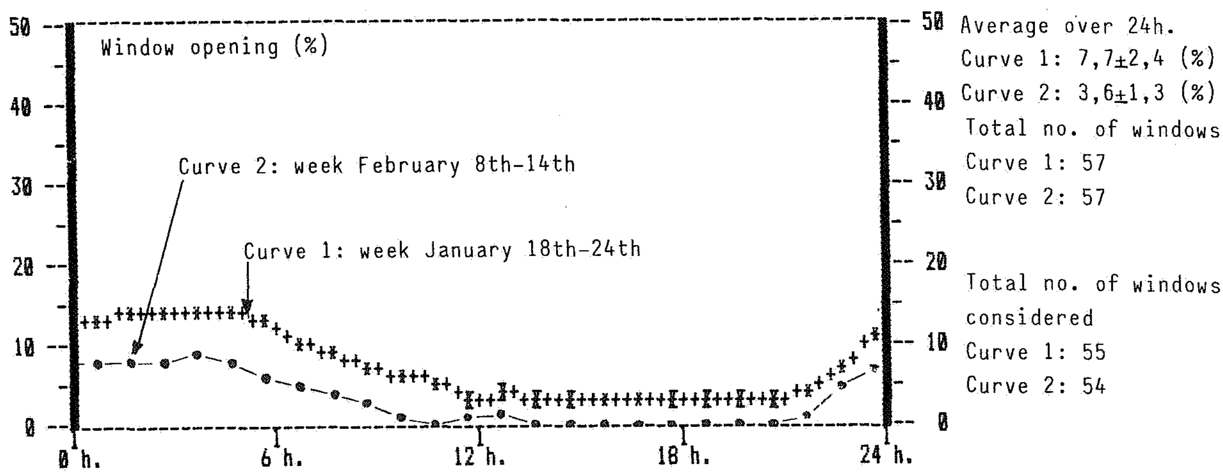

Fig. 2: Daily profile (hourly rate) of window openings over the "cold" and the "warm" weeks for all the rooms of the building

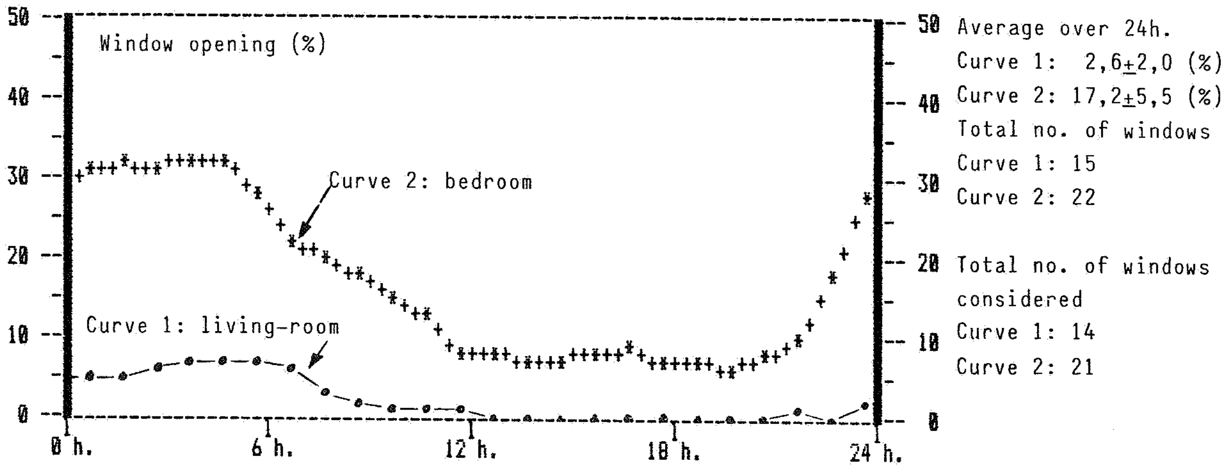

Fig. 3: Daily profile (hourly rate) of window openings over the warmest week for the living-rooms and bedrooms only

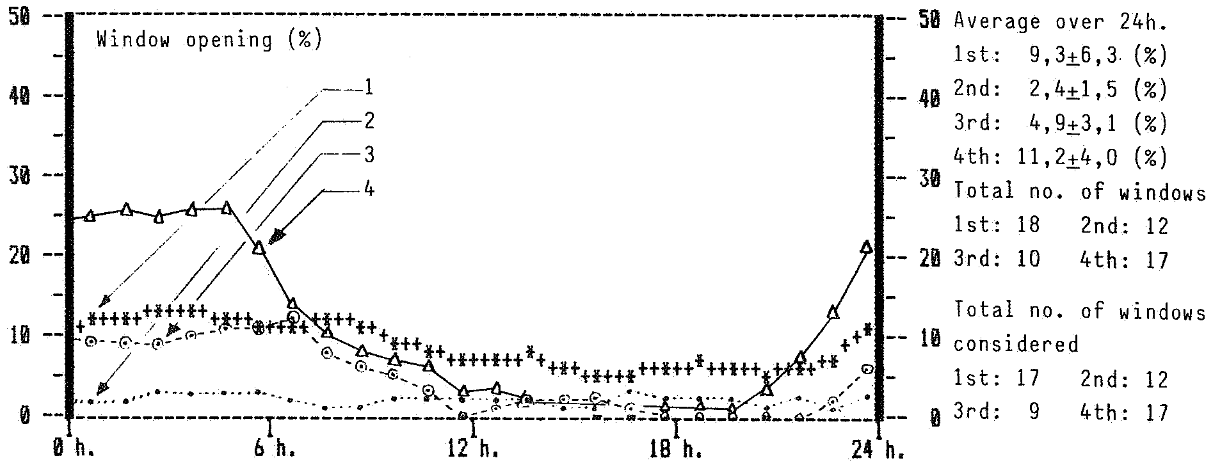

Fig. 4: Daily profile (hourly rate) of window openings over the warmest week for all the rooms of a floor only

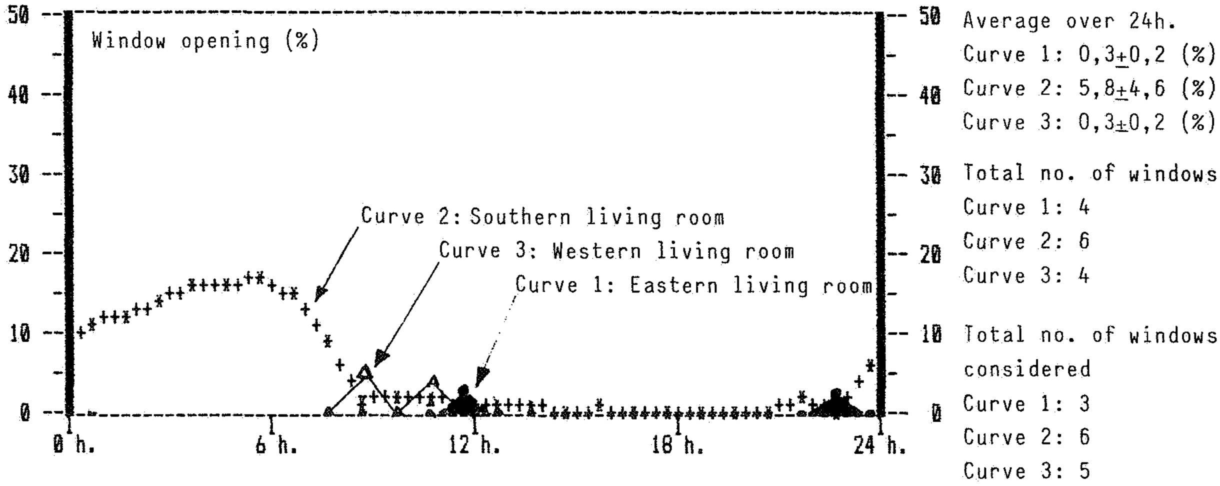

Fig. 5: Daily profile (hourly rate) of window openings over the warmest week for the living-rooms only, according to their orientation

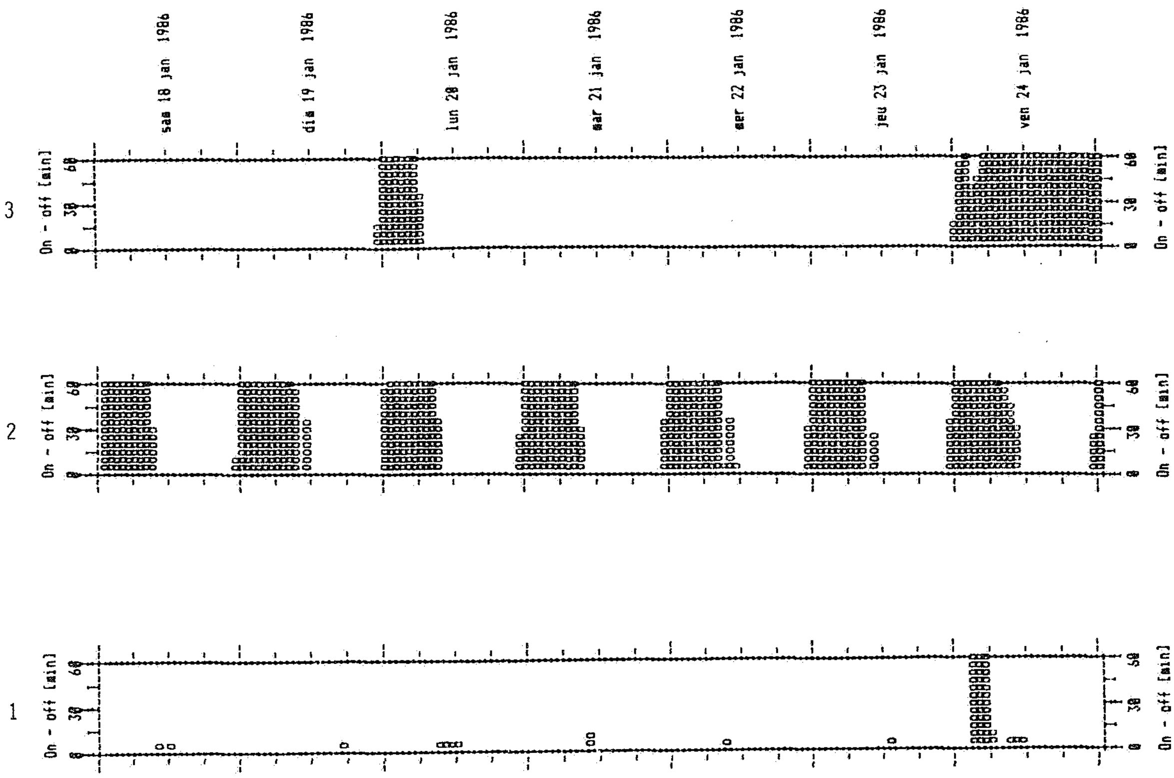

Fig. 6: Three single user-behaviours in bedroom window openings: comparison for the same week with a thrifty opener (1), a "generous" opener (2) and an anarchical opener (3). Each small circle represents a five-minute opening.

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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PAPER 13

VENTILATION REQUIREMENTS FOR MOISTURE CONTROL IN DIFFERENT CLIMATES.

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1 VENTILATION AS A MEASURE FOR MOISTURE CONTROL IN DWELLINGS

One of the most important reasons for ventilation of dwellings is moisture control.

The ventilation need is mainly based on comfort and durability aspects. The ventilation behaviour of the inhabitants depends on both air temperatures, inside and outside, and indoor moisture (and odour) conditions.

As outdoor conditions are very different in various climatic zones, the ventilation strategies differ between different countries during different parts of the year.

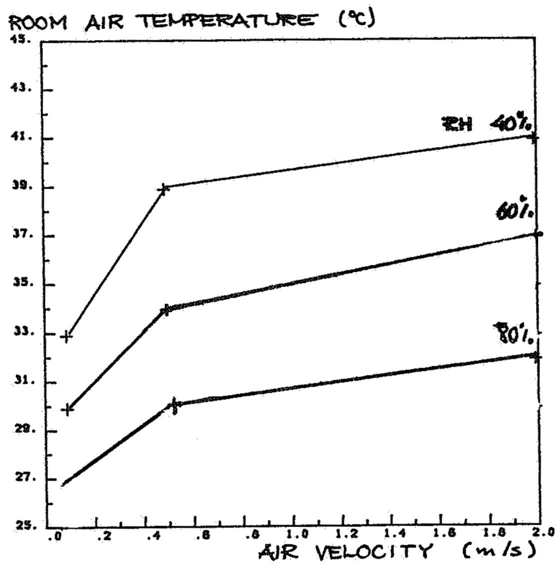
Many of the design data are fairly well known while others, for example criteria for mould growth, are not. A parameter which differs a lot between various countries and cultures is the amount of moisture generation in the house, due to cooking, cleaning etc.

1.1 Comfort aspects

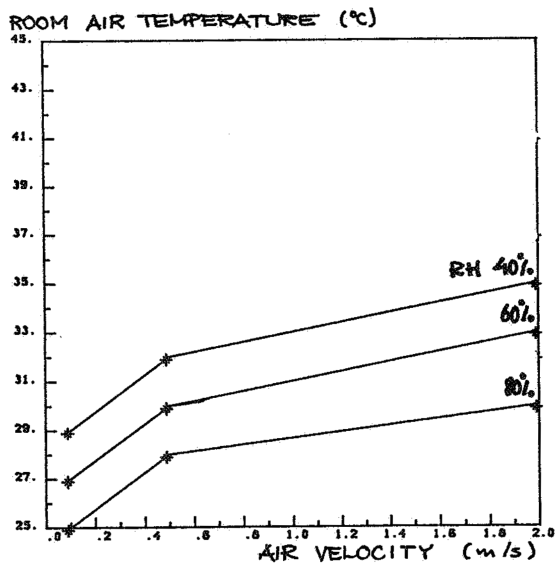
Indoor air temperature, air velocity and relative humidity, as well as radiative indoor temperatures, are important parameters for people's feeling of comfort in buildings.

In the high temperature range Markus and Morris (1980), for example, give comprehensive comfort charts for these parameters as well as the activity level and clothing of people.

Adamson (1986) gives a condensed table based on the work mentioned above. Figure 1.1a and 1.1 b are produced from this table.



a



b

Figure 1.1 Maximum room air temperature, at which 70% (a) or 80% (b) are satisfied, for sitting people (1.0 met) with light clothing (0.6 clo) as a function of air velocity for different relative humidities.

From the results it can be seen that high indoor temperatures are more endurable if the relative humidity is low and/or the air is in motion. This is of course due to the metabolic heat balance of the human body. Lower relative humidities increase the rate of evaporative heat loss from the surface of the body in the same way as high convective flows.

In the low temperature range the risk of feeling cold is of course the most important overall design criterion. Figure 1.1c is based on Fanger (1973) but plotted in a somewhat different way to be comparable to the figures 1.1a and b.

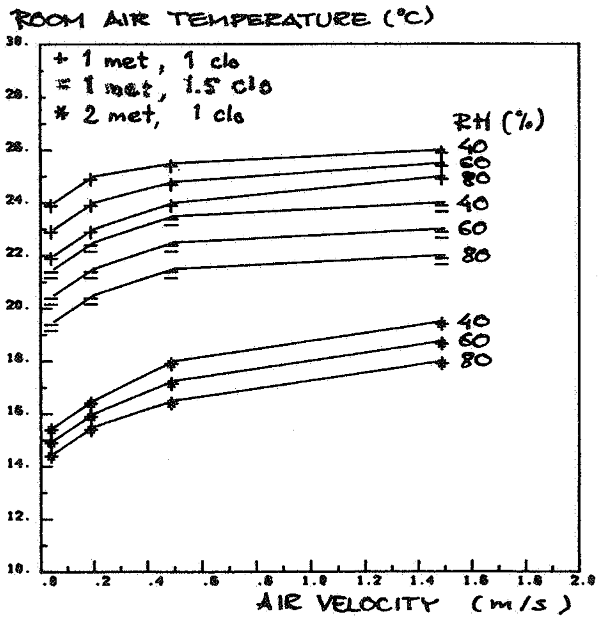


Figure 1.1c Optimum air temperature as a function of air velocity for different relative humidities.

It can easily be seen from the figures that both the metabolic rate (1 met = sitting people, 2 met = medium activity, for example domestic work) and clothing (1 clo = medium clothing, 1.5 clo = warm clothing) influences the comfort for different air temperatures, air velocities and relative humidities.

At low activity levels draught from windows etc must be compensated by higher indoor air temperature. Low indoor air temperatures are more endurable if the relative humidity is high.

For sitting people with medium clothing in a calm room, an indoor temperature of around 22-23^{o}C seems to be optimum, while for domestic work with medium clothing the optimum temperature seems to be quite low, around 15^{o}C. Warm clothing, sweater etc, can create acceptable comfort for sitting people at around 20^{o}C provided that no draught occurs.

Keeping all other parameters than relative humidity constant, it can be seen that comfort is not very much influenced by the relative humidity level. The comfort "gap" corresponds in most cases to approximately 2^{o}C, meaning that the same comfort can be created at a lower temperature with high relative humidity or at a higher temperature with low relative humidity.

1.2 Durability aspects

Two main durability aspects of indoor moisture conditions will be pointed out here and analysed further on in the paper- risks for condensation of moist air and mould growth.

Condensation is the phenomenon created when water in vapour phase is transferred into liquid phase. Generally, this occurs on a cold surface with a surface temperature lower than or equal to the dew point temperature (corresponding to RH=100%).

Mould growth on a surface is possible if there exists:

- an organic material to grow on (substratum)
- a suitable temperature (generally greater than appr. +5^{o}C)
- a suitable humidity level (most often quoted to be RH=70% or more).

The mould growth is generally of low intensity at lower temperatures but the activity is strongly stimulated by increasing temperature. Sometimes it is also claimed that mould growth is possible only if the surrounding air is calm. This, however, does not seem to have been proved.

Analyses of risks for surface condensation or mould growth on the inner part of a building's envelope thus involves estimations of local surface temperatures and the moisture condition of indoor air.

In the same manner as mould can grow and condensation can occur on inner surfaces of a building, these phenomena may take place within a building component or an adjacent space, for example an attic.

The risk criteria are the same, i.e. moisture conditions above a relative humidity of appr. 70%, at certain temperatures and under longer periods may be harmful to organic material.

Of the two transfer mechanisms, moisture diffusion and moisture convection, the latter one is without doubt the more harmful. Except in very special cases, such as freezing-houses, etc., moisture diffusion can be neglected in the design procedure. This is due to the fact that diffusion is a very slow process and possible condensation amounts are small.

However, conditions with higher air pressure inside a building than outside, may create very unfavourable moisture convection problems. The moist air is transferred out from the building through cracks etc and creates high relative humidities or condensation when the heated and moist air (in cold climates) meets parts in the construction which have lower temperatures.

Examples of severe moisture damage caused by moisture convection are moisture accumulation, mould and rot in roof constructions and attics.

1.3 Air humidity and ventilation

The relationship between outdoor and indoor moisture conditions is:

$$v_i = v_o + \frac{G}{nV}(1-e^{-nt}) \qquad (1.3a)$$

where

v_i = vapour concentration in indoor air g/m^3

v_o = vapour concentration in outdoor air g/m^3

G = moisture supply, kg/h

n = ventilation intensity, h^{-1}

V = room (house) volume, m^3

t = time, h

The expression G/(nV) corresponds to the so called moisture addition, (g/m^3).

The factor $(1-e^{-nt})$, which stands for the non-steady state case, must be taken into account sometimes, for example if a considerable moisture supply is started in a small poorly ventilated space, while in many other time averaged cases the factor can be neglected. By writing eq. 1.3a in a somewhat different way:

$$v_i = \frac{G}{V} \frac{1-e^{-nt}}{n} + v_o \qquad (1.3b)$$

the total influence of time and ventilation intensity can be studied by plotting time vs. $(1-e^{-nt})/n$ for different n-values, figure 1.3.

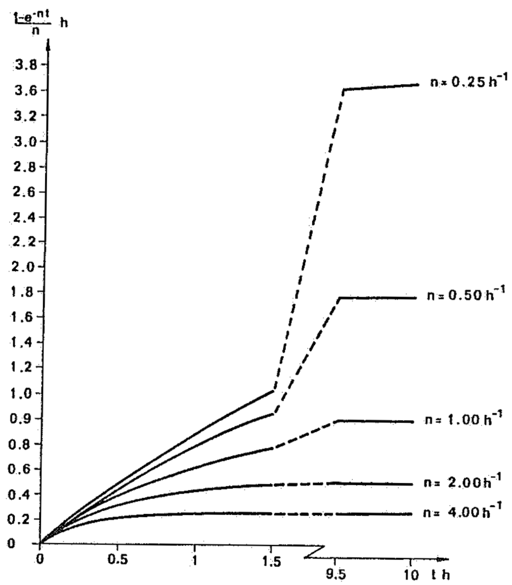


FIGURE 1.3

The indoor relative humidity RH_i, is:

$$RH_i = \frac{v_i}{v_s(\vartheta_i)}$$

where v_s (ϑ_i) is the vapour concentration at saturation point at the indoor temperature ϑ_i.

In order to make proper estimations of indoor moisture conditions two main questions must be answered:

- What magnitude of moisture supply

and

- what ventilation intensity

could be expected in practice?

The magnitude of the moisture supply in dwellings is far from well-known and, in many cases, this is also true of ventilation intensity.

It is also important to take into account where the moisture is supplied and if there are any ventilation devices there, taking care of the moist air. In many countries flats are normally equipped with exhaust ventilation devices in kitchens and in bathrooms, i.e. rooms where moisture supply is high and frequent.

Sandberg (1973) states that if air is extracted from a room where moisture is supplied, the water vapour concentration in other rooms around will not noticeably rise. Hence, it is possible to study the moisture behaviour of each room separately.

If ventilation devices for extracting air from rooms with high moisture supply do not exist or are not used, the moisture situation in the dwelling as a whole will be much more critical. The anticipation of no (or very little) influence on the moisture condition in adjacent rooms does not hold any longer.

A correct estimation for a non-intentionally ventilated flat (only "natural ventilation" due to leaky walls, windows etc.) is that all the rooms in the flat will get about the same ventilation intensity. This could vary due to wind, air temperatures etc.

Table 1.3a gives approximate values for possible moisture supplies to a flat.

Supply source	Moisture supply kg/h
People, low activity	0.03 - 0.06
medium work	0.12 - 0.30
heavy work	0.20 - 0.30
Bath room, tub bath	0.7
shower	2.6
Kitchen, cooking etc	
electrical stove	0.6 - 1.5
gas fired stove	2.0 - 3.0
daily mean, electrical	0.1
gas	0.2
Wash-drying	0.05 - 0.5
Plants, small (per plant)	0.005 - 0.01
medium	0.007 - 0.015
large	0.01 - 0.02
Aquarium	0.01

Table 1.3a Possible moisture supplies in a dwelling. Mainly from Erhorn & Gertis (1986).

An accumulative and approximate calculation of the moisture supply to a dwelling can now be made.

	Supply kg/h	Accumulated min	Accumulated max
Plants, 20 small	0.1 - 0.2	0.1	0.2
10 medium	0.07 - 0.15	0.17	0.35
5 large	0.05 - 0.1	0.22	0.45

Aquarium	0 - 0.01	0.22	0.46
2 persons low to medium work	0.06 - 0.60	0.28	1.06
Kitchen, electrical stove (E)	0.1	0.38	1.06
gas stove	0.2	0.38	1.26
Bath room, rough estimate	0.1	0.48	1.36
Washing, drying clothes etc	0 - 0.25	0.48	1.61

Thus the total moisture supply to a dwelling could be estimated to 0.4 - 1.6 kg/h or 10 - 40 kg/24 h. This moisture supply interval could be compared to values claimed by other authors, Table 1.3b.

Loudon (1971)	Bonafont (1969)	Croiset (1968)
15.4 kg/24 h (washing day) 7.2 kg/24 h (average day)	8.5 kg/24 h	10 kg/24 h

Table 1.3b Daily moisture supply to dwellings.

For a flat with a volume of 250 m^3, this corresponds to moisture additions (G/(nV) of the following magnitude, Table 1.3c.

n (n^{-1})	G/(nV) (g/m^3) G = 0.4 kg/h	 G = 1.6 kg/h
0.5	3.2	12.8
1	1.6	6.4
2	0.8	3.2
5	0.32	1.3
10	0.16	0.6

Table 1.3c Moisture additions (g/m^3) for different moisture supplies and ventilation intensities.

The other main question concerns which ventilation intensity could be expected in practice in different situations.

Estimations of the resulting ventilation intensity, due to different ventilation measures performed by the occupants, have been reported by Gertis (1983), based on results from several authors, Table 1.3d.

Ventilation measure	Ventilation intensity (h^{-1})
Windows and doors closed	0 - 0.5
Windows ajar and Venetian blind closed	0.3 - 1.5
Windows slightly open, no Venetian blind	0.8 - 4.0
Windows half open	5.0 - 10.0
Windows completely open	9.0 - 15.0
Windows and window-door completely open	40

Table 1.3d Estimated ventilation intensities due to different ventilation measures. After Gertis (1983).

The relatively large intervals for the ventilation intensity in the table is of course due to different wind - and stack-effect actions that can be expected on a building.

2 PRINCIPLES FOR RISK ANALYSES

In this chapter we will deal with combined effects of moist air, cold surfaces on the inner side of the dwelling envelope and risks for condensation, mould growth etc.

2.1 Surface phenomena

The surface temperatures of different parts of the inner side of the building envelope (walls, roofs, windows etc) are of essential interest in order to analyse the humidity conditions for a building.

The thermal analysis could be simplified by using a local formulation of the heat transmission coefficient of a building component, U_{loc} (W/(m^{2}K)). This formulation implies that there is only one-dimensional heat flow in the vicinity of the local "spot". (No cross-conduction). The indoor surface temperature, ϑ_{si} of a building component etc. could be written:

$$\vartheta_{si} = \vartheta_{ai} - \frac{U_{loc}}{\alpha_i}(\vartheta_{ai} - \vartheta_{ao}) \qquad (2.1a)$$

where

ϑ_{ai} and ϑ_{ao} = air temperature indoors and outdoors respectively, ^{o}C

α_i = indoor surface heat transfer coefficient, W/(m^{2}K)

In a given climate situation

$$\vartheta_{si} = \vartheta_{si}(U_{loc}, \alpha_i) \qquad (2.1b)$$

The local U-values for some building components are given in table 2.1a.

Building component	U_{loc} (W/m^{2}K))
0.25 m masonry (brick)	1.7
0.15 m concrete	3.0
0.15 m wood	0.7
0.15 m steel	4.0
Window, single-glazed	5.0
double-glazed	3.0
triple-glazed	2.0

Table 2.1a Local U-values for some building components.

The indoor surface heat transfer coefficient, α_i, is by definition:

$$\alpha_i = \frac{q}{\vartheta_{ai} - \vartheta_{si}} \tag{2.1c}$$

where

q = heat flow density, W/m^2

The magnitude of the indoor surface heat transfer coefficient in different situations has been studied by several authors.

Gertis (1983) gives the following approximate values suitable to practical design:

Situation	α_i (W/(m^{2}K))
Undisturbed, free vertical surface	8
Corner, no furniture	6
Corner, behind furniture	4

Table 2.1b Practical design values of indoor surface heat transmission coefficient. Gertis (1983).

For windows it is worth-while carrying out a special discussion on local phenomena of heat transmission.

Windows with air cavities, such as double- or triple-glazed ones, have no constant U-value along the height of the glass. Due to natural convection within the cavities there is a local maximum of the U-value in the bottom part of the window of the magnitude $1.5\ U_{mean}$.

Partly as a result of this, also the inner surface heat transmission coefficient varies from top to bottom of the glazed part of a window.

From a practical point of view it is desirable to describe these variations in an acceptable way by varying only one of the parameters, keeping the other at an averaged value. In Jonsson (1985) such a formulation is worked out.

In brief, from Jonsson's results, a versatile design approach for estimating minimum inside surface temperatures for double and triple-glazed windows in a cold climate could be:

- Let the mean U-value, U_{mean} of the window represent the overall heat transmission of the window.

- Let the minimum temperature be calculated as a function of U_{mean} and α_{min}.

α_{min} appears normally in the bottom of the window glass, and for most cases a value of

$$\alpha_{min} = 5\ W/(m^2K)$$

is applicable.

An analysis of surface related moisture problems in general is however rather complex. A number of parameters must be set and/or calculated:

- volume of room or dwelling

- ventilation intensity
- moisture supply
- outdoor and indoor temperature and relative humidity
- risk criterion on inner surface (set critical value of RH)
- indoor surface heat transfer coefficient
- local heat transmission coefficient

Possibilities to study the sensitivity, in different aspects, due to changes in level of one or more parameters, could be done in a rather simple way by means of a multi-diagram (figure 2.1a).

The use of the multi diagram is shown in the following example.

Example

Investigate the ventilation need for a dwelling (volume 250 m^3) under winter condition, in order to avoid moisture conditions for mould growth on the wallpaper behind a sofa for two different levels of moisture supply; 0.4 and 1.0 kg/h.

Wall: 0.25 m brick masonry.
Outdoor conditions:
air temperature + $1^{o}C$
relative humidity 90%

Indoor air temperature = $20^{o}C$ and $15^{o}C$

Solution:
Study figure 2.1b.

Result:
Minimum ventilation intensity (h^{-1}):

Indoor air temp ^{o}C	Moisture supply 0.4 kg/h	1.0 kg/h
20	0.4	1.0
15	0.8	1.9

Figure 2.1 a

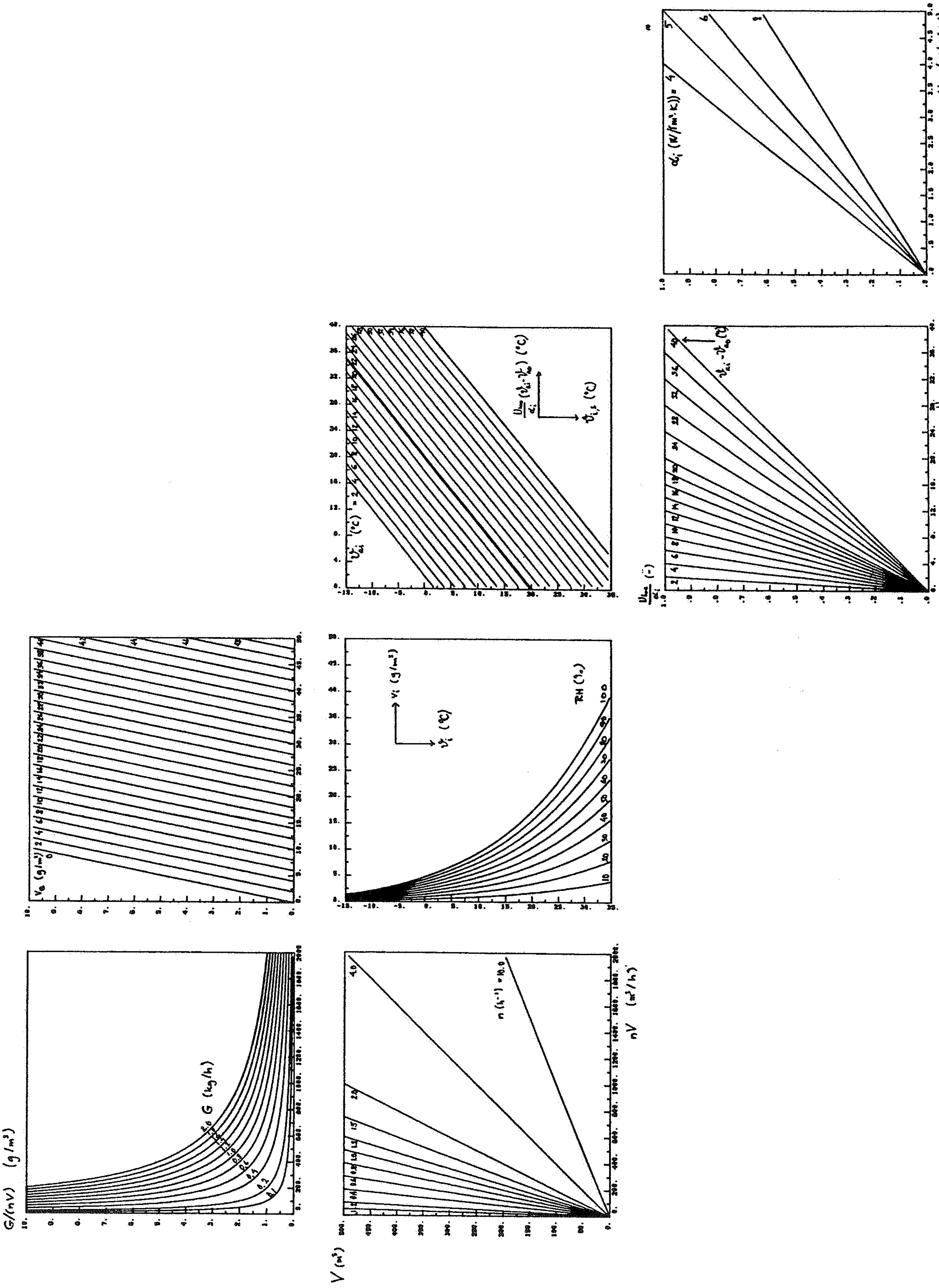
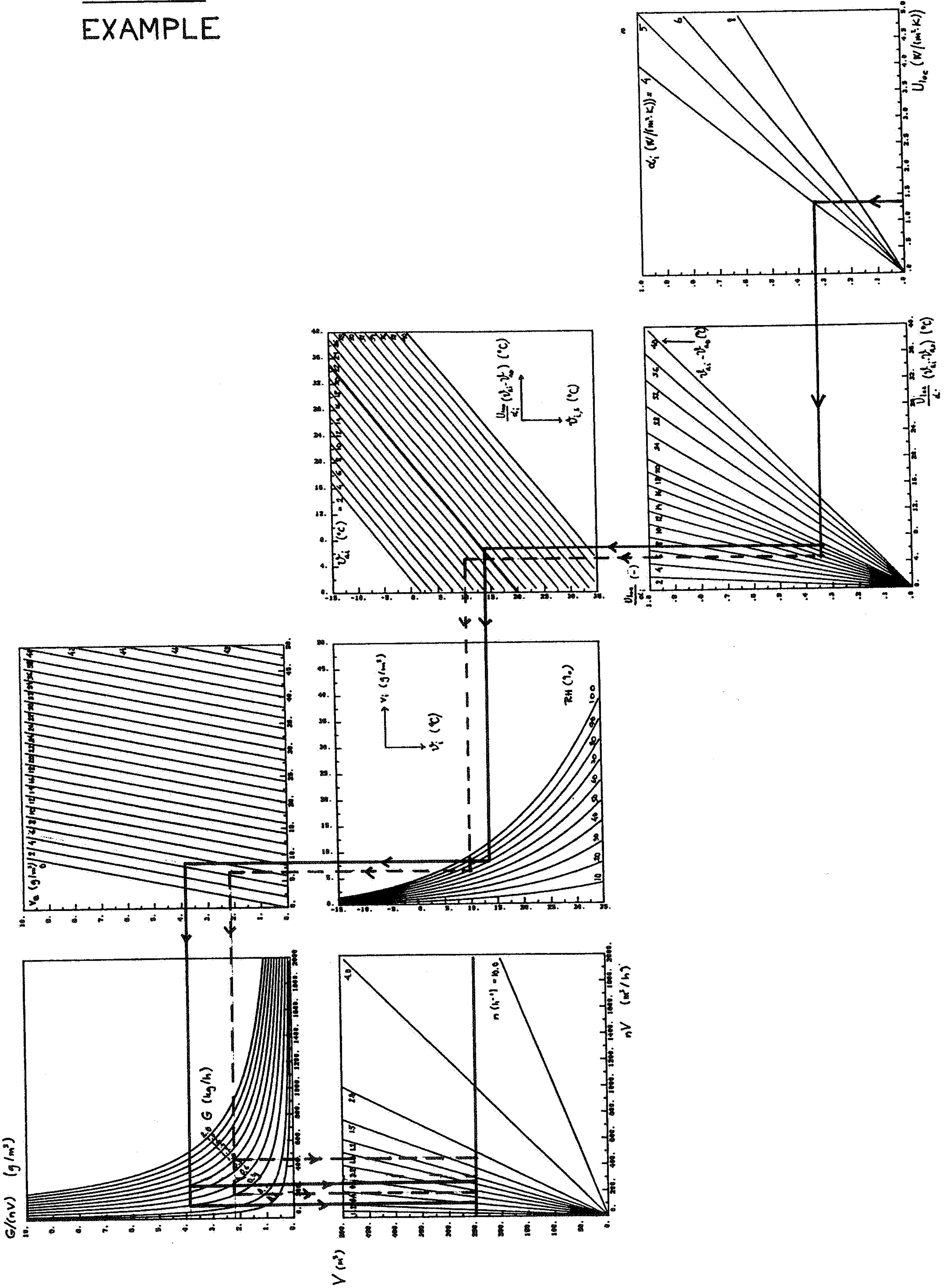


Figure 2.1b

EXAMPLE



2.2 Moisture conditions within building components

As outlined above (part 1.2), the durability or function of a building component may be diminished under influence of moist indoor or/and outdoor conditions.

If no measures, such as use of vapour barriers etc, are undertaken to protect the inner side of a building component, condensation or very moist conditions are likely to occur in some cases. The vapour transfer may be convective or diffusive.

Some apparent risk cases are:

- Outer parts of building components under relatively constant low outer temperature (cold climates)

- Inner parts of building components in artificially cooled buildings in hot climates

- Cold parts in building components, due to non-steady state conditions in all climates under certain conditions, (for example night-radiation out from roof constructions).

The risk of critical moisture conditions within building components is, of course, connected to the ventilation of a building. However, this is more a question of making a proper design and construction of the building component. Hence it will not be discussed in detail in this paper.

3 VENTILATION REQUIREMENTS IN DIFFERENT CLIMATES

3.1 Climatic data for different climatic zones

A climate of a place on Earth can be described by many parameters. Two main parameters for this study are temperature and humidity.

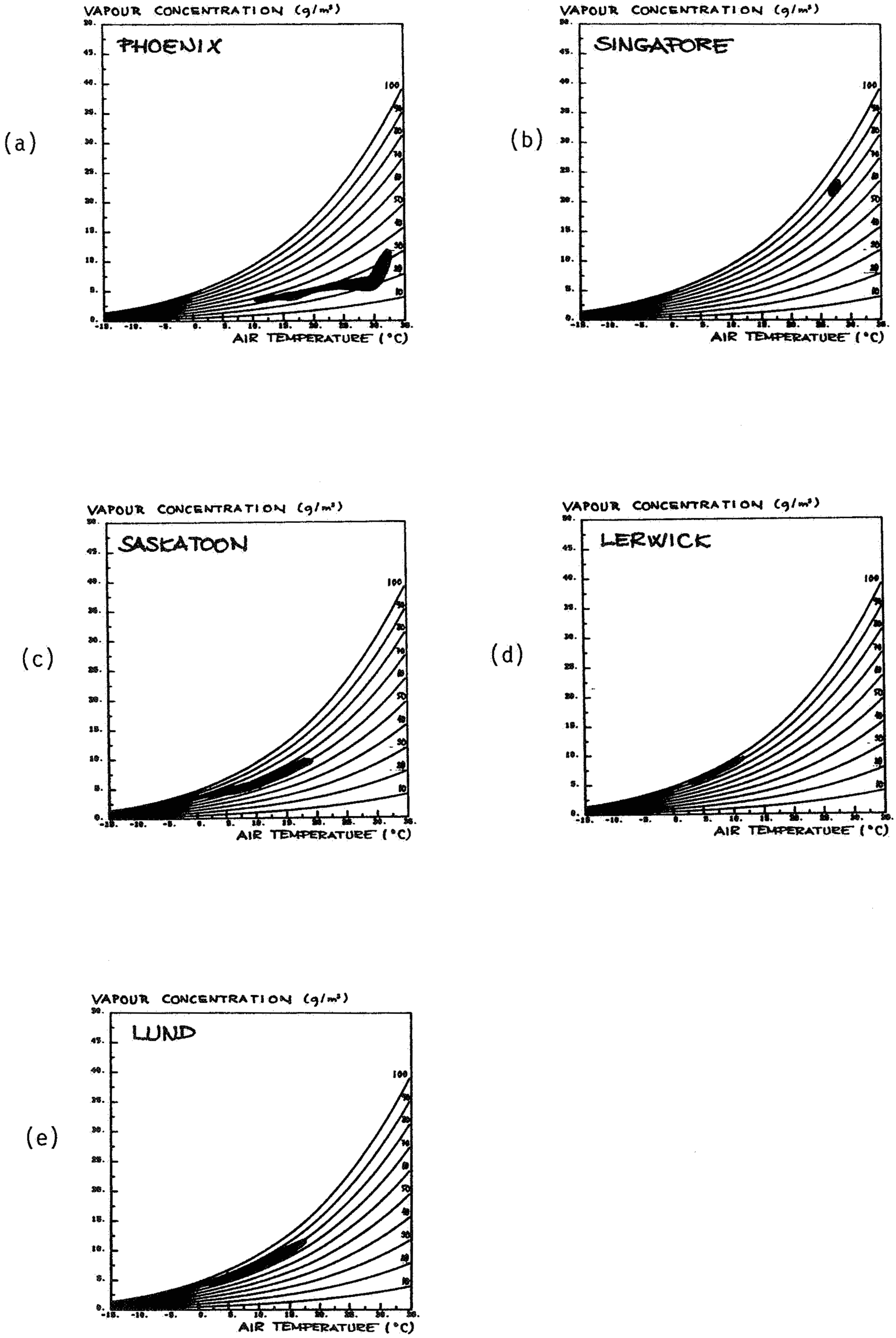
For the analyses carried out in this paper, the four possible combinations of hot and cold temperature and dry and humid moisture conditions were investigated. As a comparison, a moderate climate was investigated too, Table 3.1 .

Place	Latitude	Longitude	Elevation (m)	Climate
Phoenix, Ariz.,USA	33°26'N	112°01'W	340	hot,dry
Singapore	01°21'N	103°54'E	8	hot, humid
Saskatoon, Sask., Canada	52°08'N	106°38'W	157	cold,dry
Lerwick, Shetland Islands,UK	60°08'N	01°10'W	83	cold, humid
Lund, Sweden	55°43'N	13°12'E	73	moderate

Table 3.1

Climatic data concerning temperature and humidity of the five places are presented in Appendix 1. Main source: Landsberg (1985).

The data are presented in an illustrative way in Figures 3.1a-3.1e.



<u>Figure 3.1</u> Outdoor temperature and moisture conditions of the selected places

3.2 Principles for moisture - ventilation analysis

An analysis, in order to determine ventilation requirements for moisture control, can follow different lines. As outlined earlier in the paper the following aspects may be of interest.

What minimum ventilation intensity is required for different levels of moisture supply, in order to

- minimize human discomfort in the dwelling?
- avoid critical moisture conditions for the building material?

If really reliable results of such an analysis are desired, the heat balance of the building under non-steady conditions must also be calculated. This is important especially in hot climates, where the influence of thermal inertia is large.

For these cases, analyses carried out by Adamson (1986), fully taking into account the thermal behaviour of the building, can offer considerable help.

At least the winter case, and also to a certain degree the spring and autumn cases, can be analysed in a more simple way. The main steps in such a simplified analysis are as follows:

1. Determine outdoor temperature and moisture conditions
2. Investigate the ventilation need for different moisture supplies, (kg/h), see part 1.3
3. Set damage criteria such as condensation risk etc.
4. Perform the analysis according to point 2 for different (design) indoor temperatures

In relation to what is practically obtainable as far as moisture conditions are concerned, different targets are likely to be used in different climates.

3.3 Analyses

3.3.1 Hot and dry climate

Reference place: Phoenix, Arizona, USA

Climatic conditions: Cf. Figure 3.1a. The daily mean temperature varies between around 10 ^{0}C in January and 33 ^{0}C in July. The diurnal variations are normally large. The daily mean relative humidity never exceeds 40%. Sunshine and high night-radiation are very frequent due to clear sky.

Building design: Typical building-design strategies for passive-design (no mechanical ventilation or cooling equipment) in hot and dry climates are:

- Dense built up areas, narrow streets, courtyards, white painted walls and roofs, small windows, etc. to prevent too high solar gain on the outside of the building

- High external and internal thermal capacity in order to level out the temperature fluctuations in the building

- Thermal insulation in walls and roofs (newer buildings)

Passive-design ventilation strategies: In order to produce acceptable indoor thermal comfort, ventilation in the day time is kept at a low level (hygienic ventilation) while at night the ventilation is forced (10-40 h^{-1}, depending on season).

Analysis

Two questions are interesting to investigate

- What minimum ventilation intensity is required in the day time? (A).
- How can the high ventilation intensity at night be arranged and what hygienic phenomena can be expected? (B).

A complete thermal analysis of the thermal behaviour of a building in the Sahara has been carried out by Adamson (1986). In figure 3.3.1a the indoor and outdoor air temperatures of a building on a hot day in July are shown.

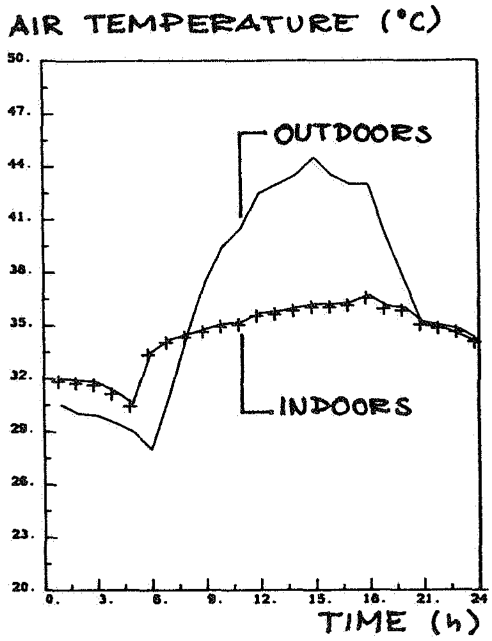


Figure 3.3.1a Computed indoor and outdoor air temperatures for a building in the Sahara on a hot July day. Day ventilation 1.1 h^{-1}, night ventilation 20 h^{-1}.

A

Since outdoor humidity is very low, it is easily shown that the indoor relative humidity never can reach high critical levels even with very high levels of moisture supply. Hence, the minimum ventilation intensity is settled by other factors than indoor humidity such as odour control.

B

In many cases in hot, dry climates the high ventilation intensities during night time are arranged by means of a so called wind scoop (figure 3.3.1b) facing the prevailing wind. As can be seen from the figure the equipment can also be used for evaporative cooling.

Mechanical ventilation is of course also possible as well as artificial refrigeration of the ventilation air. These measures are normally undertaken for office buildings etc. in hot and dry climates.

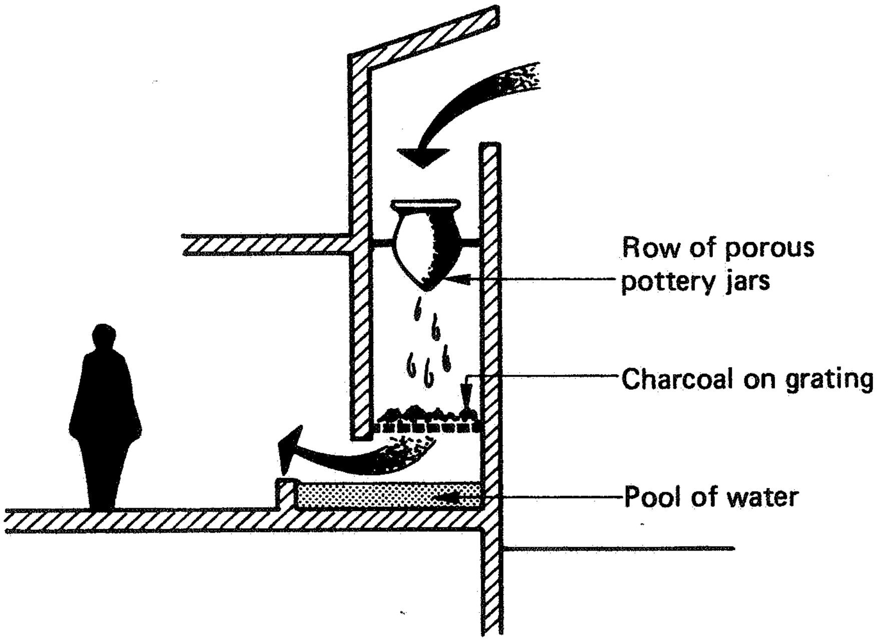


Figure 3.3.1b "Wind scoop". After Markus & Morris (1980).

3.3.2 Hot and wet climate

Reference place: Singapore

Climatic conditions: Cf. Figure 3.1.b. There are almost no variations in outdoor air temperature and relative humidity throughout the year. The yearly mean values describe the conditions quite well. They are:

Outdoor temperature	27 °C
Outdoor relative humidity	84%

Also the diurnal variations are small, mainly due to very high frequency of cloudiness.

Traditional building design in this area involves, Markus & Morris (1980):

- light-weight structure and roof construction
- ventilated space and/or insulation between roof and ceiling
- roof-overhang to shade the walls from sunshine
- possibilities to open up large parts of the facade to increase ventilation
- placing the house on poles above the ground

Analysis

As the light-weight constructions used do not give rise to any larger time-lag, which anyway had not been of any use because of the small diurnal variation of temperature, almost the same air temperature is, in principle, to be expected inside a house as outside it.

If so, analyses for hygro-thermal indoor comfort and durability can be carried out.

The combination 27^oC and 84% RH of calm air cannot be regarded as a comfortable situation. Cf. Figure 1.1! However, the human comfort can be highly increased if the air is in motion. According to figure 1.1 an air velocity of around 0.5 m/s or more seems to provide acceptable comfort for most people.

Hitherto the influence of moisture supply to the indoor air has been neglected. The outdoor vapour concentration is not far from saturation point. For the yearly mean case, for example, the vapour concentration is 21.3 g/m^3 as the saturation point corresponding to $+27^oC$ is 25.8 g/m^3; a difference of 4.5 g/m^3.

If RH = 90% is chosen as an absolute limit for indoor comfort the highest permissible moisture addition is $25.8 \times 0.9 - 21.3 = 1.9$ g/m^3. For a dwelling with a volume of 250 m^3, this corresponds to maximum moisture supplies according to table 2.3.2a. ($G = 1.9\ V\ n$).

Ventilation intensity h^{-1}	Max moisture supply kg/h
1	0.5
2	1.0
4	1.9

It seems possible to take care of considerable moisture supplies, due to the high temperature, without reaching higher relative humidity than 90%. This, however, would seem to be very uncomfortable and it can also be criticized from durability aspects.

If compared with the criteria quoted in part 1.2 for mould growth, i.e. RH = 70% or more, it would seem impossible to avoid such growth, unless dehumidification is used. Mould growth is also a great problem in this climatic zone. From time to time it is necessary to clean walls, ceilings etc from mould, Huy Anh (1986).

A proper ventilation strategy for buildings in hot and wet climate could be:

- Keep ventilation at a minimum level, primarily for moisture control, as long as the indoor temperature is below outdoor temperature.

- Ventilate as much as possible as long as outdoor temperature is below inside temperature.

- Do cooking and other moisture generating activities, as far as is possible, outside the building itself.

- If higher hygro-thermal comfort is necessary, use artificial cooling for the building. If so, take good care with the design and construction of the building. (Vapour barriers on the hot side, air tightness etc).

3.3.3 Cold and dry climate

Reference place: Saskatoon, Sask., Canada

Climate conditions: Cf. figure 3.1c. The daily mean temperature varies between -18°C in January and around 20°C in July. The diurnal variations are relatively large, especially in the summer-time. The relative humidity is low at summer-time.

Building design and ventilation system: Due specially to cold outdoor conditions in the wintertime, at least newer buildings are well insulated and air tight. Many newer buildings are equipped with mechanical ventilation; otherwise natural ventilation is used.

Analysis

In order to achieve an acceptable indoor temperature it is necessary to run the heating system most times of the year except in the summer. With a proper temperature control, by means of thermostats, it is possible to keep a relatively constant indoor temperature.

For this, a complete thermal analysis of the building is not necessary in order to predict indoor surface temperatures, relative humidities etc.

Hence, the analysis procedure outlined in part 3.2 is completely applicable.

1. Outdoor conditions:
   These are taken from the appendix. As condensation risks etc. are greatest when the outdoor temperature is at daily minimum, this temperature is chosen. Though meteorologically not completely correct (Geiger, 1965) the daily mean outdoor vapour concentration is treated as constant during the day. However, if this leads to saturation, a value of RH of 97%, at temperature minimum, is chosen. Four season-representative months (January, April, July and October) are chosen for the analyses.

2. Moisture supplies:

   Three levels are investigated; 0.2 (low), 0.4 (medium) and 0.8 kg/h (high).

3. Damage criteria:

   No condensation on the inside of window glasses is allowed. There should be no opportunity for mould growth on the wallpaper behind sofas etc.

4. Indoor temperatures:

   Two indoor air temperatures are investigated: +20^{o}C and +18^{o}C.

Such analyses as these outlined above are quite easily made solely by means of the multi-diagram (figure 2.1a) However, if a great number of calculations are to be made it is easier to perform the calculations using a computer.

The results of such calculations for Saskatoon are shown in table 3.3.3 .

Conclusions

The low indoor temperature case, 18^{o}C, is excluded for summertime, which seems to be reasonable, because of the relatively high outdoor temperature at this time of the year.

In all cases except summer-time it is the "no condensation on windows" criterion that governs the ventilation need. It varies between 0.43 ac/h (spring and autumn) and 0.65 ac/h (winter) for the 20^{o}C-case at medium moisture supply (0.4 kg/h) and double glazed windows. Corresponding values for triple-glazed windows are 0.26-0.31 ac/h.

Table 3.3.3

SASKATOON
MINIMUM VENTILATION INTENSITIES (ac/h)

MOISTURE (kg/h)	WINDOW DOUBLE	TRIPLE GL.	WALL BEHIND FURNITURE U=1.0	U=0.4 W/m2/K
WINTER, INDOOR TEMP 18 DEGC				
0.2	.36	.17	.16	.1
0.4	.71	.34	.32	.21
0.8	1.42	.68	.64	.41
SPRING, INDOOR TEMP 18 DEGC				
0.2	.24	.15	.19	.14
0.4	.48	.29	.39	.28
0.8	.96	.58	.78	.56
AUTUMN, INDOOR TEMP 18 DEGC				
0.2	.24	.15	.2	.15
0.4	.48	.29	.41	.29
0.8	.96	.59	.82	.59
WINTER, INDOOR TEMP 20 DEGC				
0.2	.33	.15	.14	.09
0.4	.65	.31	.28	.18
0.8	1.31	.61	.57	.37
SPRING, INDOOR TEMP 20 DEGC				
0.2	.22	.13	.16	.12
0.4	.43	.26	.33	.23
0.8	.86	.51	.66	.47
SUMMER, INDOOR TEMP 20 DEGC				
0.2	.23	.17	.68	.41
0.4	.46	.34	1.35	.81
0.8	.93	.67	2.7	1.63
AUTUMN, INDOOR TEMP 20 DEGC				
0.2	.21	.13	.17	.12
0.4	.43	.26	.34	.24
0.8	.86	.52	.68	.49

In summer-time, however, it is risk of conditions for mould growth behind furniture that settles the ventilation need. For example in the "well-insulated" case (U_{loc} = 0.4 W/m^2K) the ventilation need is 0.81 ac/h.

Rough recommendations for minimum ventilation for moisture control could be:

Well insulated house, triple-glazed windows	
Summer	0.8 ac/h
Other seasons	0.3 ac/h

Badly insulated house, double-glazed windows	
Summer	1.4 ac/h
Other seasons	0.7 ac/h

3.3.4 Cold and wet climate

Reference place: Lerwick, Shetland Islands, UK

Climatic conditions: Cf. figure 3.1d. The daily mean temperature varies between around 3^{o}C in the winter-time and 12^{o}C in the summer. The diurnal variations are rather small. The relative humidity is around 90% or more throughout the year.

Building design: The more specific building design of houses on the Shetland Islands is not known to the author, but the climate in general seems to give reasons for good insulation and air tightness of the houses.

Analysis

As conditions for an analysis are similar to that of a cold and dry climate (part 3.3.3) the same procedure is used.

The results of the computer calculations for Lerwick are shown in table 3.3.4 .

Table 3.3.4

LERWICK
MINIMUM VENTILATION INTENSITIES (ac/h)

MOISTURE (kg/h)	WINDOW DOUBLE	TRIPLE GL.	WALL BEHIND FURNITURE U=1.0	U=0.4 W/m2/K
WINTER, INDOOR TEMP 18 DEGC				
0.2	.24	.15	.23	.17
0.4	.49	.3	.47	.33
0.8	.98	.61	.94	.67
SPRING, INDOOR TEMP 18 DEGC				
0.2	.25	.16	.26	.19
0.4	.5	.31	.53	.37
0.8	1	.63	1.06	.74
AUTUMN, INDOOR TEMP 18 DEGC				
0.2	.27	.17	.39	.26
0.4	.53	.35	.78	.52
0.8	1.07	.7	1.56	1.04
WINTER, INDOOR TEMP 20 DEGC				
0.2	.22	.13	.19	.14
0.4	.43	.26	.38	.27
0.8	.86	.53	.76	.54
SPRING, INDOOR TEMP 20 DEGC				
0.2	.22	.14	.21	.15
0.4	.44	.27	.42	.3
0.8	.87	.54	.83	.59
SUMMER, INDOOR TEMP 20 DEGC				
0.2	.25	.17	.49	.3
0.4	.5	.33	.97	.6
0.8	1	.67	1.94	1.21
AUTUMN, INDOOR TEMP 20 DEGC				
0.2	.23	.15	.28	.19
0.4	.46	.29	.55	.38
0.8	.91	.59	1.1	.76

Conclusions

As in the Saskatoon case, the low indoor temperature ($18^{o}C$) in the summer-time is excluded.

For the case with bad insulation (U = 1.0 $W/(m^2K)$) and double-glazed windows with medium moisture supply at an indoor temperature of $18^{o}C$ (except summer-time ($20^{o}C$)), it is, in all cases but winter, the risk for high relative humidity on walls behind furniture that settles the minimum ventilation need. It varies from 0.53 ac/h (spring) to 0.97 ac/h (summer). The winter condition is governed by the risk for condensation on windows giving a minimum ventilation value of 0.49 ac/h.

If the indoor air temperature is increased to $20^{o}C$ it is, in winter and spring, the "no condensation on window" criterion that settles the minimum ventilation need at 0.43-0.44 ac/h and in summer and autumn, the risk for high relative humidity; 0.55 ac/h (autumn) and 0.97 ac/h (summer).

For the case with good insulation (U = 0.4 $W/(m^2K)$) and triple-glazed windows with medium moisture supply at an indoor temperature of $20^{o}C$, it is during all seasons the risk for high relative humidity near the wall behind furniture, that settles the minimum ventilation need. It varies from 0.27 ac/h in the winter to 0.60 in the summer.

Rough recommendations for minimum ventilation for moisture control could be:

Well insulated house, triple-glazed windows	
Summer	0.6 ac/h
Other seasons	0.3 ac/h

Badly insulated house, double-glazed windows	
Summer	1.0 ac/h
Other seasons	0.8 ac/h

3.3.5 Moderate climate

Reference place: Lund, Sweden

Climatic conditions: Cf. figure 3.1e. The daily mean temperature varies between around -1^{o}C (January and February) and around 17^{o}C (July and August). The seasonal variations in temperature are more pronounced than they are for Lerwick but less than for Saskatoon. The diurnal variations are moderate. The yearly mean relative humidity is 82%, i.e. in between the value for Saskatoon (71%) and Lerwick (93%).

Building design: See part 3.3.3, (Saskatoon).

Analysis

The same analysis procedure as the one used for Saskatoon and Lerwick is used for Lund.

The results of the computer calculations for Lund are shown in table 3.3.5 .

Conclusions

As for the other places, the low indoor (18^{o}C) temperature case is excluded for summer-time.

For the case with bad insulation ($U = 1.0$ W/(m^{2}K)) and double-glazed windows with medium moisture supply at an indoor temperature of 18^{o}C (except summer-time (20^{o}C)), it is, during all seasons but winter, the risk for high relative humidity on walls behind furniture that settles the minimum ventilation need. It varies between 0.5 ac/h (spring) and 5.42 ac/h (summer).

If the indoor air temperature is increased to 20^{o}C the minimum ventilation need varies between 0.43 ac/h (winter, spring, condensation on windows) and 5.42 ac/h (summer); see above.

Table 3.3.5

LUND
MINIMUM VENTILATION INTENSITIES (ac/h)

MOISTURE (kg/h)	WINDOW DOUBLE	TRIPLE GL.	WALL BEHIND FURNITURE U=1.0	U=0.4 W/m2/K
WINTER, INDOOR TEMP 18 DEGC				
0.2	.24	.14	.19	.14
0.4	.48	.29	.38	.27
0.8	.96	.58	.76	.55
SPRING, INDOOR TEMP 18 DEGC				
0.2	.25	.16	.25	.18
0.4	.49	.31	.5	.36
0.8	.99	.62	1.01	.71
AUTUMN, INDOOR TEMP 18 DEGC				
0.2	.26	.17	.35	.24
0.4	.52	.34	.71	.48
0.8	1.05	.68	1.41	.96
WINTER, INDOOR TEMP 20 DEGC				
0.2	.22	.13	.16	.12
0.4	.43	.26	.32	.23
0.8	.86	.51	.65	.46
SPRING, INDOOR TEMP 20 DEGC				
0.2	.22	.13	.2	.14
0.4	.43	.27	.4	.29
0.8	.87	.54	.8	.57
SUMMER, INDOOR TEMP 20 DEGC				
0.2	.29	.2	2.71	.78
0.4	.58	.4	5.42	1.56
0.8	1.16	.81	10.84	3.13
AUTUMN, INDOOR TEMP 20 DEGC				
0.2	.22	.14	.26	.18
0.4	.45	.29	.51	.36
0.8	.9	.57	1.03	.72

For the case with good ventilation ($U = 0.4\ W/(m^2K)$) and triple-glazed windows with medium moisture supply at an indoor temperature of 20°C, it is, during all seasons but winter, the risk for high relative humidity on walls behind furniture that settles the minimum ventilation need. It varies between 0.29 ac/h (spring) to 1.56 ac/h (summer). As before the winter case is governed by the risk for condensation on windows, 0.26 ac/h.

Rough recommendations for minimum ventilation for moisture control could be:

<u>Well insulated house, triple-glazed windows</u>

Summer	1.6 ac/h
Other seasons	0.4 ac/h

<u>Badly insulated house, double-glazed windows</u>

Summer	5 ac/h
Other seasons	0.7 ac/h

4 CONCLUDING REMARKS

The analyses carried out in the paper result in the following general recommendations for ventilation for moisture control in dwellings in different climates:

Hot and dry climate: No real problem exists from moisture point of view. The ventilation is needed more for thermal control.

Hot and wet climate: Ventilation should be kept at a minimum, primarily for moisture control, as the temperature outside the house is higher than inside. When temperature conditions are the opposite the ventilation should be as large as possible. Avoid high moisture supply within the building. In many cases artificial cooling is necessary for reasonable comfort.

Cold and dry climte: For newer houses of good quality and workmanship the ventilation need is around 0.3 ac/h except in the summer-time when 0.8 ac/h is necessary.

Cold and wet climate: For newer houses of good quality and workmanship the ventilation need is around 0.3 ac/h except in the summer-time when 0.6 ac/h is necessary.

Moderate climate: For newer houses of good quality and workmanship the ventilation need is around 0.4 ac/h except in the summer-time when 1.6 ac/h is necessary.

5 APPENDIX

PHOENIX, ARIZ.
Latitude 33 deg, 26 min N, longitude 112 deg 01 min W
Elevation 340 m.

Month	Temperature (deg C)			Mean rel. humid. (%)	Mean vapour conc. (g/m3)
	mean	mean daily max.	mean daily min.		
Jan.	10.4	17.8	3.0	39	3.8
Febr.	12.5	20.1	5.0	35	3.8
Mar.	15.8	23.9	7.7	28	3.8
Apr.	20.4	28.9	11.9	29	5.2
May	25.0	33.9	16.2	22	5.1
June	29.8	38.7	20.9	18	5.7
July	32.9	40.3	25.5	33	11.3
Aug.	31.7	38.7	24.7	35	12.1
Sept.	29.1	36.9	21.4	26	7.9
Oct.	22.3	30.4	14.2	30	5.9
Nov.	15.1	23.3	7.0	35	4.5
Dec.	11.4	19.0	3.9	37	3.8
Annual	21.4	29.3	13.5	31	5.9

SINGAPORE
Latitude 1 deg, 21 min N, longitude 103 deg 54 min E
Elevation 8 m.

Month	Temperature (deg C)			Mean rel. humid. (%)	Mean vapour conc. (g/m3)
	mean	mean daily max.	mean daily min.		
Jan.	25.6	29.9	22.9	85	20.3
Feb.	26.1	30.8	23.1	83	20.4
Mar.	26.5	31.1	23.6	84	21.1
Apr.	27.1	31.2	24.1	85	22.0
May	27.3	30.9	24.5	84	22.0
June	27.6	30.8	24.7	83	22.1
July	27.3	30.6	24.7	82	21.5
Aug.	27.1	30.5	24.4	83	21.5
Sept.	27.0	30.4	24.2	83	21.4
Oct.	26.7	30.4	23.9	84	21.3
Nov.	26.2	30.1	23.7	86	21.2
Dec.	25.7	29.9	23.2	86	20.6
Annual	26.7	30.6	23.9	84	21.3

SASKATOON, SASK.
Latitude 52 deg, 08 min N, longitude 106 deg 38 min W
Elevation 157 m.

Month	Temperature (deg C)			Mean rel. humid. (%)	Mean vapour conc. (g/m3)
	mean	mean daily max.	mean daily min.		
Jan.	-17.6	-12.9	-22.4	92	1.0
Feb.	-14.9	-9.7	-20.2	79	1.1
Mar.	-7.9	-2.8	-13.1	83	2.1
Apr.	3.6	9.7	-2.5	65	4.0
May	11.2	18.3	4.1	54	5.5
June	15.4	22.1	8.7	59	7.7
July	19.3	26.6	12.1	59	9.6
Aug.	17.6	24.8	10.4	63	9.5
Sept.	11.6	18.3	5.0	62	6.4
Oct.	4.9	11.1	-1.3	71	4.8
Nov.	-5.8	-1.4	-10.2	86	2.6
Dec.	-13.2	-8.8	-17.6	74	1.2
Annual	2.0	7.9	-3.9	71	4.6

LERWICK, SHETLAND ISLANDS, UK
Latitude deg, min N, longitude deg min
Elevation m.

Month	Temperature (deg C)			Mean rel. humid. (%)	Mean vapour conc. (g/m3)
	mean	mean daily max.	mean daily min.		
Jan.	3.1	5.0	1.2	93	5.6
Feb.	2.9	5.0	1.9	93	5.5
Mar.	3.9	6.0	1.8	91	5.8
Apr.	5.4	8.1	2.8	88	6.1
May	7.8	10.5	5.1	88	7.2
June	10.0	12.6	7.4	88	8.3
July	12.0	14.4	9.7	92	9.6
Aug.	12.1	14.4	9.7	92	9.9
Sept.	10.6	12.9	8.4	93	9.1
Oct.	8.2	10.1	6.2	92	7.7
Nov.	5.9	7.8	4.1	93	6.7
Dec.	4.4	6.2	2.7	94	6.1
Annual	7.2	9.4	5.0	93	7.3

LUND, SWEDEN
Latitude 55 deg, 43 min N, longitude 13 deg 12 min E
Elevation 73 m.

Month	Temperature (deg C)			Mean rel. humid. (%)	Mean vapour conc. (g/m3)
	mean	mean daily max.	mean daily min.		
Jan.	-0.7	1.6	-3.0	89	4.1
Feb.	-0.8	1.6	-3.3	88	4.0
Mar.	1.3	4.7	-1.7	84	4.4
Apr.	6.2	10.4	2.2	76	5.6
May	11.3	16.1	6.1	71	7.2
June	15.2	19.7	10.2	73	9.5
July	17.4	21.7	12.7	78	11.6
Aug.	16.8	21.0	12.3	79	11.3
Sept.	13.5	17.4	9.6	84	9.8
Oct.	8.7	11.9	5.5	87	7.5
Nov.	4.8	7.0	2.5	89	5.9
Dec.	1.9	3.9	-0.1	91	5.0
Annual	8.0	11.4	4.4	82	7.4

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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PAPER 14

MEASUREMENT OF CARBON DIOXIDE OF THE INDOOR AIR TO CONTROL THE FRESH AIR SUPPLY

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SUMMARY

In order to save energy, i.e. ventilation heat losses, the fresh air change rate should be adapted to the prevailing need. Even though it is a fact, that reducing the fresh air change rate will result in a ventilation heat gain, the fresh air flow rate should not be kept too low, so that pollutants, humidity and body odour can accumulate.
The results of measurements in a climatic chamber and in a lecture theatre show a significant relationship between the concentration of carbon dioxide and body odour of the indoor air under nonsmoking conditions. The upper limit of carbon dioxide, where the indoor air quality is still acceptable to persons entering a room, is between 0.1 % and 0.15 % vol, whereas for occupants in the room this limit is higher because of adaptional effects.

1. INTRODUCTION

A new environmental problem has increased in the last ten years: in modern, energy efficient buildings some of the occupants show reactions similar to those known to be caused by formaldehyde, but even when the concentration of that pollutant is well below known reaction thresholds. These symptoms are explained as the net result of a summation or interaction of numerous subthreshold sensory stimuli. Many sensory systems may be involved, but the perceptual mechanisms are largely unknown [1].
Since many people spend an important part of their time in artificially ventilated or climated rooms, a healthy and comfortable indoor climate will attract more and more attention.
In other words: the temperature should be adapted to the activities of the occupants and humidity, pollutants and annoying odours must not accumulate [2].
The prevailing need of fresh air depends on the number of persons and on their activities in a certain space. Often, the fresh air supply is controlled by temperature; but does temperature really reflect the effective occupancy of a room ? The aim of this work is to point out the relationship between temperature, concentration of carbon dioxide and body odour of the indoor air, with the intention of working out a leading component

of the indoor air quality.
The natural concentration of carbon dioxide, an odour- and colourless non-toxic gas, in the athmosphere is about 0.035 % vol. Animals as well as human beings exhale carbon dioxide as combustion product of their biological metabolism; for man in sitting position the amount is around 20 l per hour [3].
If man is the only source of odours and pollutants in a room, the concentration of carbon dioxide seems to be suitable to control the fresh air supply.

2. METHOD

Measurements have been carried out in a climatic chamber and in a lecture theatre. The climatic chamber had a volume of 30 m³. The volume of the lecture theatre was 950 m³ and there was space for 160 students. The air inlet was situated at the ceiling and the air outlet on the floor.
Fresh air flow rate and humidity were always kept constant, while the temperature and the concentration of the indoor carbon dioxide were measured continuously. Discharge air was sucked off and offered to a test panel outside. They subjectively compared the perceived odour intensity with some pyridine reference odours, and they also answered some questions concerning the acceptance of the indoor air quality after 15, 60 and 90 minutes (lecture theatre), or after 30, 60, 90 and 120 minutes (climatic chamber). Together in time, the persons in the chamber replied to those questions, while the students in the lecture theatre did the questioning only at the end of the lectures.
All the measurements are summarized in tables 1 and 2.

3. QUESTIONING AND ODOUR INTENSITY MEASUREMENT

The questions are listed in table 3. The first question "measures" the subjectively perceived odour intensity by category scaling. In a similar way, Yaglou already did that in 1936 [4].
The percentage of persons, who judge an odour as not acceptable, depends on the demands one makes on the comfort of indoor air quality (second question).
The annoyance reaction (third question) is composed of an impact of former experiences. It always has to be

seen in context of the immediate environment of the exposed person.
The last question was only asked the students in the lecture theatre. Amongst temperature, the subjective perception of temperature also depends on the clothing. However, that was not registered, but all the tests were carried out on cold winter days.
In the case of the lecture theatre measurements, bottles with different pyridine concentrations in water were used as reference odours; but they were produced by dynamic olfactometry for the climatic chamber experiments. The odour concentrations were: 0.67, 1.2, 2.2, 3.9 and 7.0 mg/m³ (lecture theatre) and 0.11, 0.19, 0.35, 0.62 and 1.1 mg/m³ pyridine (climatic chamber). Direct comparison of the two sets of odours showed, that the odours in bottles were subjectively valued six times less intense than the odours offered by dynamic olfactometry. In order to be able to compare the results of both of the places, the two sets of reference odours were standardized.

4. RESULTS

The answers of the students in the lecture theatre were subdivided into the following seven subgroups of different environmental conditions:

< 0.08 ≤ 21.0	0.08-0.15 ≤ 21.0	
< 0.08 21.1-22.0	0.08-0.15 21.1-22.0	> 0.15 21.1-22.0
	0.08-0.15 > 22.0	> 0.15 > 22.0

CO_2	% vol
T	°C

Because of the small number of persons in the climatic chamber, that classification could not be done there. Also the answers of the two test panels outside were only divided into soubgroups of different carbon dioxide concentrations.
Between the classifications "faint odour" and "distinct odour" on the *category scale* (figure 1), the percentage of the judgements "not acceptable" rose from 15 to 60%.

This limit was reached by the test panels outside the room at a carbon dioxide concentration of 0.08 % vol, while the occupants inside tolerated a concentration higher than 0.15 % vol.
The *annoyance scale* (figure 2) indicates a limit between 2 and 3 on the self-rating "thermometer". The persons outside reached that value at a carbon dioxide concentration of 0.08 % vol, the occupants in the lecture theatre at 0.15 % vol and the occupants of the climatic chamber at concentrations over 0.22 % vol.
At a certain carbon dioxide concentration, the students inside the lecture theatre judged the air quality as worse as higher the temperature was (figures 1 and 2).
The test panels outside perceived the strong odours of the indoor air subjectively more intense by the *reference odour method* than by *category scaling* (compare fig. 1 and 3). No reason was found to explain that result.
The *acceptability* of an odour (question 2) was interpreted together with the *odour intensity* (figure 1) and the *annoyance* by an odour (figure 2).
Within the indoor temperature conditions of the experiments in the lecture theatre, about 50 % of the occupants felt comfortable. The subjective *perception of temperature* showed some dependence on the indoor carbon dioxide concentration, as figure 4 shows.

5. CONCLUSIONS

The measurements in the climatic chamber and in the lecture theatre confirmed the expected relationship between the concentration of the carbon dioxide and the subjectively perceived body odour intensity. A Spearman rank order correlation coefficient of 0.66 between the odour intensity and the carbon dioxide concentration was found for the data of the climatic chamber, and one of 0.4 for those of the lecture theatre. These coefficients are the result of the correlations between the carbon dioxide concentration and the time on the one hand, and between the odour intensity and the time on the other hand. A correlaton between the carbon dioxide concentration and the odour intensity exists, if man is the only source of both of these pollutants and if the emission rate is constant over time; and so, the concentration of the indoor carbon dioxide can be seen as a good and useful indicator of the indoor air quality

under non smoking conditions.
As an upper limit of the indoor carbon dioxide concentration we would propose 0.15 % vol abs. (that is approximately adequate to 0.1 % vol rel. increase). At that concentration not more than 15 % of the occupants inside complained of an unpleasant odour. If the limit is set by newly entered persons, the concentration may be kept at 0.1 % vol abs., because of their higher sensibility of odour perceptions.
Carbon dioxide fails as a leading component during smoking occupancies. In that case, the concentration of carbon monoxide [5], or an air quality sensor may give better results.

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fresh air a-c h^{-1}	fresh air $m^3/h*p$	CO_2 % vol start	CO_2 % vol end	N of pers. occup	N of pers. panel	T °C start	T °C end	CO_2 l/h*p
0.1	1.5	0.05	0.31	2	4	19.8	22.0	21.6
0.16	2.4	0.05	0.26	2	4	19.5	21.7	18.3
0.4	4.0	0.05	0.34	3	4	20.8	23.3	22.2
0.3	3.0	0.05	0.35	3	4	20.9	23.2	19.8
0.16	2.4	0.06	0.31	2	4	22.9	25.1	21.9
0.16	2.4	0.05	0.31	2	4	23.0	23.7	21.9
0.16	4.8	0.04	0.17	1	4	20.0	23.0	21.6
0.16	2.4	0.05	0.28	2	4	23.5	25.4	20.1
0.16	2.4	0.05	0.31	2	4	22.8	24.9	22.2

table 1
summary of the *climatic chamber* measurements

symbols

a-c:	air change
occupants:	persons inside
% answ.:	% of the students in the lecture theatre who answered the questions
panel:	test panel outside
h :	hours
l :	litres
p :	persons
CO_2 (l/h*p):	calculated values

fresh air		CO_2 % vol		occupants		T °C		pa-nel
a-c h^{-1}	m^3/h*p	start	end	N	% answ	start	end	
1.1	27	0.05	0.11	39	92	22.0	22.5	7
2.0	16	0.05	0.18	115	96	22.0	22.5	6
1.1	14	0.045	0.14	73	90	22.0	22.0	13
1.1	14	0.045	0.16	77	95	21.5	22.5	7
0.5	23	0.045	0.09	21	95	21.5	22.0	6
0.5	-	0.035	0.04	-	-	21.5	21.5	9
0.5	4.5	0.05	0.21	105	87	21.5	23.0	6
0.5	6.7	0.045	0.18	71	77	22.0	22.5	9
0.5	4.5	0.06	0.21	104	88	21.5	22.5	8
0.5	16	0.05	0.11	30	97	21.5	22.0	5
0.5	14	0.045	0.12	35	-	20.5	21.3	5
0.5	4.3	0.06	0.21	110	74	20.7	22.0	6
0.5	7.3	0.04	0.18	65	64	21.0	22.0	6
0.5	6.7	0.055	0.2	71	89	20.0	21.5	6
0.5	14	0.055	0.14	35	94	20.3	21.0	5
1.1	27	0.055	0.1	39	95	20.0	20.3	9
1.1	10	0.06	0.19	109	88	20.2	21.5	3
1.1	21	0.045	0.14	50	82	20.0	20.8	8
1.1	16	0.05	0.15	65	85	20.0	21.0	8
1.1	30	0.04	0.11	77	77	20.0	21.5	6
5.0	56	0.05	0.08	85	90	20.5	20.5	-
5.0	59	0.07	0.08	80	96	21.4	21.5	-

table 2
summary of the *lecture theatre* measurements
(*symbols:* see table 1)

1. Is there .... in this room ?

no odour	|_|	1
very faint odour	|_|	2
faint odour	|_|	3
distinct odour	|_|	4
strong odour	|_|	5
very strong odour	|_|	6
unbearable strong odour	|_|	7

2. The odour in this room is ....

acceptable.	|_|
not acceptable.	|_|
I am not sure	|_|

3. Mark the level of annoyance by an odour on this supposed self rating "thermometer"!

_	10	unbearable annoyance
|_|	9	
|_|	8	
|_|	7	
|_|	6	
|_|	5	
|_|	4	
|_|	3	
|_|	2	
|_|	1	
|_|	0	no annoyance

4. The temperature in this room is ....

too cold.	|_|
right.	|_|
too warm.	|_|

<u>table 3</u>
questions concerning the *indoor climate*

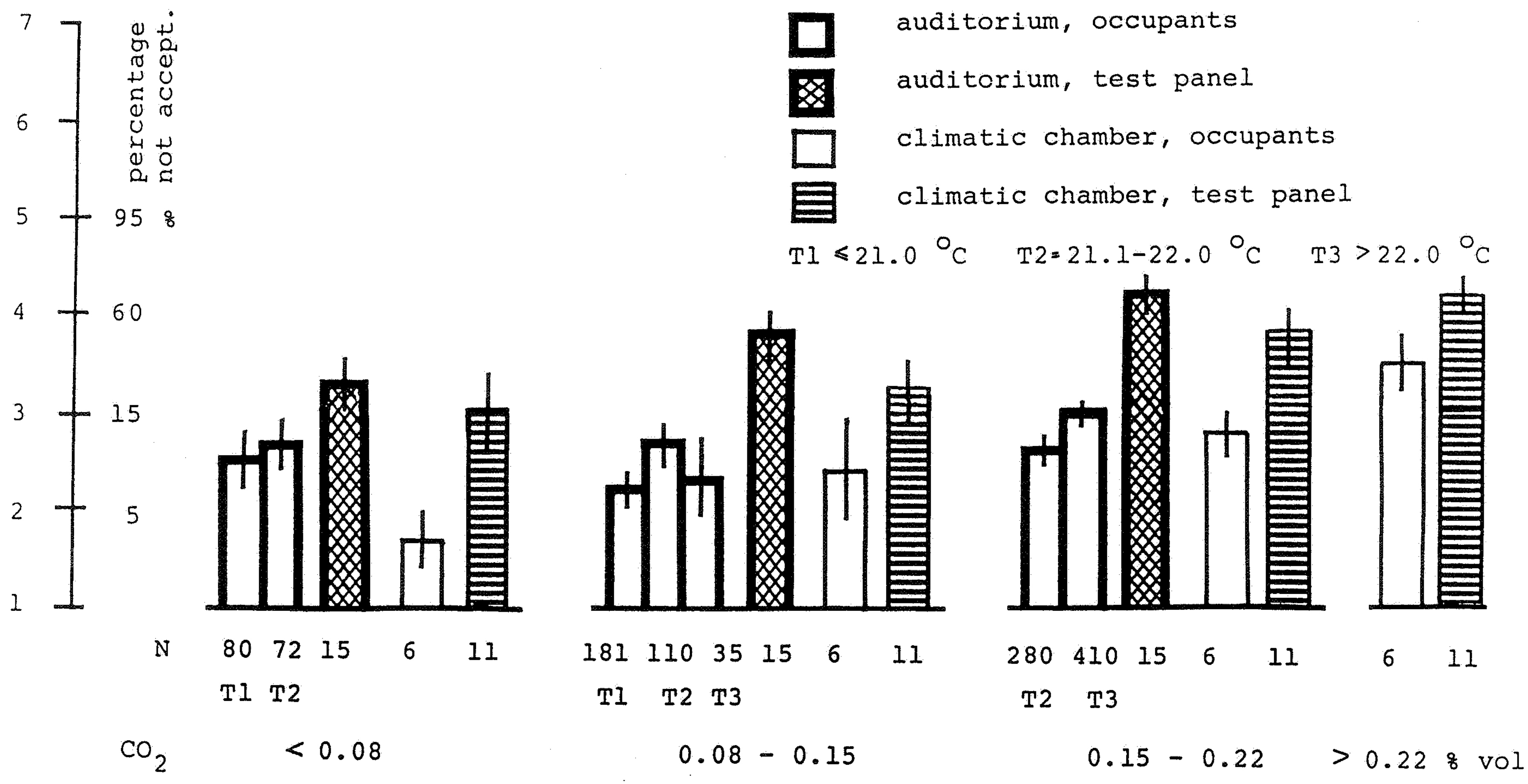

Figure 1: ODOUR INTENSITY (Category scale; see table 3, question 1)

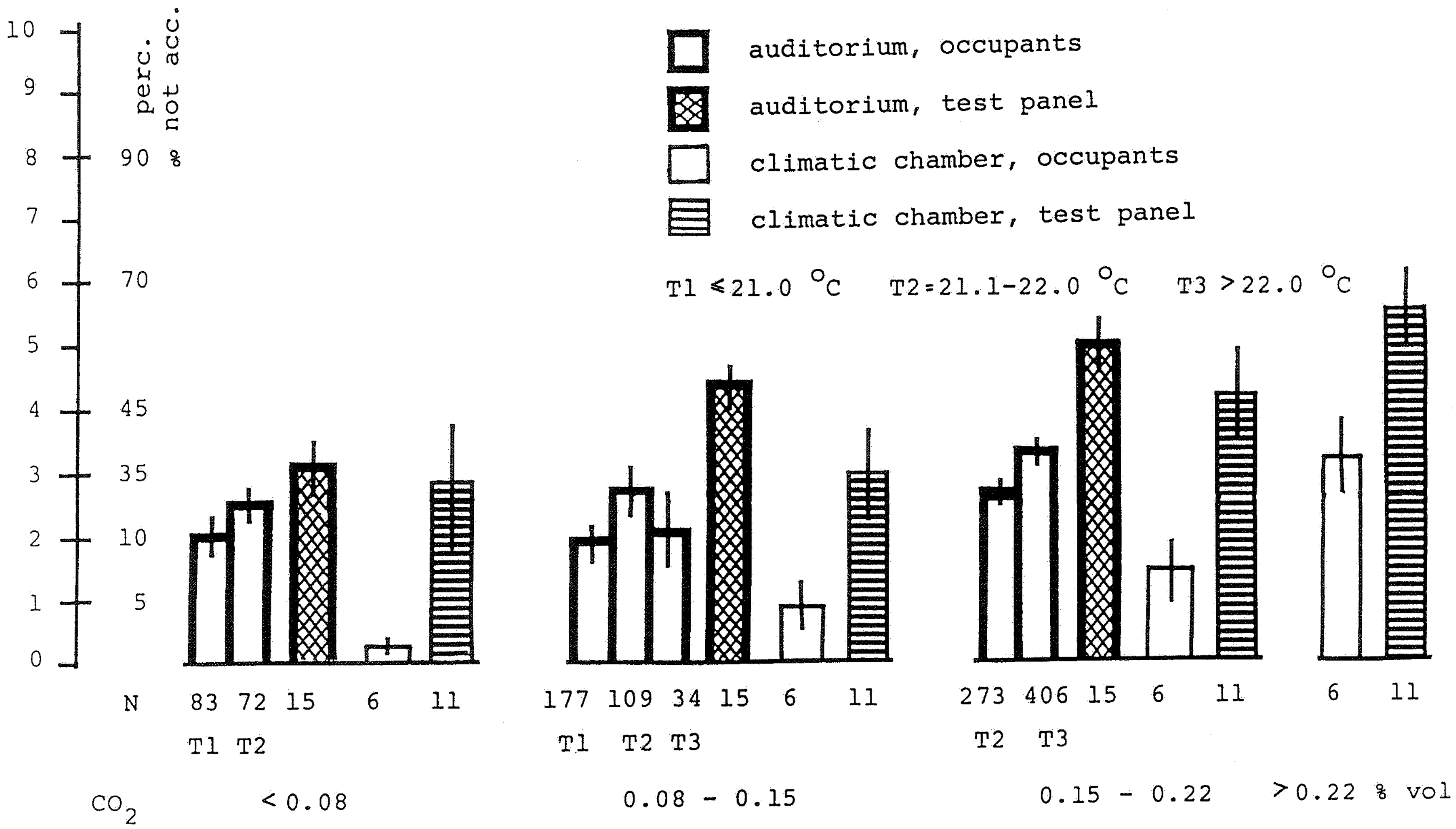

Figure 2: ANNOYANCE BY ODOURS (See table 3, question 3)

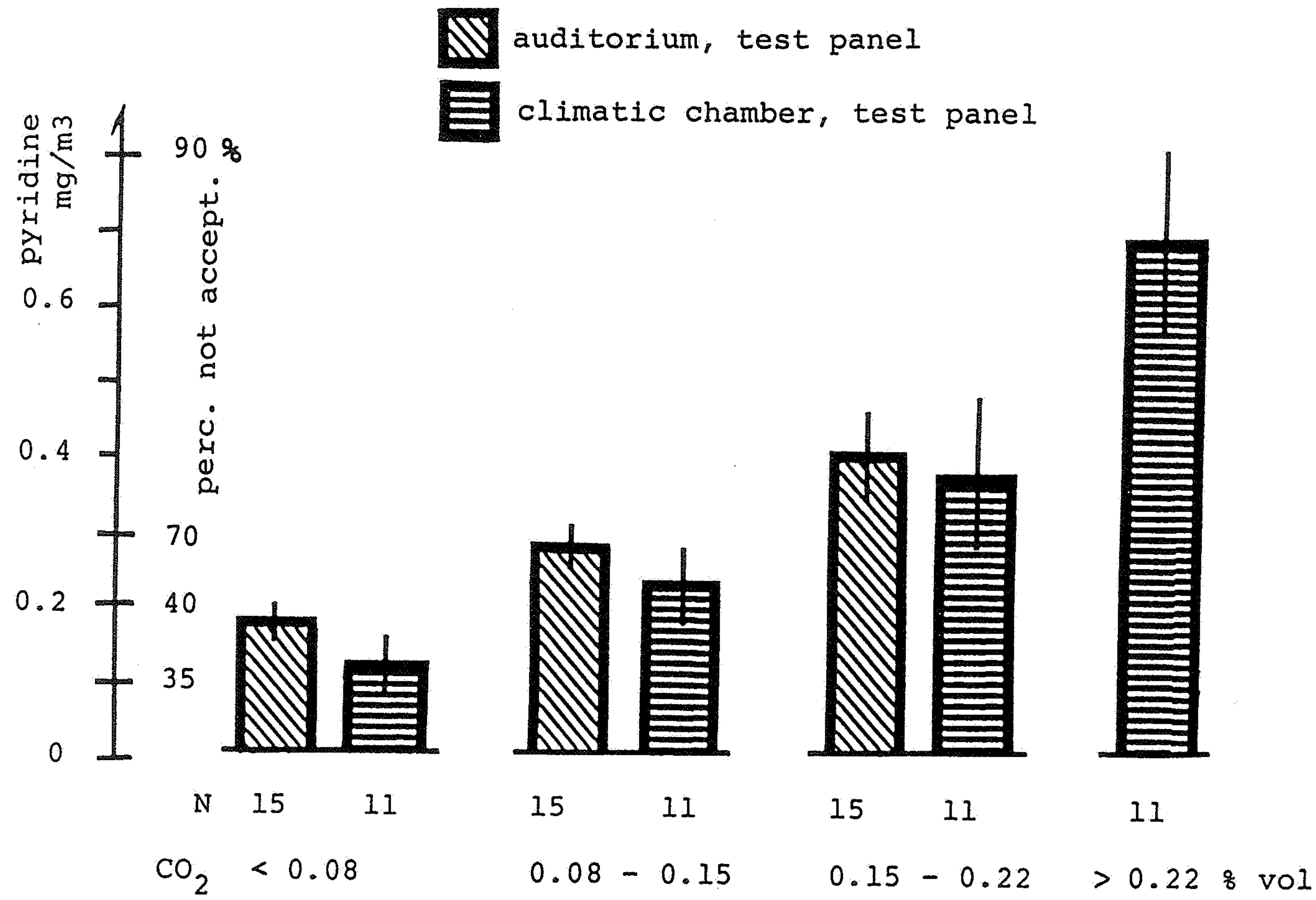

Figure 3: ODOUR INTENSITY (Reference odours)

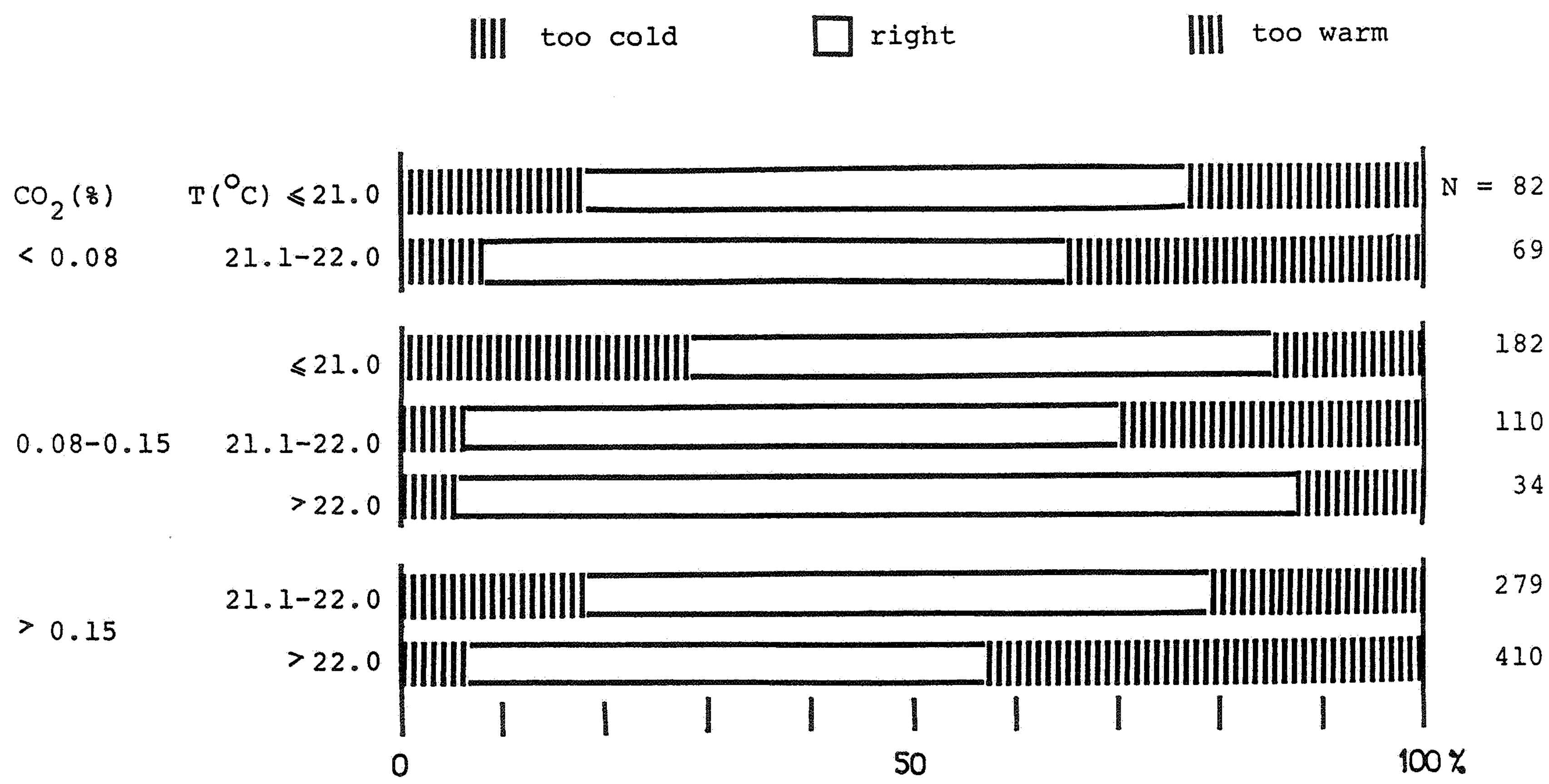

Figure 4: SUBJECTIVE PERCEPTION OF TEMPERATURE (see table 3, question 4)

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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PAPER 15

GRAVITY DRIVEN FLOWS THROUGH OPEN DOORS

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SYNOPSIS

Occupants can significantly influence both the heating energy requirements and the indoor air quality of a building by opening and closing doors and windows. If the effects of these actions are to be accurately estimated, both the quantity and character of these exchange flows must be determined. In this paper, data on gravity-driven exchange rates through open doors obtained from field experiments at the Alberta Home Heating Research Facility are compared with laboratory model simulations and theoretical predictions. Experimental results are presented which show that simple theoretical models provide both physical insight and an accurate estimate of air flow through doorways.

Tracer gas techniques and thermocouple arrays were utilized in full scale experiments to determine air exchange rates and gravity current frontal velocities. These tests were conducted over a range of indoor-outdoor temperature differences from 3°C to 45°C. Experiments were also performed using a 1:20 scale model with salt water mixtures to simulate indoor-outdoor temperature differences. In spite of a Reynolds number mismatch of a factor of 7, the model and full scale exchange flow rates and gravity current frontal velocities were in very good agreement when opening times were adjusted using a buoyancy time scale based on Froude number similarity.

NOMENCLATURE

Fr_f	frontal Froude number
g	local gravitational acceleration, m/s^2
g'	effective gravitational acceleration, m/s^2
H	opening height, m
K	door orifice coefficient
L	hallway length, m
Q_n	net flow rate, m^3/s
T_i	indoor temperature, °C
T_o	outdoor temperature, °C
t	time, s
t_{cr}	critical time at which steady flow begins to diminish, s
t_c	closing time from 90° to 0°, s
t_d	duration of decreasing flow, s
t_{eq}	equivalent opening or closing time, s
t_h	fully open hold time, s
t_o	opening time from 0° to 90°
t_s	duration of steady flow, s
U_f	frontal velocity, m/s
U_o	average inflow velocity at doorway, m/s
V	net volume exchange during one opening/closing cycle, m^3
V_c	net volume exchange during the closing period, m^3
V_{cr}	net volume exchange at time t_{cr}, m^3
V_d	net volume exchange during decreasing flow period, m^3
V_h	net volume exchange during the fully open period, m^3
V_H	room volume beneath a horizontal plane at height H, m^3
V_{max}	maximum net volume exchange, m^3
V_o	net volume exchange during the opening period, m^3
V_s	net volume exchange during the steady flow period, m^3
W	opening width, m

W_c	hallway width, m
ΔT	indoor-outdoor temperature difference, °C
$\Delta \rho$	indoor-outdoor air density difference, kg/m^3
Δ	fractional density difference
ρ	average indoor-outdoor density, kg/m^3
ρ_i	indoor air density, kg/m^3
ρ_o	outdoor air density, kg/m^3

1.0 INTRODUCTION

If you live in a northern climate you have probably been told at some time to shut the door because someone's feet were getting cold. Or, perhaps you have felt cool air-conditioned air flowing from open shop doors in a tropical location. In either case, a significant energy cost is associated with these flows. The distribution of indoor air contaminants can also be influenced by air flow through doorways, with important implications for clean room areas, hospital operating theatres and other similar applications. The advent of airtight residential construction methods has caused concern about maintaining adequate indoor air quality, a condition which is partially ameliorated by air flow through open doors and windows.

An understanding of both the quantity and characteristics of exchange flows is essential if proper energy estimates are to be made and if effective designs are to implemented. The long term goal is the developement of a comprehensive model for the prediction of air exchange. Toward this end, the authors conducted both full scale experiments and scale model simulations of air exchange flows through doorways. The primary objectives were to determine the essential information necessary for the construction of an air exchange prediction model, and to evaluate the accuracy and usefulness of scale modelling techniques.

In this report, our attention will be focused on the most important cause of air exchange through large openings in buildings, namely gravity-driven flow. Several simple models will be developed to predict gravity flows through doors and experimental methods will then be briefly described. Finally, some of the experimental data will be used to evaluate the proposed models.

2.0 AIR EXCHANGE THROUGH DOORWAYS

The transport of air through doorways can be caused by a number of different mechanisms. These include indoor-outdoor temperature difference, occupant motion, pumping action of the door, interior air circulation and wind generated turbulence. The total exchange depends on the magnitude of these various driving mechanisms and to some degree their interaction with one another.

Experimental results showed that gravity-driven air flow, caused by an indoor-outdoor temperature difference, is the dominant source of air exchange except at very small temperature differences. Gravity-driven flow is characterized by the flow of warm buoyant interior air out the top of the opening and flow of cold heavier exterior air in through the bottom. The flow rate depends on the height, width and thickness of the opening, and on the indoor-outdoor temperature difference. The total air exchange that occurs for a single door opening-closing cycle will depend on the flow rate, the amount of time the door is open, and in some cases the shape and volume of the interior space.

At the extreme of small temperature differences, gravity-driven flow is small and inertia driven flows, such as the pumping action of a door or the motion of an occupant, become dominant. Under these circumstances, the air transfer will depend entirely on factors such as how quickly the door is opened or how fast the occupant passes through the opening. For a given inertia force, there will always be a range of temperature differences for which the buoyancy and inertial forces are of the same order of magnitude. The results of our study show that simple superposition is inappropriate under these circumstances. Discussion of inertia driven flows in this report will be limited to situations in which they significantly affect the buoyancy flow regime.

3.0 GRAVITY-DRIVEN FLOW MODELS

3.1 Gravity-Driven Air Exchange During a Typical Door Cycle

Figure 1 illustrates the exchanged air volume as a function of time for an idealized door cycle. The curve represents the exchange process that occurs when a residential door is swung open, left open for some time and then shut. The interior could be an entry vestibule or large room. Four time periods have been identified.

- Opening Period (t_o)- This period begins with the initial motion of the door and ends with its arrival at a 90° open position. The exchange rate increases as the opening width enlarges.

- Fully Open Steady Flow Period (t_s)- Steady state flow persists until the door begins to close or until a finite interior volume causes a reduction in flow rate.

- Decay Period (t_d)- This period exists only if the flow rate decreases because of a finite interior volume.

- Hold Period (t_h)- The hold period is the total time that the door is open 90° or more, and is equal to t_s+t_d. If the door is not open long enough for the decay period to exist, then $t_d=0$ and $t_s=t_h$.

- Closing Period (t_c)- This period begins when the opening width starts to decrease because the door is closing. This period is the reverse of the opening period, beginning as the door passes the 90° open position and ending when it is fully closed. The volume exchanged during this period depends on both the decreasing opening size and on the steady state flow rate that exists when the door begins to close.

3.2 Steady Gravity-Driven Flow

When an indoor-outdoor density difference $\Delta\rho$ exists, it is possible to define an effective gravitational acceleration in terms of the fractional density difference and the local gravitational acceleration as,

$$g' = g\ (\Delta\rho/\rho) \qquad (1)$$

This effective gravitational force will cause steady counterflow through an open door or window at a rate of exchange given by Shaw[1] as,

$$Q_n = \frac{K\ W}{3}\ (g'H^3)^{1/2} \qquad (2)$$

All viscous effects such as surface drag and interfacial mixing are included in the orifice coefficient, K. The effect of interfacial mixing is to cause some of the outgoing warm air to be entrained by the incoming cold air, reducing the net exchange rate. The amount of interfacial mixing between the incoming cold air and the exiting warm air may be affected by the turbulence levels in both the indoor and outdoor reservoirs, and by the Reynolds number which governs shear induced mixing at the cold air - warm air interface. Once the coefficient K is determined, Equation 2 can be used to find the air exchange V_s, that occurs during the steady flow period.

3.3 Flow During Door Opening and Closing

Often, the coming and going of occupants occurs so rapidly that the door spends very little time in the fully open position and most of the exchange occurs while the door opens and closes. Is it possible to approximate the gravity-driven exchange that occurs during the opening and closing period by assuming quasi-steady flow?

For a door swinging at a constant speed, it is easy to show that the average opening width is $W(2/\pi)$. Integrating Equation 2 over the opening time t_o, results in,

$$V_o = \frac{K\ W\ 2/\pi}{3}\ (g'H^3)^{1/2}\ t_o \qquad (3)$$

Rather than thinking of this as flow through an average orifice of width $W(2/\pi)$ for a time t_o, it is more convenient to treat it as flow through an orifice of width W, for a reduced period of time, $t_o(2/\pi)$. With this in mind, Equation 3 is rewritten in terms of the net flow rate Q_n, and an equivalent time t_{eq}, which in this case is $t_o(2/\pi)$.

$$V_o = Q_n t_{eq} \tag{4}$$

The same approach can be applied to the closing period, so that $V_c=Q_n t_{eq}$, assuming that the opening and closing motions are identical, and that decreasing flow has not begun. It is important to take note of two assumptions made in the integration of Equation 2. First, that the fully open door orifice coefficient is the same for all door positions, and second that the startup time of the gravity flow is negligible. Experimental data will be used to assess the validity of these assumptions.

Often the opening and closing motions are similar, and the hold period is short enough that decreasing flow does not occur. In this case, the total gravity-driven exchange for the complete door cycle is given by

$$V = V_o + V_h + V_c = Q_n (t_h + 2t_{eq}) \tag{5}$$

If decreasing flow begins before the door starts to close, then the opening and closing exchange will not be the same and Equation 5 is not valid. In this case, the closing exchange must be determined independently from the opening exchange. The flow rate that is occurring at the moment the door begins close must be used rather than Q_n.

3.4 The Start Of Decreasing Flow Due To A Finite Interior Volume

Steady flow into a room of finite volume cannot last forever, and there must be some critical point at which the flow begins to decrease. The mechanism which determines when flow reduction begins is the return of a reflected gravity wave to the entry. Consider the simple, but none the less important case of flow into a long narrow room or hall from a door located at one end. The gravity current will flow down the length of the hall at a uniform velocity, strike the end wall and reflect back to the doorway. It is the arrival of this reflected wave at the doorway that signals the chocked flow condition that a limited interior volume exists.

The onset of decreasing flow is important because the justification for building a small enclosed entry is the potential energy savings associated with limiting the total possible amount of air transfer. The smaller the entry, the sooner the gravity wave returns to the door and the sooner the flow starts to diminish.

An estimate of gravity current frontal velocity in a long hallway can be made from classical lock exchange experiments by Benjamin[2]. For steady flow through an opening, given by Equation 2, the density current draft will advance along the floor of a long hallway of width W_c, at a frontal velocity of,

$$U_f = Fr_f^{2/3} \left[\frac{K}{3}\right]^{1/3} \left[\frac{W}{W_c}\right]^{1/3} (g'H)^{1/2} \tag{6}$$

It is reasonable to expect the frontal Froude number to lie near the counterflow critical value of $2^{-1/2}$ derived by Benjamin. For a hall of length L, the critical time t_{cr}, at which decreasing flow begins is simply determined as $2L/U_f$. This concept will be evaluated using the full scale and model frontal velocities, and exchange flow information determined experimentally. First, the measured frontal velocities will be compared to Equation 6, and then exchange data will be examined to determine if in fact, decreasing flow begins at a time equal to $2L/U_f$.

If the gravity current flows into an open room, the flow rate will probably not exhibit the sudden decrease in flow expected in the long hall case. Instead, it is likely that a smooth departure from steady flow occurs because a series of gravity waves return to the door as the gravity front reflects off numerous interior surfaces.

3.5 Predicting The Decreasing Flow Rate

The following assumptions are used to develop a simple expression for decreasing flow rate as the room fills with outside air.

- o The flow rate smoothly departs from steady flow at some critical time t_{cr}, and critical volume V_{cr}.
- o The ratio of steady state to actual flow is exponential in form.
- o The exchange volume approaches a maximum value V_{max}, at an infinite time.

Equation 7 satisfies these assumptions and boundary conditions.

$$V = V_{max} \left(1 - e^{-A(t-B)}\right) \tag{7}$$

$$\text{for} \quad t > t_{eq} + t_s$$

where

$$A = \frac{Q_n}{V_{max} - V_{cr}}$$

$$B = \frac{V_{cr}}{Q_n} + \frac{\ln\left(1 - V_{cr} / V_{max}\right)}{A}$$

It is obvious that the maximum exchange V_{max}, must be related to the room volume. Warm interior air is effectively trapped in the space between the top of the door and the ceiling. Therefore it is reasonable to expect that the maximum exchange will be approximately equal to the volume beneath this height H, defined as V_H. Experimental results will be examined to determine if in fact, the measured value of V_{max} is close to V_H, and how well Equation 7 predicts the decreasing flow process.

4.0 MEASURING AIR EXCHANGE FLOWS IN HOUSES

Air exchange through an exterior doorway was studied experimentally at the Alberta Home Heating Research Facility. The test house used in this study was a detached single storey wood frame structure with overall interior floor dimensions of 6.5 m x 7.1 m and an interior wall height of 2.4 m. Plastic sheets were used to seal the basement from the main floor to simplify the interior geometry. For some tests, a partition was erected to make the room into a closed hallway, 1 m wide and 7.1 m long, with the exterior door located at one end.

Air exchange through the 2.05 m high and 0.89 m wide exterior door was measured using SF_6 as a tracer gas. With the door closed, tracer gas was added to the room and mixed with fans until a uniform concentration was established. The mixing fans were then turned off and interior turbulence allowed to dissipate. Following this, the exterior door was opened at a selected swing speed, held open for a time and closed at the same swing speed. The door was driven by a electric door actuator and controlled by a computer, producing an accurate and repeatable door motion. The fans were then turned on again to mix the air. Knowing the interior volume, initial concentration and final concentration, it was possible to determine the net exchange. For a constant indoor-outdoor temperature difference, tests were repeated for varying door opening durations. The volume exchanged verses opening time curve was then constructed and its slope used to determine the steady state flow rate through the door. For all of the tests, the door swing speed was maintained constant and only the fully open time was varied.

Fast response thermocouples were also employed during these exchange tests to determine information about the flow structure. Two types of measurements were made. First, a horizontal line of thermocouples was located on the centerline of the hall configuration, 15 cm above the floor. Monitoring these thermocouples with a computer allowed the frontal velocity of the cold incoming air to be determined. Second, thermocouples were spaced 10 cm apart on the vertical centerline of the door opening to determine temperature profiles during the exchange.

5.0 LABORATORY MEASUREMENTS

The 1:20 scale model of the house was inverted and suspended from a load cell in a reservoir of fresh water. A computer controlled stepping motor drove a small door at varying door swing rates and fully open time intervals. With the door closed, the model was filled with a salt water solution. The density of the saline solution was selected to match the desired indoor-outdoor temperature difference to be simulated. When the door was opened, the denser saline solution poured from the model and was replaced by lighter fresh water, resulting in a weight variation throughout the exchange. This change in weight was monitored by rapidly sampling the load cell with a computer. The slope of the weight-time curve gave the net flow rate of the fresh water through the door into the model house.

The water filled model with its 15 times smaller kinematic viscosity had a Reynolds number 7 times smaller than the full scale flow. However, the use of water rather than air as the working fluid reduces the Reynolds number mismatch considerably. If the experiments had been done using air, the difference would have been a factor of 100.

A model of the hallway partition used in the full scale tests to measure density front velocities was constructed in the model. Fast response electrical conductivity detectors were used instead of the thermocouples employed in full scale, to measure the time dependent position of the density front as it passed along the floor of the model house.

6.0 TEST RESULTS

Selected full scale and model results will now be used to evaluate the flow models discussed in the previous sections. Our attention will be focused on answering the following important questions.

- What orifice coefficient should be used for an open door?
- Can a quasi-steady flow approximation be used during door opening and closing?
- Is it the return of a reflected gravity wave that informs the flow through an open door that a finite interior volume exists?
- If decreasing flow starts, does it decay exponentially and what is the maximum volume that can be exchanged assuming that interior circulation fans are not operating?

6.1 Steady State Gravity-Driven Flow

Some of the steady flow data from both full scale and model tests are shown in Figure 2. The theoretical curve given by Equation 2, using a door orifice coefficient of $K=0.6$, is also shown. With this orifice coefficient, the model data is in very good agreement with the theoretical prediction. Because the full scale flow rates were computed from a series of tests at varying opening times, the larger scatter in the full scale measurements is not surprising.

It is apparent from Figure 2 that the full scale results are consistently lower than the model predictions for a given temperature difference. If the orifice coefficient is correlated with temperature difference as shown in Figure 3, we find that the model value is $K=0.6$ for the entire test range, compared to the full scale results which correlate well with,

$$K = 0.40 + 0.0045\ \Delta T \tag{8}$$

A comparison of full scale temperature profiles measured at the opening, with model salinity profiles at the same location reveals an important fact. At large density differences both the full scale and model flows exhibit relatively little interfacial mixing across the counterflow interface. This is indicated by a steep gradient in temperature and salinity at the respective interfaces. At smaller density differences, the full scale flow showed increased interfacial mixing, as indicated by a more gradual variation in temperature. The model however, showed no significant increase in mixing at smaller density differences. Interfacial mixing causes transfer of inbound outdoor air into the outflow stream and a corresponding transfer of outbound indoor air into the inflow stream, thereby reducing the net exchange rate. The decrease in magnitude of the full scale orifice coefficient is therefore a direct result of an increasing level of interfacial mixing. This is why K depends on temperature difference.

Why is there less interfacial mixing in the model compared to the full scale case? One possible answer to this question is the Reynolds number mismatch. The lower Reynolds number in the model suggests that its flow regime is more stable, implying reduced interfacial mixing.

6.2 Gravity-Driven Exchange During Door Opening and Closing

It is possible to evaluate the assumption of quasi-steady flow while the door is opening and closing by examining data obtained with a very short hold time. Figure 4 shows full scale exchange volumes for a hold time of 0.5 s and a swing time of 3.75 s. Equation 5, which was developed on the basis of quasi-steady flow, is also shown. The agreement is very good down to about 4°C, at which point pumping exchange caused by the swinging door begins to make a small contribution to the total exchange volume. Clearly, pumping exchange can be neglected for all but the smallest temperature differences.

Model data similarly confirmed the accuracy of the quasi-steady flow assumption for the opening and closing period. It should be noted that the factor of $2/\pi$ is specific to the case of a constant swing speed door and can be derived for other swing motions or other types of doors.

6.3 Wave Return Time

If the door is open for a short period of time, or if the flow is entering into a very large room, the flow rate will probably not begin to diminish before the door closes. However, long durations and small rooms are often involved, and determining the time at which decreasing flow begins becomes important. In this section it will be shown that this critical time is dependent on gravity wave return time.

Figure 5 illustrates some hallway frontal velocities from both model and full scale experiments. The agreement between the model and full scale data is remarkably good and strongly supports the $20^{1/2}$ time scale obtained from Froude number similarity scaling. Unlike net flow rate, which has been shown to depend on mixing and entrainment, gravity current frontal velocity is unaffected by its entrainment rate as shown by Simpson and Britter[3]. This explains how it is possible for the model and full scale flow rates to differ at small temperature differences, while their frontal velocities agree so well.

A frontal Froude number of 0.75 provides that best theoretical fit to the data over the entire range, this is close to the expected value of 0.71 for pure counterflow. It is particularly interesting to note the excellent agreement between the model and full scale results at the small temperature differences. Here the scale model tests do better at predicting full scale frontal velocities than the inviscid theoretical prediction.

We now turn our attention to the question of wave return time and decreasing flow. Figure 6 shows some of the exchange volume data as a function of time for the long room geometry. This data is plotted so that results from a wide range of temperature differences collapse onto the same curve. Using Equation 6, a frontal Froude number of 0.75, and the assumption that the critical time equals $2L/U_f$, allows an estimate to be made of the critical time when departure from steady flow will occur. Substituting the physical dimensions of L=7.1 m and W_c=1 m, results in the predicted departure point indicated on Figure 6. A more accurate prediction of the departure point could not be hoped for. This result strongly confirms that the flow rate begins to decrease when the gravity wave has traveled down the length of the hall and back to the door at frontal speed U_f. The data also exhibits the rather sudden change in slope expected a the return wave uniformly at the door.

6.4 Predicting Decreasing Flow

From Figure 6 it is apparent that the exchanged volume does approach a maximum value as expected. Equation 7 was proposed to describe the volume exchange between the time of departure from steady flow until a maximum exchange has occurred or until the door begins to shut. Equation 7 is shown in Figure 6 with best fit values of $V_{cr}=8.0\ m^3$ and $V_{max}=19.2\ m^3$. This function underpredicts the departure point slightly because of the forced boundary condition of smooth transition from steady flow, however it still provides a good fit to the data. The best fit value of $V_{max}=19.2\ m^3$, is slightly larger than the theoretical maximum value of $V_H=17.8\ m^3$. This is reasonable, because it is likely that entrainment causes some of the buoyantly trapped air above height H to be mixed down to participate in the exchange.

From these results we see that the flow begins to decrease when about half of the theoretical volume is exchanged and continues until the entire amount is replaced with exterior air. This estimate can be used for most interior geometries with reasonable accuracy.

7.0 A COMPLETE GRAVITY-DRIVEN FLOW MODEL

We are now in a position to estimate the gravity-driven exchange given the house dimensions, temperature difference and the door motion.

First it must be determined if departure will occur before the door closes. If so, Equation 7 can be used with the generalized results from the last section to determine the total exchange, including opening and closing contributions. If departure does not occur then Equation 5 applies.

Combining the information obtained in these experiments, the following simplified calculation for estimating gravity-driven exchange volumes for simple interiors is given. For a given problem the following must be provided;

$$T_i,\ T_o,\ W,\ H,\ t_o\ (=t_c),\ t_h,\ V_H$$

Then calculate;

$$\Delta = \Delta\rho/\rho = 2\ (T_i - T_o)\ /\ (T_i + T_o) \qquad \text{(T in degrees kelvin)}$$

$$\Delta T = 295\Delta\ /\ (1 + \Delta/2) \qquad \text{(22°C indoor reference temperature)}$$

$$K = 0.4 + 0.0045\Delta T$$

$$t_{eq} = (2/\pi)\ t_o \qquad \text{(only for constant swing speed)}$$

$$Q_n = K\ (gW^2H^3/9)^{1/2}\ \ \Delta^{1/2}$$

$$t = 2t_{eq} + t_h$$

The gravity-driven exchange is found using;

If $Q_n\ t\ /\ V_H > 0.5$ then $V = V_H\ (1 - e^{-A(t-B)})$

where $A = 2Q_n\ /\ V_H$

$B = (0.5\ V_H/Q_n) - 0.69/A$

If $Q_n\ t\ /\ V_H < 0.5$ then $V = Q_n\ t$

CONCLUSIONS

Some of the questions concerning the nature of gravity-driven flow through doorways have been answered in this report. Experimental data obtained at the Alberta Home Heating Research Facility and from laboratory simulations, supports the proposed theoretical models designed to estimate gravity-driven air exchange through doorways.

The reader should however be cautioned, the model can only be expected to provide reasonable estimates of air exchange if conditions are similar to those tested here. For example, inertial effects, which are of particular importance at small temperature differences, have not yet been accounted for in the model. Increased interior or exterior turbulence levels may cause substantially increased interfacial mixing, dramatically altering the door orifice coefficient and net flow rate. The presence of an occupant in the opening causes a blockage, reducing gravity-driven flow, an effect totally unaccounted for as of yet. Fortunately, in many applications these effects will be small and the proposed model will produce a good estimate.

ACKNOWLEDGEMENTS

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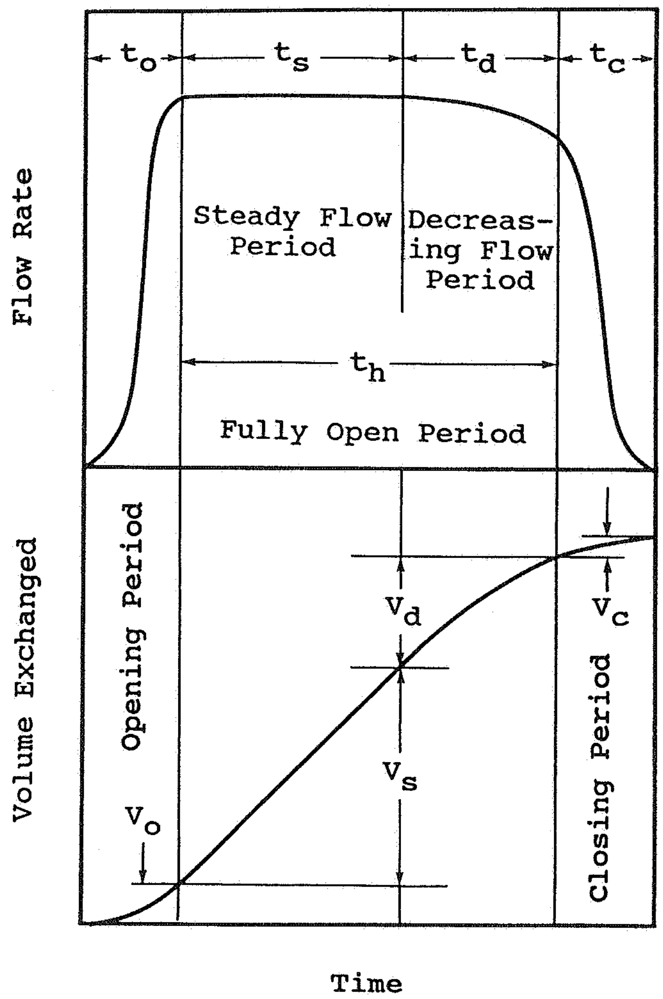

Figure 1: Idealized flow rate and volume exchange for a typical door cycle.

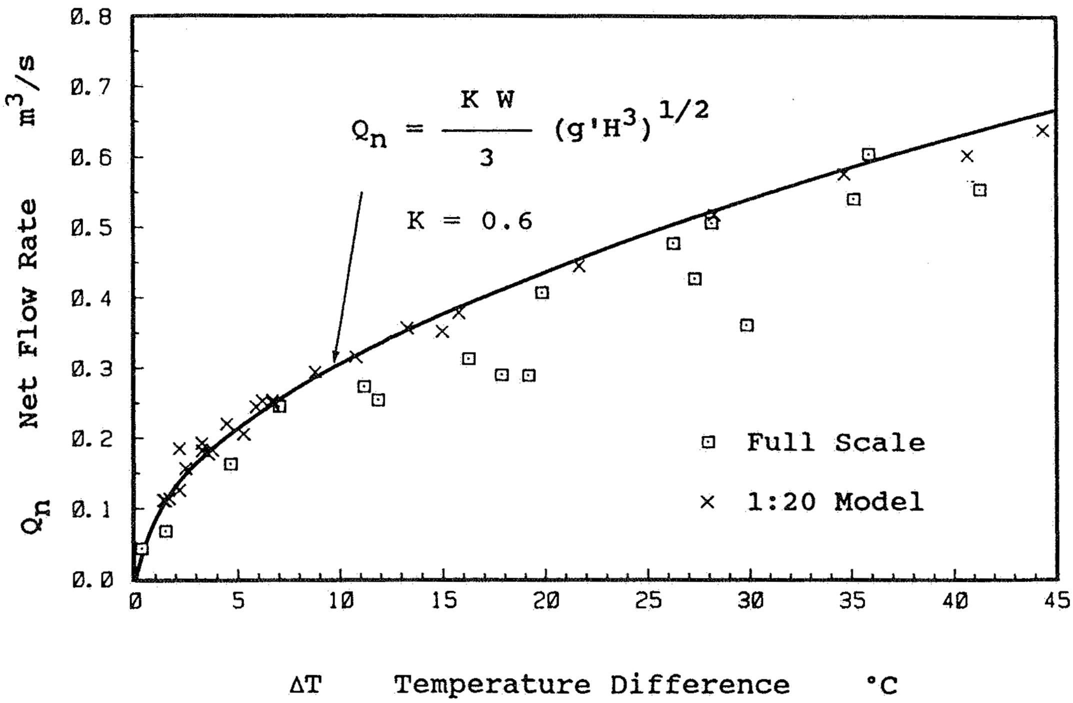

Figure 2: Comparison of model and full scale steady state flow rate variation with temperature difference.

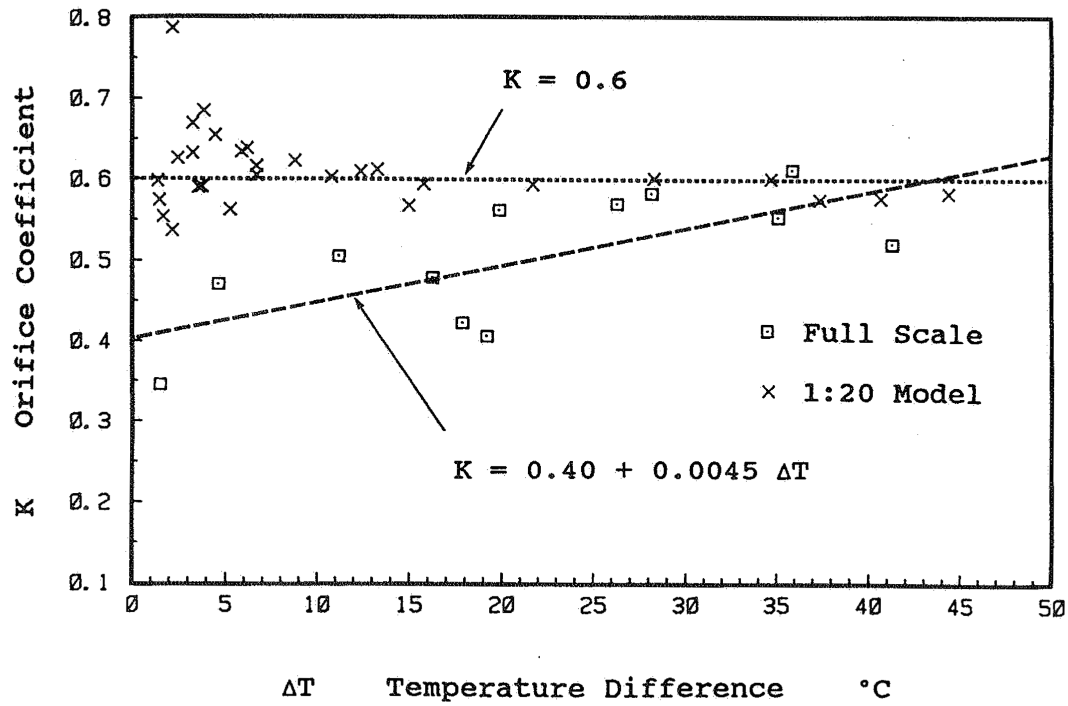

Figure 3: Comparison of model and full scale door orifice coefficient variation with temperature difference.

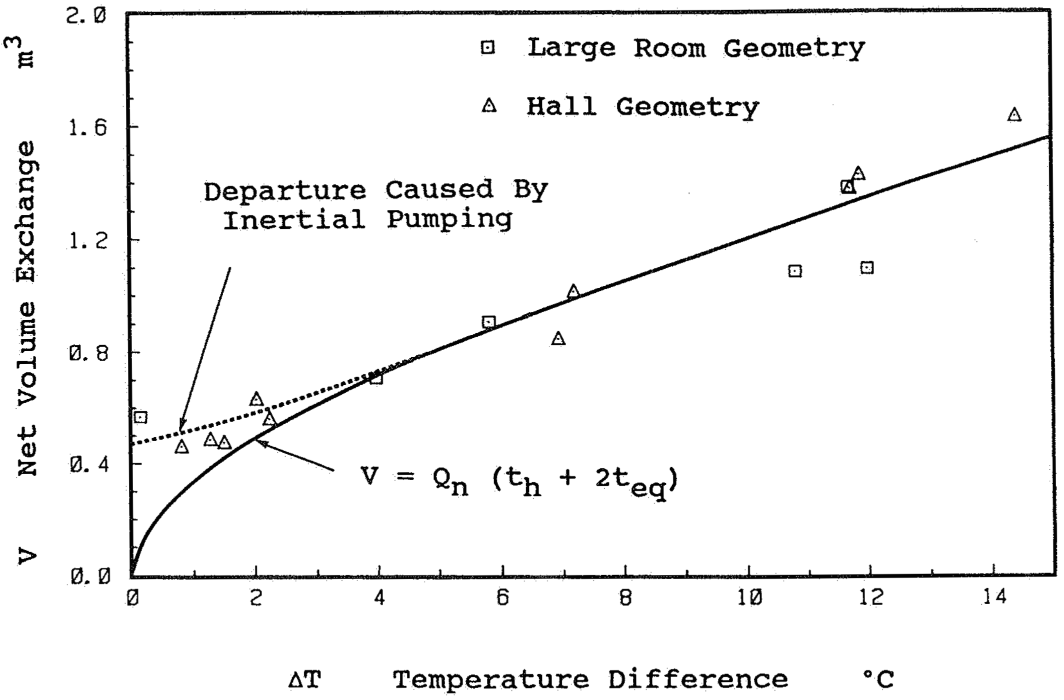

Figure 4: Correlation of short duration exchanges with temperature difference to test quasi-steady flow assumption, t_o = 3.75 s, t_c = 3.75 s and t_h = 0.5 s.

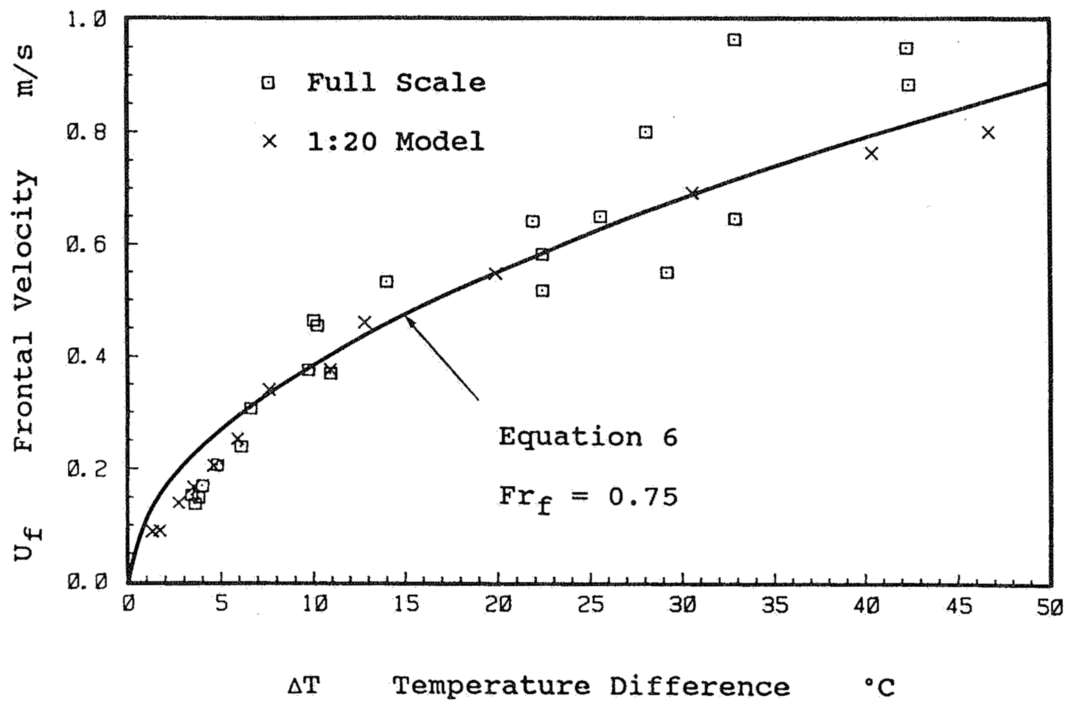

Figure 5: Comparison of model and full scale hall frontal velocity variation with temperature difference.

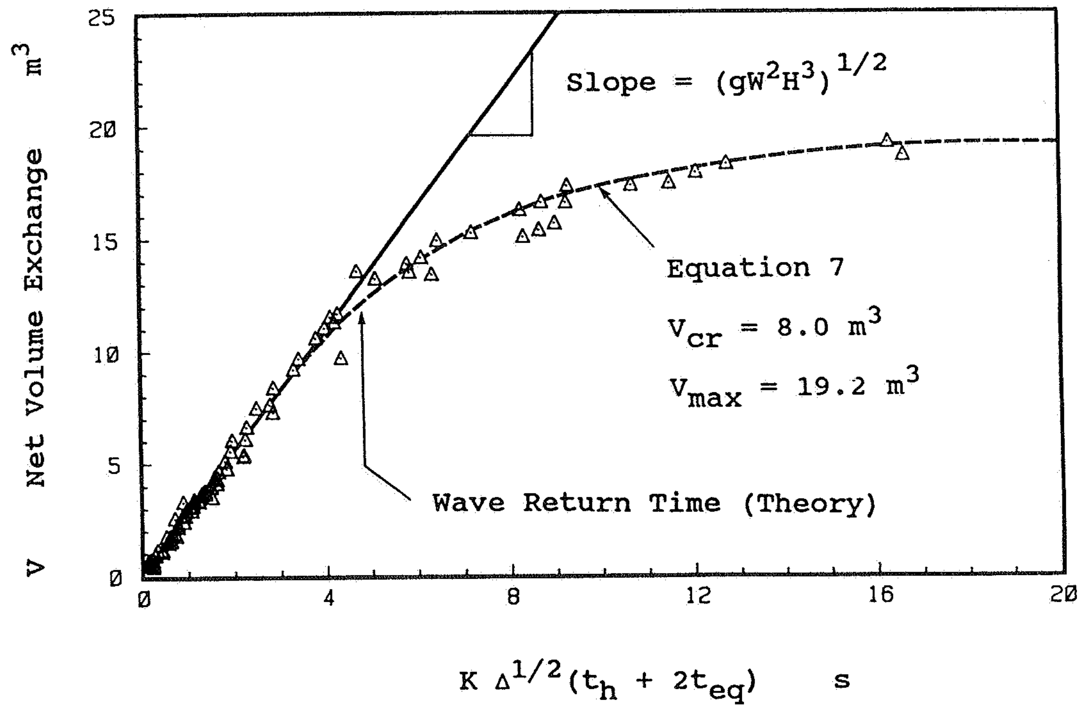

Figure 6: Critical departure time and decreasing flow for the hall geometry.

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
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PAPER 16

THE USE OF PASSIVE VENTILATION SYSTEMS FOR CONDENSATION CONTROL IN DWELLINGS, AND THEIR EFFECT UPON ENERGY CONSUMPTION

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SYNOPSIS

The need for reduced energy consumption has led to an overall decrease of air infiltration rates in buildings, particularly in dwellings. Unfortunately, this has given rise to a significant number of problems involving condensation, with resulting damage to the structure and contents of affected buildings. Various means of condensation control are available. The use of a passive ventilation system to achieve this aim has several attractions, not the least of which is that the occupants of houses fitted with such a system need little, if any, knowledge of the principles involved, or instruction in its use, to derive maximum benefit.

This paper describes a program of work which compares the performance of a passive ventilation system, installed in the kitchen and bathroom of a house of timber framed construction, in comparison with the use of mechanical extraction, window head ventilators, and opening of windows, as alternative means of ventilation. Particular emphasis is placed upon the influences of wind speed and wind direction. Using the ventilation rate measurements in conjunction with dry and wet bulb temperature data, rates of moisture extraction due to the four different means of ventilation are calculated, and the effects upon condensation risks are assessed in the light of predicted minimum ventilation rates required to avoid condensation. Comparison of predicted minimum and measured ventilation rates leads to the estimation of the effect of each type of ventilation upon space heating energy consumption.

1. INTRODUCTION

Modern domestic energy conservation techniques have led to increases in both the thermal resistance and air tightness of the typical building envelope. The effect of increasing air tightness is to reduce the whole house ventilation rate, and hence to generally increase the moisture content of the air inside the house. The danger of condensation on cold surfaces within the occupied space is thus greatly increased. Considering that up to 12 kg of water can be released inside a house in a day[1], it is clear that some provision for removal of water vapour directly from areas of high production rate (for example, kitchen and bathroom) would be highly desirable. Several methods have been suggested, for instance extraction fans and dehumidifiers.

One method of moisture extraction which has recently been put forward as a means of reducing condensation problems in the United Kingdom is the use of passive ventilation systems[2]. (It should be acknowledged that such systems have been in use in the rest of Europe for a signficiant length of time). Such systems use ductwork, terminating at roof level, to provide direct extraction of air from areas of high moisture production: temperature induced buoyancy effects (the so-called "stack effect") and wind induced suction effects provide the driving force for extraction. The use of a passive ventilation system has several advantages: prominent among these are that the occupants of a house fitted with such a system can derive full benefit from its presence with no instruction in its use, and also that maintenance costs on such a system are negligible with mechanically driven alternatives.

The purpose of this paper is to briefly compare the performance of a passive ventilation system with three alternative methods, namely mechanical extraction by wall mounted fans, window head slot ventilators, and window opening: the effects of wind speed and wind direction difference are also demonstrated. The ventilation rates produced by each method of extraction are compared with a predicted minimum ventilation rate for condensation avoidance, and thus the effect of each type of method of ventilation is assessed. In addition, multiple tracer gas measurements have been used to measure the airflows, to and from areas of high moisture production, associated with each method of ventilation.

2. ASSESSMENT OF SIGNIFICANCE OF COMPONENTS OF PASSIVE VENTILATION DUCT FLOW

As has mentioned previously, the principle of passive ventilation relies upon the stack effect and wind-induced suction effects. At this juncture, it would be useful to assess the likely order of magnitude of the contribution of each mechanism to the overall passive ventilation effect. For the calculations described below, it is assumed that house air is at 50% relative humidity at 20°C, whilst outside air is at 100% relative humidity at 0°C.

Let us first consider the contribution of the stack effect. The maximum available pressure difference for buoyancy driven airflows in a duct (in Pascals) is given by:

$$Pb = (Do-Dh).h.g. \qquad (1)$$

where

Do = air density at outside temperature = 1.2853 kg/m³.
Dh = air density at room temperature = 1.1906 kg/m³,
g = acceleration due to gravity (9.81 m/s²),
and
h = vertical duct length (metres)

The presence of a moving air stream across the duct discharge induces a velocity pressure, which can be given simply by:

$$P_V = \tfrac{1}{2}\, do.V^2 \qquad (2)$$

where V = velocity of the air stream (m/s)

The relative sizes of the two contributions are shown in Table 1, for both the kitchen and bathroom ducts. It can be seen that the contribution due to stack effect is likely to be smaller than the wind-induced component for both ducts. It should also be borne in mind that:

(a) these calculations do not take into account wind direction or the geometry of the duct termination unit at roof level;

(b) the overall flow through a duct of a given length and cross-section will be influenced by resistance effects.

Both of these two considerations will be discussed later on in this paper.

3. EXPERIMENTAL

(a) Details of test house

The house used for the site measurements is situated at Willow Park, near Chorley, and is part of the Central Lancashire New Town Development. It is a four bedroom detached residence, of timber frame construction, and is built to a special low energy design[3]. Figure 1 shows the plan layouts of the two floors of the house, together with an artist's impression of the exterior. It can be seen that, in addition to the bathroom, there is also an en-suite adjacent to the master bedroom. A passive system was fitted in this en-suite, with a view to further work, but was sealed off during this investigation. The whole house volume is approximately 320 m³, of which the kitchen and bathroom comprise approximately 34 m³ and 13 m³ respectively.

The passive ventilation ductwork installed in the test house is of 150 mm x 100 mm rectangular cross-section. It is fabricated from UPVC, and is supplied complete with factory-applied rigid foam insulation, in order to minimise the risk of condensation within the duct itself during use. The ductwork layout used is shown in Figure 2. The terminals used are Glidevale type G5 tile ventilators, situated two-thirds of the way up the roof. Each ductwork system is connected to its terminal by means of a length of fibreglass insulated 100 mm diameter flexible duct. Each of the duct systems is terminated at ceiling level by means of a rectangular grille of adjustable open area.

(b) Measurement details

The ventilation and air movement measurements carried out during this investigation were performed using the multiple tracer gas apparatus developed at UMIST. This technique is well documented (see for example reference (4)) and will not be described here. With regard to ventilation measurements, tests were performed under the following sets of conditions for both the bathroom and kitchen:

i) No passive ventilation, windows and trickle ventilators closed;

ii) As per (i), but with trickle ventilators open;

iii) As per (i), but with windows open 2";

iv) Passive ventilation, windows and trickle ventilators closed;

v) As per (iv), but with trickle ventilators open;

vi) As per (iv), but with windows open 2".

Doors are closed, unless specifically mentioned. In addition to these single-cell tests, a handful of measurements were made of the two-way airflows between the kitchen and the rest of the ground floor, for various ventilation regimes. Duct air velocities, inside/outside temperatures and wind speed and direction were also monitored.

4. RESULTS AND DISCUSSION

Measured ventilation rate values, together with other relevant data, are presented in Table 2 (kitchen), and Table 3 (bathroom): two-way airflow values between kitchen and the rest of the house are shown in Table 4. From the data sets, the following points can be discerned:

(a) The passive ventilation system used is sensitive to wind speed and direction. From Table 2, it can be seen that an increase in wind speed from 2 m/s to 5 m/s from the West has the effect of raising the air velocity in the kitchen duct by between 27% and 40%, depending on room conditions. Table 4 shows that a south westerly wind gives an appreciable increase in kitchen duct flow rate: a 3.5 m/s south westerly wind gives a flow rate of 16.2 m^3/hr for the duct and trickle vent combination, compared to the 8.1 m^3/hr flow rate measured under a 5 m/s westerly wind. Bearing in mind that the house ridge runs east-west, it is probable that the reason for this increase is that the system terminal is under greater suction for a south westerly wind than for a westerly. From this observation, it might be inferred that certain wind directions might actually reduce the performance of the system: however, this study did not collect sufficient data to confirm or disprove this theory.

(b) Comparing Table 2 with Table 3, it can be seen that the bathroom duct outperforms the kitchen duct for a given wind speed and direction. For instance, for the case of a 2 m/s westerly wind, the bathroom duct gives an extraction rate which is approximately 40% greater than that of the kitchen duct. Such results are in direct conflict with the findings of Johnson et al.[2], who claim that a kitchen duct will consistently outperform a bathroom duct, due to the enhanced buoyancy effects present in the former case. It is the contention of the authors of this paper that (especially in view of the small temperature differences and duct sizes involved) the greater resistance to flow of the longer kitchen duct is far more dominant a factor than the increased stack effect, and hence the shorter bathroom duct should outperform the kitchen duct. To underline this point, it should be noted that, at a length of 3 m, the bathroom duct used during this study is 40% shorter than the 5 m long kitchen duct.

(c) Table 4 demonstrates the effect of having the kitchen door open. Whilst it cannot be denied that having the door open greatly increases the kitchen flow rate, it is also quite clear that this practice also leads to the migration of large amounts of moist kitchen air to the rest of the house. In view of the fact that the purpose of the passive ventilation duct is to remove moisture at source, it therefore follows that the practice of leaving the kitchen door open is ill-advised.

Aside from the above points, a particularly worrying discovery was made during this study. At wind speeds in excess of 9 m/s, the flow direction in the ducts actually reversed: in other words, the passive ducts were providing an inflow of air into the house. This discovery obviously puts a big question mark against the usefulness of passive systems at higher wind speeds. Further investigations are planned: at the moment, it is thought that this flow reversal is a function of the aerodynamic characteristics of the tile ventilator used. One suggestion which has been made is to make use of a ridge tile ventilator as a termination device. Unfortunately, the authors have shown[4] that flow reversal takes place in ridge tile ventilators at higher wind speeds, which is quite surprising in the light of the popular opinion that ridge tile ventilators are always in a state of suction.

5. ENERGY IMPLICATIONS OF DIFFERENT VENTILATION METHODS

At this point, it is appropriate to give some brief mention of the likely order of magnitude of minimum ventilation rate required in order to avoid surface condensation, and, in addition, to examine the energy penalties incurred by the use of the different ventilation regimes considered during this study. According to Meyringer [5], for a house of approximately 300 m^3 volume, with 3 or 4 occupants producing 12 kg of moisture per day, the minimum ventilation required to avoid surface condensation is likely to lie between 65 to 85 m^3/hr, corresponding to a whole house air change rate of between 0.22 to 0.28 ach. However, considering that the kitchen and bathroom are almost certain to be the areas of maximum moisture production, it is more appropriate to express individual minimum ventilation rates for these two rooms.

Taking the case of the kitchen, and assuming a daily moisture production of 6 kg, a minimum kitchen ventilation rate of between 0.96 and 1.25 ach is required, corresponding to a volume flow rate of between 32.5 to 42.5 m^3/hr. Similarly for the bathroom, assuming a daily moisture production rate of 2 kg, a minimum bathroom ventilation rate of between 0.85 and 1.1 ach is required, that is, a volume flow rate of between 11 and 14 m^3/hr. Examination of Tables 2 and 3 shows that use of a passive system in the kitchen gives ventilation rates of between 0.84 and 1.17 ach, whilst the bathroom system provides a ventilation rate of the order of 1.04 ach. Therefore, it can be seen that, under the test conditions experienced during this study, the use of a passive system should, in most cases, give a background ventilation rate which is adequate to prevent surface condensation.

Finally, Table 5 shows the ventilation energy penalties associated with various means of ventilation, together with an assessment of whether a specific method would satisfy the minimum ventilation criteria for the avoidance of surface condensation in the test house, as set out above. The quoted values are calculated on the basis of the energy required to heat the replacement air, at 0°C with 100% RH, to 20°C, with 60% RH. Two main points emerge: firstly, window head trickle ventilators fail to provide the necessary minimum ventilation rates in both the bathroom and kitchen: and secondly, the use of passive systems would appear to provide a very energy efficient means of moisture control for the test conditions experienced.

6. CONCLUSIONS

(1) The results obtained during this study would appear to indicate that under the test conditions experienced, the use of the passive systems provides a satisfactory, energy efficient means of condensation control.

(2) However, the study has shown that the systems are extremely sensitive to wind fluctuations, both in speed and direction. Because of this, the authors are far from convinced that the passive system used during this study would provide the minimum ventilation rates necessary to avoid surface condensation over the whole range of wind conditions likely to be experienced during day to day use. In particular, the phenomenon of flow reversal at higher wind speeds gives great cause for concern.

(3) The practice of leaving doors open in order to increase duct flow rates is not to be recommended, since it encourages the migration of warm, moist air to other parts of the house.

(4) In view of the possibility of a requirement for some form of passive ventilation provision becoming enshrined in the Building Regulations, it is essential that a far more broad based, extensive study of the operation of passive ventilation systems of differing configurations is carried out, with the intention of both identifying the optimum design, and quantifying the optimum performance which can be achieved.

(5) It is felt that particular attention should be given to roof terminator design, in order to produce a terminator which avoids flow reversal at higher wind speeds, satisfies existing rain penetration criteria, whilst fulfilling the requirements of architectural aesthetics.

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Duct Length	Pressure induced bystack effect[Pa]	Wind induced pressure m/s Pa		
		2	4	6
1	0.93	2.57	10.28	23.14
3	2.78	"	"	"
5	2.78	"	"	"
7	6.51	"	"	"

TABLE 1

Pressure components in duct system due to stack effect and windspeed.

Conditions	N_K ACH	N_K m³/hr	Duct Flow m/s	Duct Flow m³/hr	% of N_K due to duct		Speed (m/s)	Direct.	Δ T°C
All sealed	.23	7.82	-	-	-	-	2	W	11
Trickle vents open	.59	20.06	-	-	-	-	2	W	12
Duct and trickle vent open	.84	28.56	0.11	5.9	20.7	-	2	W	12
Duct and windows 2"	3.00	102.00	0.15	8.1	7.9	-	2	W	12
Duct open only	.37	12.58	0.10	5.4	42.9	-	2	W	12
Windows open 2" only	2.57	87.38	-	-	-	-	2	W	12
All sealed	.31	10.54	-	-	-	-	5	W	13
Trickle vents open	.63	21.42	-	-	-	-	5	W	13
Duct and trickle vent open	1.17	39.78	0.15	8.1	20.3	-	5	W	12
Duct and windows 2"	3.67	124.78	0.25	13.5	10.8	-	5	W	12
Duct open only	.53	18.02	0.14	7.6	42.2	-	5	W	12
Windows open 2" only	2.74	93.16	-	-	-	-	6	W	13

TABLE 2 : Results for kitchen ventilation tests

Conditions	N_B ACH	N_B m³/hr	Duct flow m/s	Duct flow m³/hr	% of N_B due to duct	Wind Speed (m/s)	Wind Direct.	Δ T°C
All sealed	.35	4.55	-	-	-	2	W	14
Trickle vent open	.58	7.54	-	-	-	2	W	14
Duct and trickle vent open	1.04	13.52	.16	8.6	63.6	2	W	14
Duct and windows 2"	3.19	41.47	.24	12.9	31.1	2	W	14
Duct open only	1.03	13.39	.15	8.1	60.5	2	W	14
Windows open 2"	2.72	35.36	-	-	-	2	W	14

TABLE 3 : Results for bathroom ventilation tests

Conditions	N_K ACH	N_K m³/hr	N_H ACH	N_H m³/hr	$F_{K H}$ m³/hr	F_{H-K} m/s	Duct flow m/s	Duct flow m³/hr	Wind Speed (m/s)	Wind Direct.	T°C
Door shut, trickle vents open	.55	18.7	.20	64.0	10	10	-	-	3.5	SW	13
Door open, trickle vents open	1.29	43.9	.23	73.6	35	40	-	-	3.5	SW	13
Kitchen duct open, trickle vents open, door shut	1.12	38.1	.24	76.8	10	10	0.30	16.2	3.5	SW	13
Kitchen duct open, trickle vents open, door shut	3.00	102.0	.22	70.4	77	100	0.55	29.7	3.5	SW	13

TABLE 4 : Two-way flows between the kitchen and the rest of the house

ROOM	METHOD OF VENTILATION	VENTILATION RATE (m^3/hr)	ENERGY CONSUMPTION (KW)	MINIMUM RATE ACHIEVED
Kitchen	Window head Vents open	20	0.25	No
	Passive vent + Window vents	34	0.42	Yes
	Kitchen windows open	89	1.1	Yes
	Extract fan	100	1.23	Yes
Bathroom	Window head vents	7.5	0.1	No
	Passive vent & Window vents	13.5	0.17	Yes
	Bathroom window open	35.5	0.43	Yes
	Extract fan	100	1.23	Yes

TABLE 5 : Ventilation energy penalty for different ventilation methods

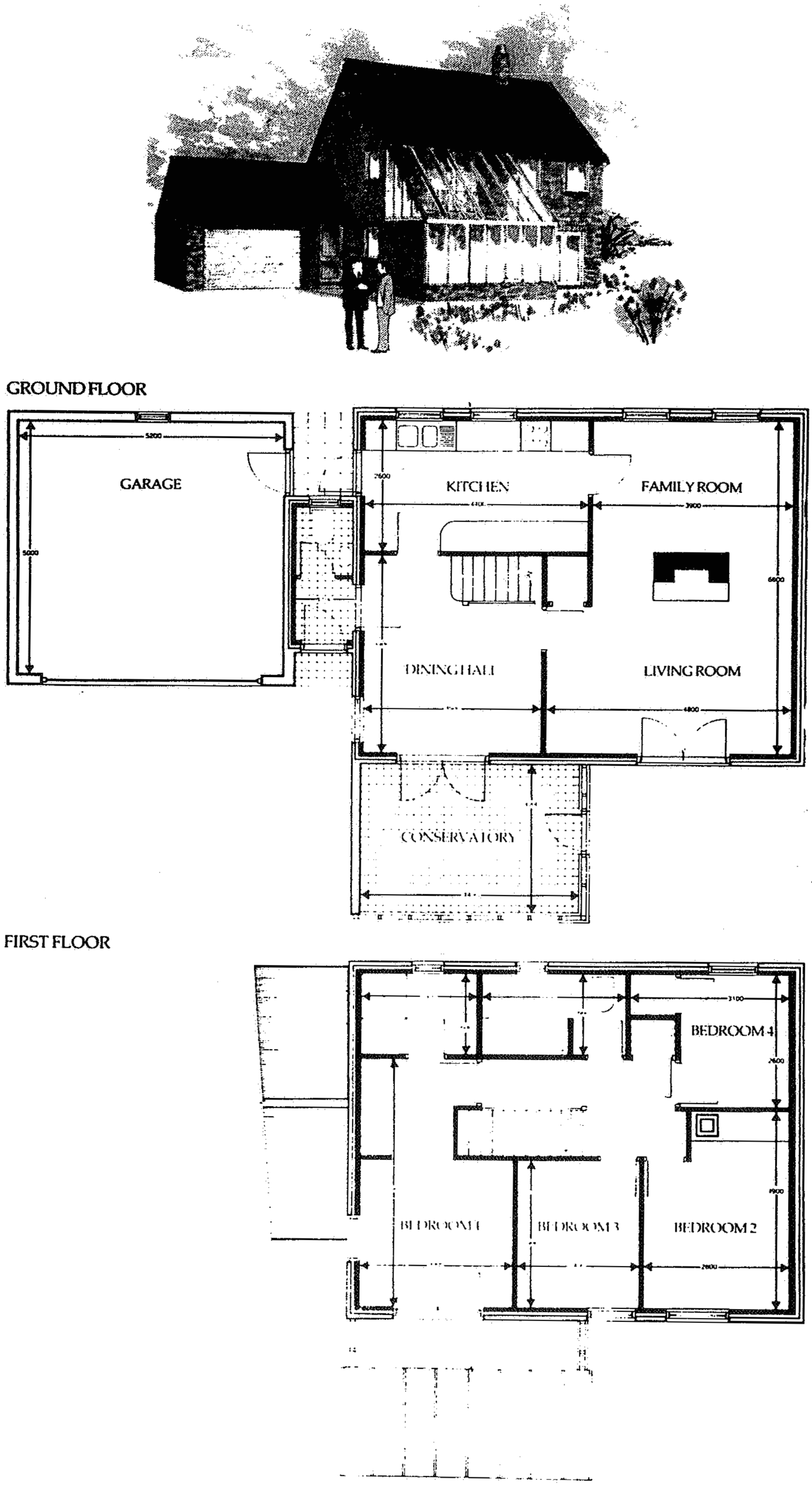

FIGURE 1: Test house

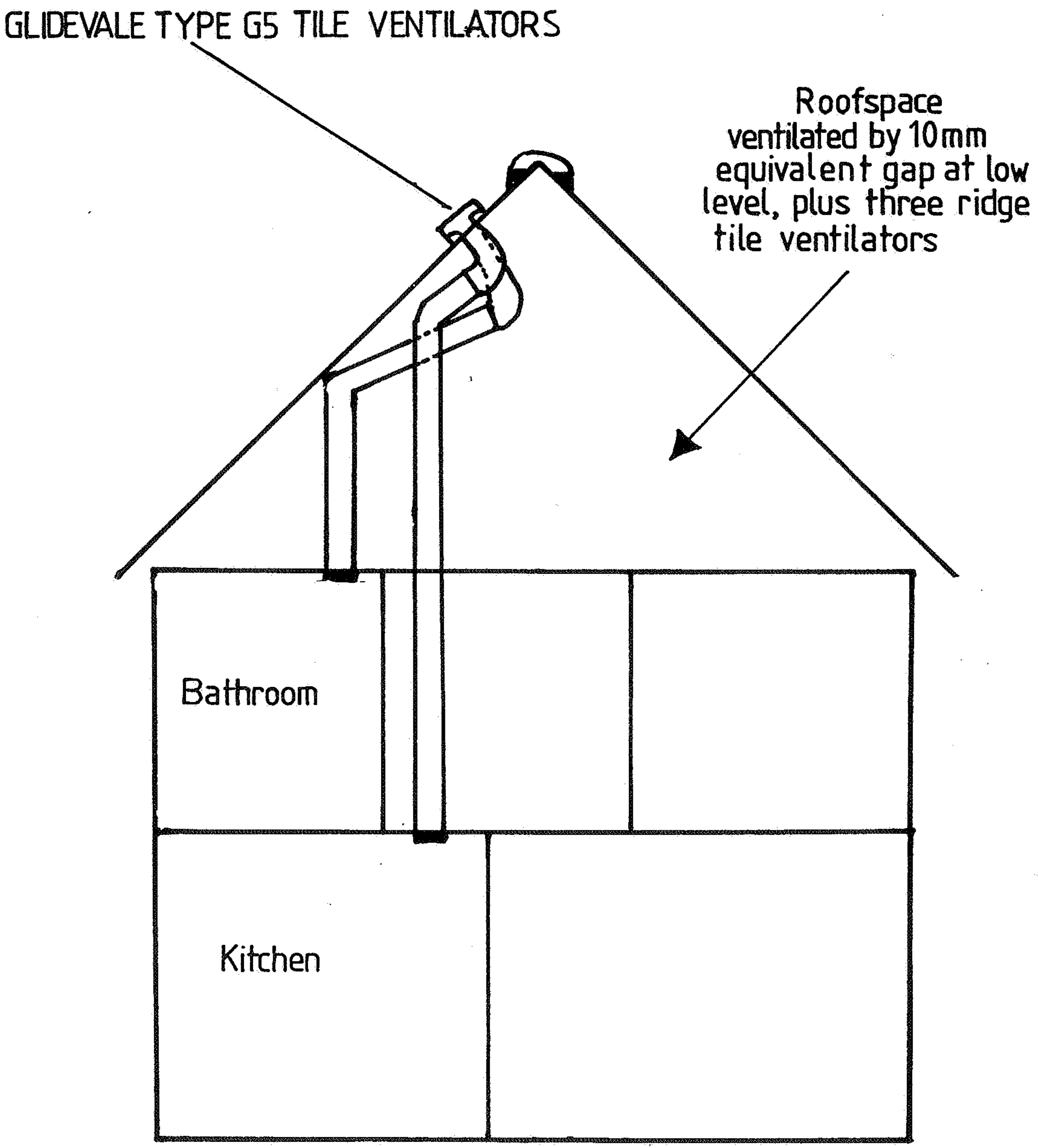

FIGURE 2: DUCT LAYOUT

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

7th AIC Conference, Stratford-upon-Avon, UK
29 September - 2 October 1986

POSTER P1

VENTILATION STRATEGIES AND OCCUPANTS' BEHAVIOUR

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SYNOPSIS

Each occupant in a room should be able to control his own indoor environment. Individual control can be achieved in many ways: from simple window-opening to automatically arranged personal mini-environment.

Individual control is not utilized effectively today. This is partly caused by lack of proper information, and partly by the fact that builders pay more attention to construction than to use and operation.

Even technically complicated systems can be easy to operate -what is needed is sufficient, but not too difficult user information.

In this paper, practical examples of user-friendly ventilation in residential and office buildings will be analyzed. Information problems, technical limitations and consequences of various individual control strategies will also be discussed.

1 INTRODUCTION

The need of ventilation is primarily caused by people and their activities, secondarily by other sources of heat and pollutants. People behave in different ways, and their activities vary highly individually in space and time.

Ventilation should be designed and operated so that a proper indoor air quality is achieved whenever needed. Different people may also have different objectives for indoor air quality, thermal comfort etc. (1). So, the need of ventilation depends on occupancy. Ventilation can, in principle, be designed to be operated on full capacity all the time, but this would waste energy. Continuous minimized ventilation cannot, on the other hand, guarantee good indoor air. Ventilation should, therefore, be controllable in space and time - manually, automatically, or in a suitable combination.

2 PHYSIOLOGICAL, PSYCHOLOGICAL AND TECHNICAL BACKGROUND

2.1 Attitudes against mechanical ventilation - why?

Many complaints are today made against mechanical ventilation. The words "SICK BUILDING" are presented too often in connection with a modern office or other work environment and mechanical ventilation or air-conditioning.

In many cases, further complaints can be avoided by readjustment, minor renewal, and systematic operation and maintenance. But, complaints may occur (or remain) even if there, from the technical point of view, should be no reason to. (See e.g. (2), (3)).

The causes for the "sick building syndrome" are only partly known. The psychological aspects cannot be neglected: people feel bad if they cannot control their indoor environment: temperature, air flows, noise, lighting, (4). To be able to open a window has a great positive psychological effect! People can tolerate more draught or noise if they have got some means to control them.

2.2 Technical limitations - before and now?

"Collective" ventilation has been designed and used for the past 20 - 30 years. Simply because there have been no economical alternatives. In the Nordic countries, the main ventilation system in residential buildings is mechanical exhaust, run at full capacity for a few hours per day. In offices, especially in "landscapes", a constant temperature is set throughout the building, and ventilation is run at a constant capacity during office hours. Limited individual control may be achieved in separate rooms by using e.g. radiator thermostats or controllable fan-coil units.

In many cases, energy-efficiency has been increased, at the risk of deteriorating the indoor air quality, by using minimum outdoor air rates, minimized hours of operation (in offices etc.) or maximum percentage of return air.

Today, it is technically possible to build more individual systems and controls than was technically possible in the 1970's. Energy-efficiency is achieved easily by heat recovery systems which have become cheaper and more reliable. VAV-systems allow varying heating and cooling capacity when needed. Air quality control of ventilation is rapidly developing. New components of control systems can be programmed to provide also suitable temperature fluctuations as well.

A ventilation or air-conditioning system can be designed and balanced in a way not to be disturbed by window-opening. Pressure-controlled fans allow you to control your own air change rate without influencing ventilation in other rooms. But it may remain difficult to arrange great temperature variations - although in most cases $\pm$ 1 ^{o}C is possible in indivicual spaces, which will often be sufficient in minimizing dissatisfaction.

3 HOW TO USE INDIVIDUAL CONTROL - WILL PEOPLE LEARN IT?

3.1 Technical aspects

Technical possibilities have improved, as stated before, but they are not very well utilized today.

Attitudes among builders, designers and contractors should be changed. Now they concentrate on construction and equipment instead of occupants' needs and operation/maintenance. Traditionally, the system and its control are designed more or less separately.

3.2 User-oriented technology, examples

In other branches of technology, there are numerous examples of easy-to-operate systems, which in principle are much more complicated than ventilation.

For example, at home you can switch your lights on and off, whenever needed, very simply and without any technical expertise. You get your tap water almost as easily, or open your radio, TV etc. A little more is required for adjusting the tap water temperature, or colours in your TV but you still can do it without technical skill, and your operations have no influence on your neighbours. Why not also in ventilation? Why not have a constant duct pressure (as voltage!), why not simply adjust your individual air supply and exhaust whenever needed?

A more complicated comparative example is the motor car. In order to use it you need education and a license. "A license for living in your own home" does not sound reasonable at all, but some education on one's indoor environment should be given, already at school. For the rest (the technical part) you should get instructions from the manufacturer or designer!

3.3 Windows

Windows have been used for centuries as a means of basic or additional ventilation. Because they generally can also be tightly closed (at least in the Nordic climate for all winter), other means of air supply should be used for basic ventilation. There are still periods when extra ventilation is needed or wanted: for cooling in summer, for airing if the room is exceptionally crowded etc.

Attempts to change people's window-opening habits have generally failed. People feel dissatisfied if they cannot open their windows.

3.4 Information

You cannot change people's habits, but people can be educated! The only way to do this is proper information. Both natural and mechanical ventilation need careful operation and maintenance - good, simple and clear information is necessary. Always tell people <u>why</u> (air quality, comfort), and <u>how</u> (short-period window opening, use of forced ventilation in kitchen, filter cleaning periodically). Information should not, however, mean a technical manual with hundreds of pages!

4 CASE STUDIES

4.1 General

The following examples show both positive cases of user-oriented ventilation (including limitations in application), and cases where lack of (or wrong) information has caused problems in air quality and even structural damage.

4.2 Detached and row houses

Extreme examples have been measured: air change rates of about 0.01 ac/h (!!), CO_2 concentrations of more than 5 000 ppm, i.e. beyond hygienic limit values, high humidities allowing mould growth. These observations concern tightly-sealed bedrooms in houses equipped with natural or closed-off mechanical ventilation and without any supply air arrangements. The occupants had wanted to save energy or been disturbed by draught or noise, generally they had not received any information on how to use their ventilation.

Generally, in houses with mechanical ventilation, the fan is on only during cooking, bath etc. Major problems can be avoided if the ventilation cannot be completely closed off.

In one experimental area, the manufacturers informed the residents on ventilation. In those houses, most people learned the proper use immediately, but still in some cases the fan is (especially in winter) closed off if the air change due to infiltration satisfies the minimum need for ventilation. Generally, people considered personal instruction by the manufacturer or contractor more useful than instruction manuals.

The importance of good adjustment, and noise reduction, is obvious. Measures required for maintenance should also be as simple as possible; even cleaning or changing the cooker-hood filter is likely to be forgotten if it is considered difficult.

4.3 Renovated block of flats: exhaust fan for each flat

This three-storey block of flat was built in 1951, and need for renovation became obvious in early 1980's. The existing ducts for natural ventilation were in a poor condition, and therefore the owner decided to build a new mechanical exhaust system with one small controllable fan for each flat.

Technically, this system worked, but the information was not sufficient. The advantages of good ventilation, when needed, were not pointed out to the residents clearly. The slight increase in the electricity bill caused by the exhaust fan was estimated into its maximum, some 200 FIM per year. With the consequence that, in order to save a little money, people closed off the fans in many flats. This caused frost damage due to condensation in the exhaust air duct tops and in rooftop fans. New information was soon distributed to the occupants, and now, some years later, the ventilation is satisfactory and properly operated. Supply air is taken in via cracks in the building envelope, which in some winter weather conditions causes draught.

4.4 Experiences from full speed - half speed, operation of exhaust ventilation in blocks of flats

In blocks of flats mechanical exhaust ventilation with one central exhaust fan is predominant. The full speed is generally on for one-two hours in the morning and two-three hours in the afternoon, i.e. when people are assumed to do their cooking. The rest of the day and all the night ventilation is run at half speed.
This arrangement has not worked satisfactorily. In hundreds of buildings, the exhaust fan is closed off for nights (energy, noise...), although this should not be allowed. In many cases, the timer clock is not accurate and may switch full speed on even at midnight.

But even if the system is operated correctly, people often are far from satisfied. In recent experimental projects it was found out that people's cooking habits vary so much that collective fan operation would not satisfy everyone unless the full speed were on from 7.00 to 21.00 hours.

The full speed-half speed operation also causes problems in pressure conditions. At half speed, the pressure differences are about one fourth of those at full speed (e.g. fan pressure 100 Pa vs. 400 Pa), for which the system is generally balanced and adjusted. This means that in winter, especially in high-rise buildings, or at high wind speeds, the natural forces will disturb the balance of ventilation. Problems with pressure conditions may occur even if the ventilation systems can be operated individually - floors and partition walls should be built as airtight as possible!

4.5 Modern and renovated offices

A new generation of office interiors have been recently introduced. Flexible, integrated furniture systems including lighting and air distribution are already available. This allows an individually controllable mini-environment for each occupant. Unfortunately, no experimental data is available yet concerning indoor air conditions and system performance.

In renovated offices, originally equipped with natural ventilation, many people like to keep the ventilation "as natural as possible". Very often this is not possible: the office environment is more loaded than before (office automation!), old ductwork is partly damaged, outdoor air quality requires air filtering etc. "Soft" and flexible mechanization, with as little influence on interior architecture as possible, generally brings the best result. If changes in architecture are allowed (or have already been made), then providing modern air-conditioning is possible even in an existing building. In any case, it is important to listen what the end user wants! Even mechanical systems can be "natural" - adjustable and noiseless. Lack of space for new ducts sets its own limitations; VAV or fan-coil systems are often suitable and user-friendly.

5 CONCLUSIONS AND FUTURE TRENDS

In the design of ventilation, it is necessary to pay much attention to traditions and people's habits. People want to adjust their own room temperature, and they want to open windows. Why not let them? Modern air conditioning technology allows individual control, and technical solutions can be made based on the occupants' needs and wants.

Correct information is necessary, e.g.:

- Opening a window in your office causes draught in winter and brings in dust, so if you still want to open it, just a few minutes' airing is enough, in summer do just as you like, but remember that airing when wind speed is high may cause discomfort to your neighbours (OFFICE).

- Closing off your fan makes the air bad. The minimum speed is needed even when there is nobody at home. Half speed is recommended except during cooking, when you also should open the kitchen hood damper (HOMES. The positions needed must be marked clearly).

- In summer, if it gets too warm indoors, you can run your fan at full speed or open your windows late in the evening, at night, in the morning, when it is cooler outdoors. (HOME). In offices mechanical night cooling is recommended.

People are very sensitive to draught and noise; odours are often much more easily tolerated. In order to achieve good indoor air quality, special attention should be paid to proper air distribution and noise insulation/reduction.

The future ventilation would probably be designed as follows:

1 In residential buildings: individually controlled ventilation in each flat, maybe in each room. Total air flow is controlled by fan or damper, room control by terminal devices. Window opening is, naturally, possible. If higher quality is needed, each room would be equipped with controllable air supply. To avoid problems with pressure differences, combinations of natural and mechanical ventilation (e.g. natural exhaust plus kitchen hood fan) are not allowed, supply and exhaust should be well balanced for a slight underpressure, and floors and partition walls should be built airtight.

2 In offices, schools, theatres, hotels etc, an air-conditioned individual mini-environment where you can adjust the temperature (e.g. within $\pm$ 1 ^{o}C) or its fluctuation (e.g. morning - 21 $\pm$ 1 ^{o}C, afternoon-upper limit 24 ^{o}C, "natural" rise), the amount of fresh air (constant or between minimum-maximum), direction of supply air flow. In sophisticated systems, the indoor environment can be controlled by central air conditioning (basic control) plus mini-air-conditioning (individual variations) - maybe with opening a window as a temporary addition! Rooms with temporary occupation, e.g. conference rooms are controlled separately (for example, by timer-controlled on-off dampers and air quality-controlled VAV-terminals). Integrated furniture - lighting - air distribution systems will probably be soon introduced also in office renovations.

In all cases, the best result can be achieved with a combination of manual and automatic adjustment + control. Some principles are presented in the Figures 1 and 2.

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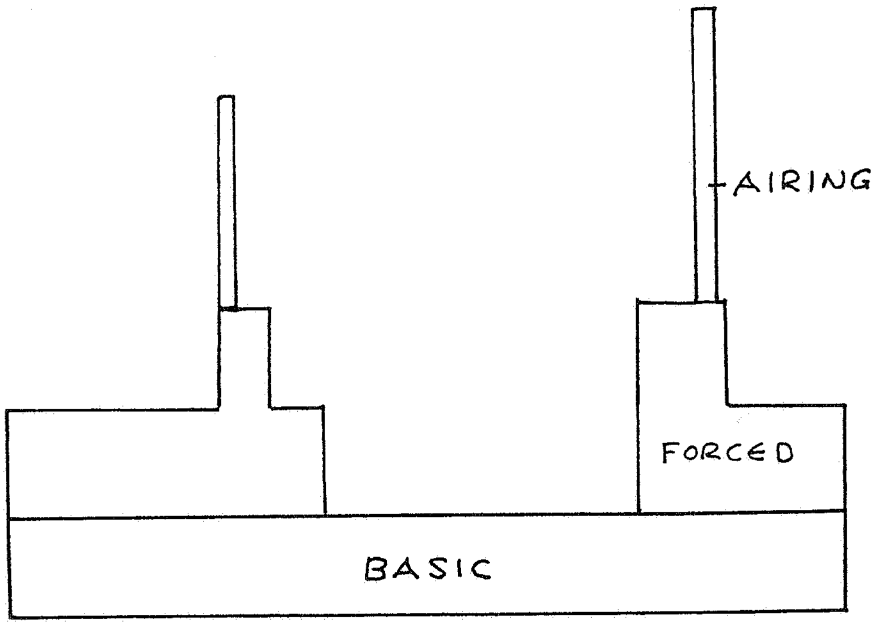

Fig. 1. How to use ventilation in residential buildings. Basic ventilation is always on, forcing is due to occupancy, cooking etc. Airing only for extra need or exceptional loads.

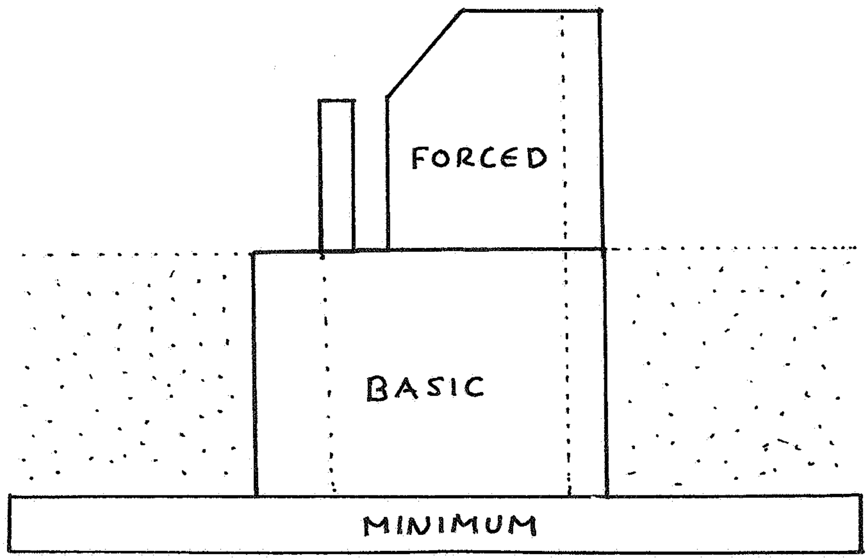

Fig. 2. Use of ventilation in offices.
Minimum = continuous exhaust from toilets etc.
Basic = ventilation due to expected occupancy (Variable if demand-controlled) forced = extra ventilation due to thermal loads .

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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POSTER P2

SPATIOTEMPORAL CONTROL OF MECHANICAL EXHAUST AIR VENTILATION

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SPATIOTEMPORAL CONTROL OF MECHANICAL EXHAUST AIR VENTILATION

Synopsis

Centrally controlled mechanical exhaust air ventilation systems in residential buildings can satisfactorily serve only a few of the inhabitants. As the need for ventilation in each apartment varies both temporally and locally, the exhaust air ventilation system should operate accordingly.

On the basis of a new cascade-control method a selfcontained constant flow exhaust air terminal device was constructed. With the device the user can, according to his own needs, increase temporarily his own exhaust air ventilation.

The new terminal devices are suitable for a spatiotemporally controlled mechanical exhaust air ventilation system provided that the ducts are tight, the pressure in the ducts is within the operation range of the terminal devices in all points of operation, and the inside of the building is tight.

1 INTRODUCTION

The mechanical exhaust air ventilation systems in residential buildings in Finland are usually constructed as so called two-speed systems. By changing the speed of rotation of the fan the flow rate of the exhaust air may be reduced to half of its statutory value at hours during which the need for ventilation is considered to be lower. In practise the result is that the higher flow rates are used only when there is considered to be a common demand for increased ventilation. The centralized control systems, however, can satisfactorily serve only a few of the inhabitants. As the need for ventilation in each apartment varies both temporally and locally the exhaust air ventilation systems should operate accordingly.

With the new cascade control system based on exploitation of the flow's own pressure energy it had become possible to build a selfcontained constant flow exhaust air terminal device with which the inhabitant can increase his own exhaust air ventilation rate. Twenty-five constant flow terminal devices were built for the investigations. Their technical properties and suitability for a spatiotemporally controlled exhaust air ventilation system were studied both in the laboratory and in one small residential house that previously had been equipped with centralized control of exhaust air ventilation. No effort was made to construct a terminal device ready for industrial production.

2 CASCADE CONTROL METHOD

Cascade control is a new method /1-11/ for conditioning and/or control of a fluid flow by exploiting the pressure difference created by the flow itself. Cascade control is based on a flow condition according to Figure 1. An intermediate chamber is arranged in the flow duct, which is connected to the inlet space having higher pressure (p_1) with orifice d_1 and with orifice d_2 to the outlet space having lower pressure (p_3). The system is characterized by that

$$\frac{p_2 - p_3}{p_1 - p_3} = \frac{1}{k\left(\frac{d_2}{d_1}\right)^4 + 1} \tag{1}$$

where

p_1	is	inlet pressure
p_2		intermediate pressure
p_3		outlet pressure
d_1		diameter of the inlet orifice
d_2		diameter of the outlet orifice
k		flow loss factor.

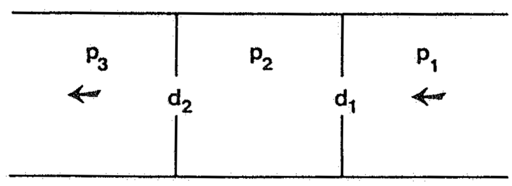


Figure 1. Flow condition in cascade control.

By equipping the intermediate chamber with a flexible wall allowing linear motion, by fastening the other end of the flow duct and by controlling with the aid of a shaped control cone for instance the free space of the outlet orifice ($d_2 = d_{ekv}$) we get a certain position between the opening and the control cone to correspond to each pressure difference ($p_1 - p_3$), Figure 2.

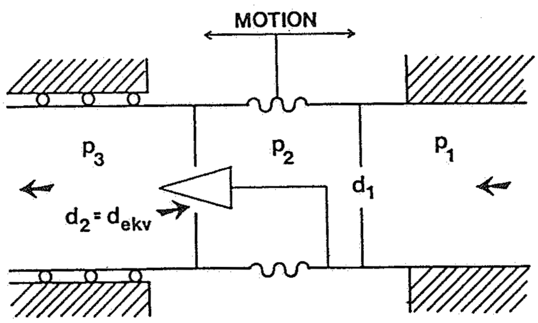


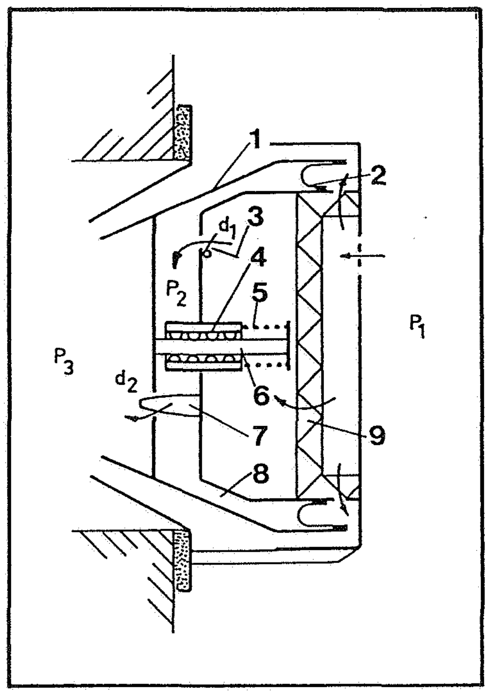
Figure 2. Cascade where the wall in the intermediate chamber is flexible and the area of outlet orifice d_2 is controlled with the aid of a control cone.

In the application the sign of the exponent on the right side of equation 1 is minus (-). In other applications the sign is according to each case either plus (+) or minus (-).

The structural principle of the selfcontained cascade controlled constant flow exhaust air terminal devices used in this investigation is shown in Figure 3. The intermediate chamber of the cascade consists of a main valve cone moving on a linear bearing. The movable valve cone is by a rolling membrane joined to the unmovable part of the intermediate chamber. The control cone has been shaped so that such a position of the movable main valve cone corresponds to each pressure difference value $p_1 - p_3$ that the main air flow of the exhaust air terminal device is constant.

A system has been connected to the constant flow terminal devices with which the control air inlet orifice d_1 can be closed. Then the main valve cone opens to a fixed open position and the main flow is increased. In this position the device is not a constant flow terminal device.

To prevent dirt from accumulating in the linear bearing and control air orifices the control air directed to the intermediate chamber is filtered.



1 Movable main valve cone
2 Rolling membrane
3 Shutter of control air inlet orifice d_1 controlled by a timer
4 Linear bearing
5 Spring
6 Shaft
7 Control cone
8 Intermediate chamber
9 Air filter

p_1 Room pressure
p_2 Intermediate chamber pressure
p_3 Duct pressure
d_1 Control air inlet orifice
d_2 Control air outlet orifice

Figure 3. Structural principle of a cascade controlled selfcontained constant flow exhaust air terminal device.

3 PRINCIPLES OF CONSTANT FLOW TERMINAL DEVICE DESIGN

The constant flow terminal devices were designed on the basis of the centrally controlled exhaust air ventilation system used in the test building, the air flow rates, the coupling sizes of the original exhaust air terminal devices, and the evaluated pressures of the exhaust air fan.

The air flows of the constant flow terminal devices were determined on the basis of the device based exhaust air flows expressed in m^3/h and presented in the Compiled Finnish Building Regulations as follows:

	Constant flow m^3/h	dm^3/s	Increased flow m^3/s	dm^3/s	Coupling size, mm
In kitchen	40	11,1	$\geq$ 80	$\geq$ 22,2	125
In bathroom	30	8,3	$\geq$ 60	$\geq$ 16,7	100

The constant flow terminal devices had to operate within the pressure difference range 100 - 200 Pa, of which the actual working range was evaluated to be 125 - 175 Pa.

Different models were made of each constant flow terminal device type both for wall and ceiling installation. Basically the different models were similar, but those of smaller air flow had been throttled more. The time for increased air flow had been limited to about 50 minutes with a timer. Different technical solutions (so called cord, mechanical, and air control) were used to set the terminal devices on increased flow, Figure 4.

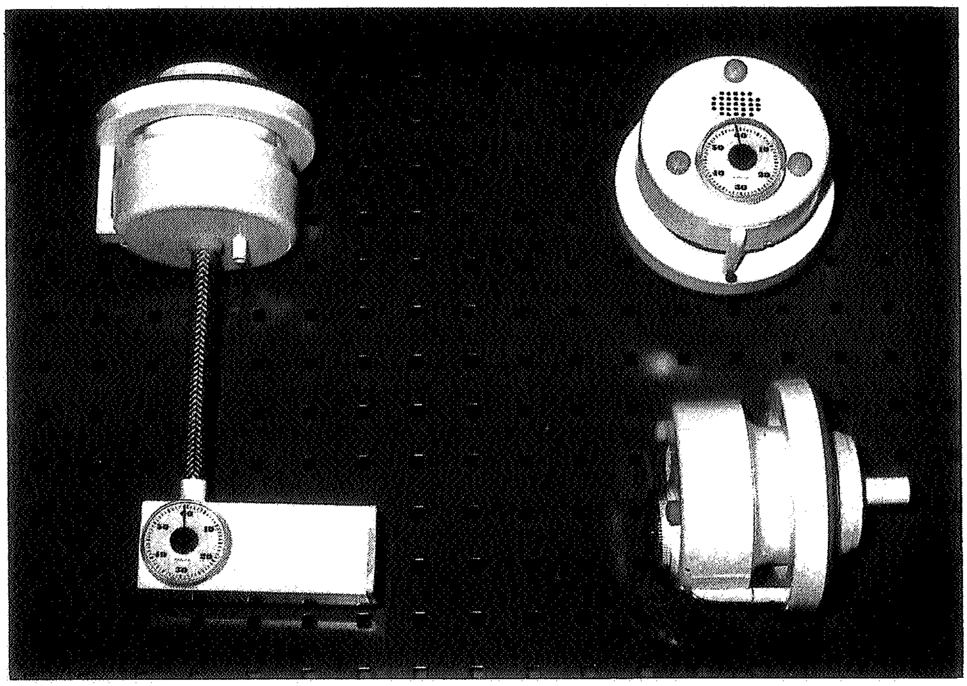


Figure 4. Two models of constant flow exhaust air terminal devices. To the left is the air operated model. The timer and the control air orifice d_1 are in a separate unit. To the right is the cord operated model. The cord to the timer is not installed.

4 PERFORMANCE OF CONSTANT FLOW TERMINAL DEVICES

4.1 Air flow

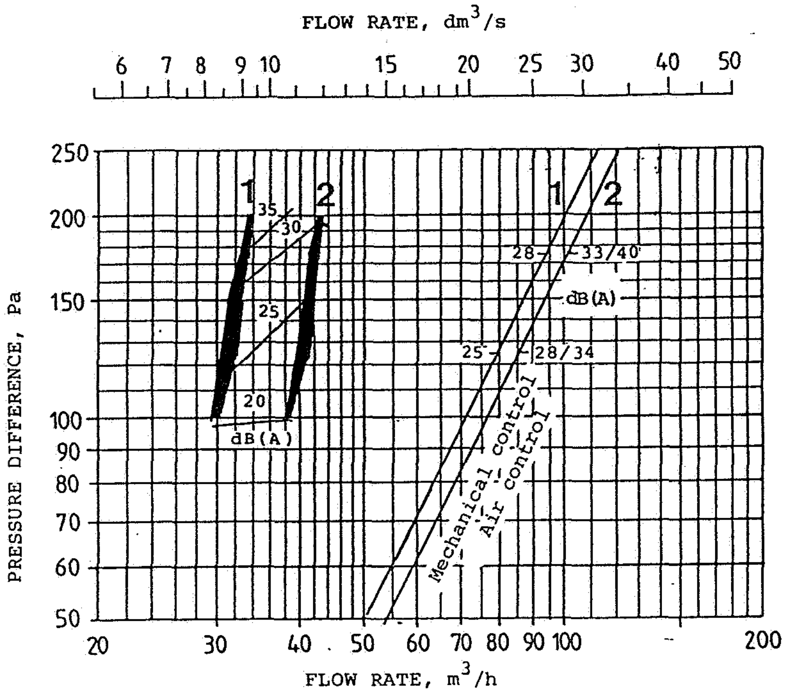
The aim was to build the constant flow terminal devices to within ± 5% air flow accuracy. As it was not possible during construction, due to production technical reasons, to realize all the known operation sensitivity affecting details (for instance mass centre of moving parts and rolling membrane dimensions) of the prototype terminal devices, the ± 10% accuracy sufficient for the air flows of ventilation installation was deemed satisfactory.

Within the pressure difference range 100 - 200 Pa the accuracy of the air flow of the constant flow terminal devices was generally better than ± 10 %, Figure 5. Within the pressure difference range 125 - 175 Pa, the accuracy of the air flow of the constant flow terminal devices installed vertically in the ceiling was better than ± 5 %. Of the constant flow terminal devices installed horizontally on the wall only one half reached this accuracy. The operation sensitivity of the constant flow terminal devices installed on the wall could be improved if the centre of the mass of the movable parts is shifted to the midpoint of the linear bearing.

The planned increased air flows were reached in bathroom terminal devices with pressure difference 70 - 80 Pa and in kitchen terminal devices with an about 110 Pa pressure difference.

4.2 Noise generation

The noise generation of the kitchen constant flow terminal devices remained below 30 dB(A) during constant flow within the whole planned pressure difference range 100 - 200 Pa. Starting from pressure difference 170 - 180 Pa a whistling sound was heard in the bathroom constant flow terminal devices. During increased flow the kitchen constant flow terminal devices were noisier than those of the bathroom, Figure 5.



1 Terminal device for 8,3/16,7 dm^3/s flow
2 Terminal device for 11,1/22,2 dm^3/s flow.

Figure 5. Average flow- and noisetechnical (10 m^2 sound absorption) properties of the constant flow exhaust air terminal devices. The values are presented at constant flow and increased flow.

4.3 Noise attenuation

The measured noise attenuation properties of one bathroom constant flow terminal device met the noise attenuation requirements presented in the Compiled Finnish Building Regulations part C6 with the exception of high frequencies, Table 1. However, at high frequencies additional attenuation of the constant flow terminal devices is easy.

Table 1. Noise attenuation of a 8,3/16,6 dm^3/s constant flow terminal device, dB.

Direction of noise attenuation	Position of adjustment	Octave band center frequency, Hz 63	125	250	500	1000	2000	4000	8000
From duct to room	100 Pa [1]	0	2	6	13	15	11	5	2
	Open [2]	0	1	4	9	11	8	5	6
From room to duct	100 Pa	1	0	4	14	16	13	5	8
	open	1	0	3	8	12	9	5	5
Calculated attenuation room→duct→room	100 Pa	1	2	10	27	31	24	10	10
	open	1	1	7	17	23	17	10	11
Requirement		-	0	4	12	14	16	16	-

[1] Constant flow at 100 Pa pressure difference
[2] Terminal device completely open (increased flow).

4.4 Duct pressure

In a spatiotemporally controlled exhaust air ventilation system the constant flow terminal devices operate as planned if the planned 100 - 200 Pa underpressure can be maintained in the ducts. Pressure stability in the ducts when the terminal devices are set on increased flow depends on the shape of the specific curves of the fan and ducts. The pressure in the ducts shall be separately adjusted when needed. If several constant flow terminal devices have to operate at the same time with various pressure differences due to for instance thermal forces, a considerably smaller variation can be allowed in duct pressure adjustment than in a situation when all the constant flow terminal devices operate almost with the same pressure difference.

4.5 Control air

The volume flow of the air used to control the constant flow terminal devices was smaller than 0,5 % of the exhaust air flow during constant flow. The control air was dimensioned to be taken from a space where the prevailing pressure was the same as that upstream of the constant flow terminal device.

If the pressure of the control air to the terminal devices differs from the pressure prevailing immediately upstream of the device, the flow will be affected. When the control air is taken from a space which has a higher pressure than that upstream of the terminal device, then the air flow decreases and when the pressure is lower, then the air flow increases, Figure 6.

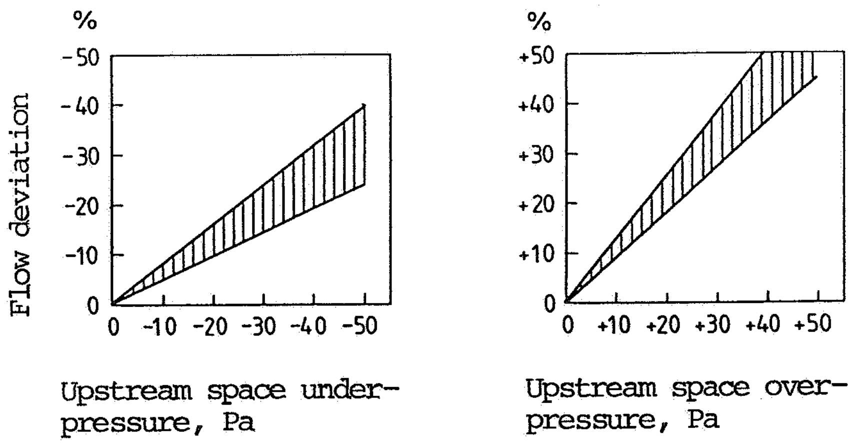


Figure 6. Flow deviation of a constant flow exhaust air terminal device at different pressure differences between upstream space of the device and the control air intake.

When the pressure difference between the control air intake and upstream of the terminal device was kept constant, the terminal device operated as a constant flow device but on a new nominal flow.

4.6 Operation speed

Measurements on the operation speed of the terminal devices showed that after a quick change of the pressure difference of the terminal devices, constant flow was reached within 10 seconds. The terminal devices did not react on quick oscillations of the pressure difference.

5 FIELD MEASUREMENTS

5.1 Follow-up measurements in the test building

The follow-up measurements were made in a small three storey residential building, where the exhaust air ventilation system used, which was equipped with centralized control (two-speed system), was first studied. Then the original exhaust air terminal devices in the existing exhaust air ventilation system were replaced with constant flow terminal devices. The aim of the follow-up measurements was to study the performance of the constant flow terminal devices and to clarify the operational prerequisites of a spatiotemporally controlled exhaust air ventilation system.

In installation and follow-up measurements of the spatiotemporally controlled exhaust air ventilation system in the test building we could not use the results of system tests made in the laboratory with constant flow terminal devices, because the laboratory tests could not be made until the follow-up measurements had started.

In measurements of the centrally controlled exhaust air ventilation system several leaks could be detected in the ducts. When the air flows in the original exhaust air terminal devices had been correctly adjusted, the total air flow of the main ducts was about 50 % larger than the planned air flow.

Reduction of the noise caused by the large leaks in the ducts was possible only by tightening the ducts where possible. The ducts were tightened during installation of the constant flow terminal devices. With tightening the noise level in the apartments could be reduced with 2 - 12 dB(A). The total air flow in the main ducts was, however, still about 12 % higher than the planned air flow.

For noise technical reasons the underpressure of the ducts was lowered during installation of constant flow terminal devices by reducing the fan rotation speed with a transformer and by throttling the suction duct of the fan. These measures decisively reduced the possibilities of increasing the air flow, i.e. keeping the duct underpressure within the planned range.

The three-month follow-up measurements showed that the constant flow terminal devices returned to constant flow after having been set on increased flow. At nights, when the constant flow terminal devices presumably were not set on increased flow, the standard deviation of the air flows was smaller than ± 4 %, and the variation was ± 10 % when the extreme values are studied.

Apartment-based measurements showed that the air flows of the bathroom constant flow terminal devices were on average according to the design values during constant flow. The air flows of the kitchen constant flow terminal devices were during constant flow about 14 - 22 % smaller than the design values. The kitchen measurement results could be influenced by the leak air flows observed in the hoods. When the results of measurements made during installation of the constant flow terminal devices were compared with measurement results after four months' use, it was observed that the deviations of single constant flow terminal devices from the design values had increased with time, but the total air flows had remained almost equal. With the constant flow terminal devices set on increased ventilation, the design values of the air flows were not reached mainly due to the poorly realized ducting.

The ventilation of the whole building was increased simultaneously with the previously used centrally controlled exhaust air ventilation system. The underpressures of the apartments with regard to outside air were then clearly larger than with the spatiotemporally controlled exhaust air ventilation system in which usually only a part of the building is in the area of increased ventilation.

5.2 Final inspection of the constant flow terminal devices

The final inspection was made after eight months of use. The constant flow terminal devices had become dirty only on the outside. Filtering of the air used to control the constant flow terminal devices had, according to visual check, kept clean the inside parts critical to terminal device operation.

5.3 Ventilation needs of the inhabitants

The follow-up measurements made in the test building showed that the inhabitants had used temporally increased ventilation rather individually. With spatiotemporally controlled exhaust air ventilation using constant flow terminal devices the ventilation needs of the inhabitants could be satisfied much better than with the centralized control of exhaust air ventilation used previously.

6 OPERATIONAL PREREQUISITES OF A SPATIOTEMPORALLY CONTROLLED EXHAUST AIR VENTILATION SYSTEM

A spatiotemporally controlled exhaust air ventilation system can be realized with cascade-control-based, selfcontained constant flow terminal devices with which the exhaust air flow can be increased. The most important prerequsites of the system are that the ducts are tight, that the dimensioned pressure differences of the constant flow terminal devices can be secured in all points of operation, and that the inside tightness of the building is good, because the supply air must be outside air and not air from a neighbouring apartment.

Acknowledgements

The study was supported by the Ministry of Trade and Industry, Finland. The constant flow exhaust air terminal devices were dimensioned and constructed by the inventor and developer of the cascade-control method Erkki J. Niskanen, Consulting Engineer.

For a study of controlled intake of fresh supply air also a prototype of a cascade-controlled constant flow supply air device has been constructed. This was dimensioned for a pressure difference of 10 - 70 Pa and an air flow of 5 - 5,5 dm^3/s.

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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POSTER P3

DESIGN OF OCCUPANCY RELATED VENTILATION CONTROL SYSTEM FOR A NEW ENTERTAINMENT CENTRE IN HONG KONG.

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SYNOPSIS

A design process is developed for an OCCUPANCY-RELATED VENTILATION CONTROL SYSTEM (ORVCS) in a new entertainment centre in Sha-tin, Hong Kong. The aim is to reduce the cost of space cooling. Little work appears to have been done in using ORVCS in conjunction with space cooling up to the present time. The design process includes (a) the selection of a control parameter to modulate the fresh air supply rate (b) assumptions about the occupancy load profile and (c) estimation of the possible energy savings.

It is concluded that for certain zones of the building the annual energy savings due to use of an ORVCS could be as high as 29% and the pay-back time about 9 months.

SYMBOL LIST

Symbol	Description	Units
La	Appliance Cooling Load	kW
Lc	Occupant Cooling Load	kW
Ls	Solar Cooling Load	kW
Lt	Fabric Transmission Cooling Load	kW
Lv	(Mechanical) Ventilation Cooling Load	kW
Qf	Maximum Cooling Load	kW
Qp1	Partial Cooling Load (Existing)	kW
Qp2	Partial Cooling Load with ORCVS	kW
Qm1	Monthly Cooling Energy Requirement (Existing)	kWh
Qm2	Monthly Cooling Energy-Requirement with ORVCS	kWh

1. INTRODUCTION

In a building having an occupancy related ventilation control system (ORVCS) an attempt is made to relate the (mechanically assisted) input rate of fresh air to the number of people occupying a given (large) zone of the building. It is therefore necessary to select a measurable physical characteristic of the building exhaust air which correlates with building occupancy (e.g. the CO_2 level in the exhaust air). Such systems have been installed in several public entertainment buildings[1] in the UK to reduce heating costs. A similar system has also been considered for installation in a university library[2]. The present work relates to the possibility of reducing the costs of cooling rather than heating a building by the adoption of an ORVCS. Here the input rate of (relatively warm) fresh air to a building zone would be reduced if the occupancy of the zone reduced and the rate of input of (relatively cool) recirculated air would be increased. The load on cooling coils and associated refrigeration equipment, would therefore be reduced and energy savings should result. The building is a new family entertainment centre located in the New Territories of Hong Kong. One of the authors (W.L.L.) was responsible for the design of the air conditioning system.

2. SHA-TIN ENTERTAINMENT CENTRE AND THE HONG KONG CLIMATE

The entertainment centre is situated in a residential area with an estimated population of 400,000 in Sha-tin New Town.[3] The ground floor area is 1956m^2 and the estimated maximum occupancy is 4050 people. It has the following facilities.

Basement Bowling centre, lounge

Ground Floor Fast food centre, coffee shop, entrance hall

First Floor Twin cinemas and foyer

Second Floor Upper part of cinemas, childrens ride area

Third Floor Theatre restaurant

Fourth Floor Family club (including multipurpose game area, gymnasium, dining area, library and conference room)

Roof Lounge

The Hong Kong climate is tropical with relatively hot summers (mean outdoor air temperature ~ 28°C July-September) and rather warm winters (mean outdoor temperatures ~ 16°C January-February). Relative humidity levels are generally high (especially during February to June when the mean level exceeds 70°%). The air conditioning requirements of the entertainment centre are therefore for cooling. There is no provision for heating. Cooling is provided either by cooling coils in the inlet air duct of given building zones or by free cooling i.e. when (during the winter months) the outside air temperature falls below the design internal temperature of 22°C there may be no need for use of the cooling coils and associated refrigeration systems. Use of ORVCS is applicable during April to October but not during the remaining months of the year when free cooling is possible.

3. SHA-TIN ENTERTAINMENT CENTRE AIR-CONDITIONING SYSTEM AND APPLICABILITY OF AN ORVCS TO CERTAIN BUILDING ZONES

The Sha-tin centre has a central refrigeration system consisting of 6 roof mounted Hitachi chillers each having a cooling capacity of 460kW. Water, chilled by these units, is pumped to cooling coils in seventeen air handling units and fourteen fan-coil units. A separate fresh air supply is ducted to each of these units and is independently controlled. It is therefore possible, in principle, to install independent ORVCS units in various building zones. Use of an ORVCS is considered to be applicable only to the first to the fourth floors of the building. It is not applicable to kitchen areas or to the basement which has a fixed requirement for fresh air at all times (and is slightly pressurised.)

Several properties of the building air were considered as possible control input parameters for an ORVCS. These were levels of CO_2, relative humidity, CO, O_2 and body odour. The choice of parameter was based on the following criteria: measurability, correlation with occupancy, provision of a sufficiently stringent ventilation requirement, availability of control equipment.

Humidity does not correlate well with building occupancy and is already used in the Shatin centre to determine when free cooling is possible. Body odour might be difficult to assess using objective techniques (e.g. gas chromatography) on a continuous basis.

Equipment is readily available to control ventilation systems using CO_2 level or O_2 plus combustible gases (e.g. CO from tobacco smoke). Either technique might be applicable to a leisure centre. There is some evidence that the second would have the advantage of dealing more effectively with smoking.[4] For the sake of simplicity the present work will be related to the use of CO_2. The CO_2 control parameter is based on the following. The CO_2 level in outdoor air is usually about 300ppm. An acceptable level of CO_2 indoors is 1000 ppm and at an exhalation rate of about $4.7 \times 10^{-6}\ M^3\ S^{-1}$ per person this corresponds to a fresh air rate of 6.7 l/s per occupant of a given zone. Contamination of outdoor air is unlikely to be a problem in Sha-tin although permitted levels for NO_x, SO_2 are exceeded in certain more densely populated parts of Hong Kong.[5]

4. SAVINGS IN CINEMA 'A' COOLING LOAD USING A CO_2 BASED ORVCS

Cinema A has a maximum occupancy of 800 people and a design maximum fresh air rate of 4.6 m^3/s. (This corresponds to approximately 1100 ppm of CO_2). It is assumed in what follows that the required fresh air rate for lower occupancies will be the corresponding fraction of the above maximum rate. In practice it is usual to set the controls to give a minimum ventilation rate regardless of occupancy. It is also assumed that for safety purposes the ORVCS could be over ridden manually if required. Cooling load and supply air rate calculations have been made for the building using ASHRAE procedures[6]. It is assumed that the total cooling load is given by

$$Q = Ls + Lt + La + Lo + Lv$$

An example of the results of the mean cooling load calculations with and without an ORVCS for cinema A in the month of July is given in table 1. The occupancy profile has been simplified to a constant level of 100% (of 800) for weekends and 33% for weekdays. (The predicted occupancies for weekdays used by the architects are 20% around noon rising to 45% later in the day). The partial occupancy of 33% is assumed to apply to 22 days per month while the remaining days correspond to full occupancy. The occupancy cooling load is taken as proportional to the number of occupants of the cinema (ie. Lop < Lo table 1). However, the ventilation cooling load (due to the requirement to cool fresh air to the design value of 22°C) will remain constant at Lv with the existing control system. Use of an ORVCS will allow this to fall to Lvp when the cinema is only partly occupied.

TABLE 1 CINEMA A. JULY COOLING LOADS AND COOLING ENERGY REQUIREMENTS WITH AND WITHOUT ORVCS

Maximum number of occupants	800
Mean partial weekday occupancy	33%
Solar Load Ls	0
Fabric Transmission Load (Lt)	2.8kW
Appliance load (La)	2.3kW
Maximum occupancy load Lo	80 kW
Partial occupancy load (Lop = 0.33 Lo)	26.4kW
Maximum ventilation load (Lv)	138 kW
Partial ventilation load (Lvp = 0.33Lv)	46 kW
Maximum cooling load (Qf = Lt + La + Lo + Lv)	223.1kW
Partial cooling load for existing control system (Qp1 = Lt + La + Lop + Lv)	169.5kW
Partial cooling load with ORVCS (Qp2 = Lt + La + Lop + Lvp)	77.5kW
Monthly cooling energy requirement for existing system (Qm1 = 12 [22 * Qp1 + 9Qf] assuming 12 hours operation per day)	68843 kWh
Monthly cooling energy requirement with ORVCS (Qm2 = 12 [22 * Qp2 + 9Qf])	44555 kWh
Saving in cooling energy requirement (Qm1-Qm2)	24288 kWh
% saving for July	35.3

Calculations show that the annual percentage saving in electrical energy usage for cinema A is 29%. This amounts to 31440 kWh. Here the coefficient of performance of the chillers in satisfying the cooling load has been taken as 3.4. The saving in energy costs is 19272 HK $ (at a tariff of 0.613 HK$/kWh). The estimated cost of the ORVCS is 13490 HK$ so that the pay back time is about 9 months. A similar time applies to the Theatre Restaurant. In general longer pay back times apply to other parts of the building.

5. CONCLUSIONS

(a) Measurement of the CO_2 level or total O_2 plus combustible gases in the exhaust air are the recommended means of regulating an occupancy related ventilation control system (ORVCS). The second method may deal more effectively with removal of tobacco smoke though more field trials would be desirable to make a comparison.
(b) An ORVCS appears to be appropriate to certain zones of a building requiring cooling rather than heating (such as the Sha-tin leisure centre). Those zones have variable occupancy and large open areas e.g. cinemas or the theatre restaurant. The estimated pay-back time for a cinema is 9 months with annual energy savings of 29%.
(c) Further work is required to develop the design of an ORVCS in conjunction with cooling systems and to evaluate actual pay-back times.

ACKNOWLEDGEMENTS

Thanks are due to Mr W Taylor together with ETSU and Energy Conscious Design Ltd for information regarding the use of an ORVCS in Rank Leisure Centres in the UK.

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OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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POSTER P4

HOUSEHOLDER RESPONSE TO AIRTIGHTNESS INFORMATION

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SYNOPSIS

20 low-income family houses were studied for Air Changes per Hour and Equivalent Leakage Area as measured by the Blower Door Test during the winter of 1985-86. The residents of 10 of these homes were given instruction on air sealing techniques and were provided a "starter kit" of retrofit materials. Upon retesting, these 10 homes showed no improvement in either ACH or ELA, indicating either a lack of interest on the part of the householders in making their homes more airtight, or an inability to do so based upon insufficient information or physical limitations.

INTRODUCTION

Although the procedures and materials for air sealing of both new and existing homes is well documented, it is not clear to what extent occupants of older homes will implement retrofit techniques. Ball State University (BSU) in Muncie, Indiana, USA, through its Center for Energy Research/ Education/Service (CERES), has been furnishing a Blower Door test to homeowners which has provided ACH, ELA, a list of leak sites, and a prioritized list of procedures for cost-effective air tightening retrofit measures.

Some clients of BSU CERES have been governmental agencies which deal with housing for low income families. The occupants of such houses receive subsidies for heat or have had their homes rehabilitated through community funds.

Occupants of homes which have been tested as part of funded projects have not indicated that they would enthusiastically implement air sealing techniques. Since many of them receive governmental assistance in paying energy bills, they do not have a strong incentive to conserve energy.

To determine if governmental agencies have been spending money in the wisest manner, this study attempted to measure occupant response to information regarding the airtightness of their homes. This project was funded by a small grant from the BSU Office of Research to David Valentine, a junior majoring in Industrial Education and supervised by James J. Kirkwood, Ph.D., Professor of Industry and Technology.

LIMITATIONS OF THE STUDY

ACH or ELA were the only variables under study. Any significant changes in ACH or ELA would reflect occupant response to the experimental condition. Such response would include heightened awareness of air infiltration, attitude change, money spent on sealing materials and would provide an indication of the effectiveness of the instruction in air sealing techniques. No attempt was made to study the specific influence of these responses.

PROBLEM STATEMENT

The problem under study was to determine the effectiveness of a simple education program which entails providing householders with specific advice for tightening their homes and a "starter kit" of low cost-no cost sealing materials. As measured by a before-and-after blower door test, this program documented the impact of air leakage information and the occupants' initiative in retrofitting their homes.

GOALS

The goals of the research were to:

1. Define common problems associated with low-income housing in the community of Muncie, Indiana which experiences about 5500 heating degree days each year.

2. Enhance awareness of the need for energy conservation among the participants of the survey.

3. Supply information to City/State heat assistance programs so they may work out an education program for heat assistance program recipients.

4. Build a data base of commonalities of air leakage in Muncie's low-income housing.

5. Improve living conditions for some of Muncie's low-income families.

HYPOTHESIS

The hypothesis tested was: "There will be a significant difference between pre and post blower door tests in ACH and ELA in favor of the experimental group of houses."

Analysis of covariance was used to test the hypothesis. Satatistical differences are accepted at the .05 level of confidence.

PROCEDURE

The research design is a randomized Pretest-Postest Control Group Design. (Campbell and Stanley, 1967)

The population consisted of all houses in Muncie inhabited by families applying for heat assistance funds through the Muncie Housing Rehabilitation Program. The sample was obtained by assigning consecutive numbers to an existing list of applicants on file in the Muncie Housing office. Using a table of random numbers, 20 homes were selected for testing and were alternatively assigned to either the experimental or control conditions.

The investigator was given every assistance by the Muncie Housing Authority. Initial contact for each house was made by the Housing Authority. The investigator was identified as a representative of both the Housing Authority and Ball State University.

Data gathering took place during the Autumn and Winter Quarter, (September, 1985 through February, 1986). Each experimental house was tested with a Blower Door made by Infiltec of Falls Church, VA. The investigator presented the householder with a handout describing the blower door test and explained what was meant by ACH and ELA. The figures for ACH and ELA were collected and the house was investigated for leak sites with the home occupant in close attendance. During the test the householder was shown the leak sites and told how to seal them. Depending on the types of leakage found, the homeowner was given appropriate equipment (such as a caulking gun) and supplies (such as silicone or latex caulk, insulation, door and window weatherstripping, and electrical outlet gaskets), and given directions for proper installation. These materials were brought to the house 3 or 4 days after the test. The approximate value of such materials was $20 per house. Occupants were told that although there were not enough materials supplied to do the entire house, such supplies were inexpensive and would pay for themselves within one heating season.

One of the 10 houses in the experimental group was not retested due to occupant reluctance to admit the investigator upon his return.

The control group of houses was simply tested to yield ACH and ELA. This group was used to control for threats to internal and external validity. Although householders were always present during these tests, leak sites were not investigated nor reported to the occupant. Upon retesting, occupants were informed of major leak sites and were given instructions as to proper sealing techniques.

Each experimental and control house was retested four to six weeks after the initial test to determine any changes in ACH and ELA.

RESULTS

EXPERIMENTAL GROUP

	ACH		ELA (Sq. Ft.)	
HOUSEHOLDER	PRE TEST	POST TEST	PRE TEST	POST TEST
SHABAZZ	23.21	22.98	2.051	2.216
SIMS	27.94	29.05	2.539	2.914
KATES	46.43	46.45	4.377	4.417
BRITTAIN	21.65	21.54	2.294	2.293
ATHALONE	30.16	32.03	3.171	3.540
CORN	40.88	47.90	4.339	3.456
SWARTZ	18.00	19.97	3.951	4.961
RASCHE	11.79	12.33	1.437	1.582
COLE	10.97	15.99	0.787	1.927
total	231.03	248.24	24.946	27.306
mean	25.67	27.69	2.772	3.034

TABLE ONE RAW DATA FOR EXPERIMENTAL GROUP

CONTROL GROUP

	ACH		ELA (Sq. Ft.)	
HOUSEHOLDER	PRE TEST	POST TEST	PRE TEST	POST TEST
BUCKNER	17.00	17.10	3.264	3.370
EDWARDS	29.41	30.06	3.624	3.830
ODELL	42.51	41.88	3.551	3.530
JACKSON	23.93	23.83	3.851	3.841
McNEILL	26.37	27.32	2.746	3.142
ORR	46.36	46.22	4.355	4.352
BOYLE	16.08	16.36	2.119	2.200
BURTLEY	25.77	25.76	3.276	3.351
THOMAS	23.70	23.31	1.735	1.635
WYATT	24.68	24.13	2.610	1.675
total	275.81	275.97	34.131	30.926
mean	27.58	27.60	3.413	3.093

TABLE TWO RAW DATA FOR THE CONTROL GROUP

ANALYSIS OF COVARIANCE

SOURCE OF VARIATION	SUM OF SQUARES	DF	F
COVARIATES			
ACH PRE-	2044.935	1	619.8875
MAIN EFFECTS			
GROUP	17.055	1	5.169929*

*Significant at the .05 level

TABLE THREE ANALYSIS OF COVARIANCE
ACH POST TEST BY GROUP WITH ACH PRE TEST

SOURCE OF VARIATION	SUM OF SQUARES	DF	F
COVARIATES			
ELA PRE-	14.665	1	64.13764
MAIN EFFECTS			
GROUP	0.278	1	1.214097

TABLE FOUR ANALYSIS OF COVARIANCE
ELA POST TEST BY GROUP WITH ELA PRE TEST

A significant difference was observed as an increase of post test ACH for the experimental group as compared to the increase of post test ACH for the control group. ELA changes were not significantly different at the .05 level.

DISCUSSION AND CONCLUSIONS

There was a significant difference in the post test scores for ACH as compated to the control group, indicating that the experimental group of houses showed an increase of leakiness between pre and post testing. This difference was not found in the ELA data. The difference is probably atrributable to errors in measurement.

To avoid such errors in future testing it is suggested that leak sites be investigated in the post test as well as in the pre-test so that forgotten areas of leakage such as an open basement window will be closed as in the pre test. Further, the second test should be conducted under winter weather conditions, similar to the pre test.

The goal of the research to define common problems associated with low income houses (Goal 1) was unexpectedly achieved by finding that there was no improvement in the airtightness of these homes after the occupants were provided information and materials to effect such improvement. The sociological nature of the study was exploratory, opening more questions than providing answers. Goal 2, to enhance awareness of the need for energy conservation among the participants of the survey was not met, nor was Goal 3, to improve the living conditions of the participants.

At the time of testing, most occupants expressed a strong interest in making their homes more energy efficient. However, many of the occupants were infirm due either to a physical handicap or old age. These people indicated that they would have some family member or acquaintance do the necessary retrofit work.

The majority of the houses had already been subjected to some retrofit work to improve the quality of the home. Much of this work was done in the name of "energy efficiency," as insulation had been added and larger cracks had been sealed. Many of the homes had new windows installed. These windows were of poor quality and were not sealed tightly. A casual observation of the investigator was that the houses which had been worked on by city-hired contractors were not any more air tight than those which had yet to be retrofitted.

Major leak sites tended to be at the windows and doors of the houses. The windows did not fit or seal properly and doors had warped and did not fit their frames. The windows and front doors were a problem in all 9 experimental houses. The rear doors were a problem in 8 of the 9. Since one of the goals (goal 4) was to build a data base of commonalities of air leakage in Muncie's low income housing, the following list is a beginning.

Other leak sites included the following:

Electrical outlets/switches: 7 houses
Heat vents/ducts: 6 houses
Floor (Trim, cracks, holes): 5 houses
Plumbing stack: 4 houses
Cracks or holes in walls: 4 houses
Attic door: 3 houses
Basement: 2 houses
Ceiling fan: 2 houses
Kitchen base cabinets: 2 houses
Furnace: 2 houses
Clothes dryer vent: 2 houses
Air conditioner: 1 house

It is obvious that the occupants in this study did not act to improve the conditions of their homes. In some cases upon being visited for retesting, the "starter kit" of air sealing materials was still in the original container, showing that the materials had never been used.

The length of time between the pre test and the post test was 4 to 6 weeks. This gave sufficient time for a motivated householder to make substantial improvement in the air tightness of the house. A longer time span would provide time for more people to initiate improvements in the building envelope. However, the testing should all occur during the winter months to measure actual user living patterns.

Since there was no improvement in air tightness as a result of the testing and instruction, it remains open to question as to whether air tightness information is reaching the average homeowner. Also open to question is whether such information is understood (as in the case of the householders in the experimental group) and whether other socio-economic factors are operating to influence the application of self-help measures in improving the quality of their homes. Further testing with a different population, perhaps with middle income families, would yield results that could provide some insight on the techniques most helpful in achieving homeowner information (Goal 3.)

The houses tested were much leakier than the average house in the city of Muncie, Indiana. These homes are in dire need of repair both structurally and cosmetically. If such repair were conducted by competent contractors and with sufficient funding, such structural and cosmetic repairs would serve to make the houses more energy efficient due to increased insulation and air tightness. If such repair were also conducted with a better understanding of energy conservation practices on the part of the contractor, the houses could easily and inexpensively be insulated and air sealed to achieve comfort and economy for the occupants.

OCCUPANT INTERACTION WITH VENTILATION SYSTEMS

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POSTER P5

EFFECTS ON VENTILATION BEHAVIOUR OF INHABITANTS IN RESIDENTIAL BUILDINGS

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SYNOPSIS

The effects on ventilation behaviour of inhabitants in residential buildings have been investigated as a part within a several years' German r and d programme. The investigations have shown that the ventilation behaviour seems to be dominated by traditional behaviour patterns, e.g. ventilating bedrooms, and subjective impressions. There is only a modest correlation between window opening and needs for indoor air quality and energy conservation. Up to now most of the inhabitants do not assess correctly their own window opening behaviour. Also different ventilating systems did almost not influence the inhabitants' window opening behaviour. The main reasons may be a lack of information and motivation.

1. THE OBJECTS

The investigations had been carried out in the following types of residential buildings

- Solarhouse Freiburg, 12 dwellings, exhaust and exhaust-supply ventilation system with preheating
- Demonstration Project Worms, 3 blocks of flats, 230 dwellings, mechanical and natural ventilation systems, heat recovery
- Demonstration Project Berlin, 9 dwellings, exhaust and supply ventilation systems
- Demonstration Project Duisburg, 24 dwellings and 4 dwellings for comparison, mechanical ventilation system with heat recovery.

As measurement techniques microswitches, observations by observers and photographs, auto-observation as well as questionnaires have been used.

2. MOTIVES FOR WINDOW OPENING

Window opening's frequency and duration is mainly a function of the type of the room. In the kitchen short-ventilation is preferred with a maximum (percentage of windows opened) about noon. In the case of bedrooms the percentage of opened windows over the whole day is highest, compared with all other rooms. There is a maximum in the early morning. Short-ventilation is practised only to some extent, more usual is day-night ventilation.

The maximum for living rooms has been observed in the early morning with a clear tendency to short-ventilation.

As a rule, inhabitants ventilate more during the day than at night, this is also valid for bedrooms. The type of room ventilation reveals that the inhabitants do not necessarily ventilate more offen during their presence. Sometimes the windows are also tilted in their absence.

Asked for the reasons of their window opening's behaviour, the preference in the inhabitants answer was the need for "fresh air" without more detailed explanations. On rank 2 the reason "to clean up" followed, especially for bedrooms. On rank 3 "to avoid odour, e.g. tobacco smoke" was quoted.

Therefore it can be assumed that the profile of motives for window opening is based on traditional habits.

3. METEOROLOGICAL EFFECTS

In the Demonstration Project Duisburg, see E. Eshorn this conference, a clear dependence of the duration of the window opening on outdoor temperature and wind speed could be shown. For all types of rooms the window's opening duration increased with increasing outdoor temperatur and decreasing wind speed, in good accordance with former investigations of other teams.

In the Demonstration Project Berlin only in the case of temperatures of below 0°C and above 25°C the tendency to ventilate a little less or more was observed. In these investigations the outside temperature affected primarily the opening time of glass doors and casement windows.

It must be suspected that for outside temperatures below 0°C in many dwellings the air exchange may not be sufficient to meet an indoor air quality necessary to avoid problems for hygiene and building physics, if no other ventilation systems are installed and work properly.

4. INFORMATION AND MOTIVATION

The inhabitants' self-assassment with regard to their ventilation behaviour, as the investigations have shown, up to now is not good correlated with the real facts. A comparison of measured window openings with inquiries of the inhabitants results in inconsistency (figure 1).

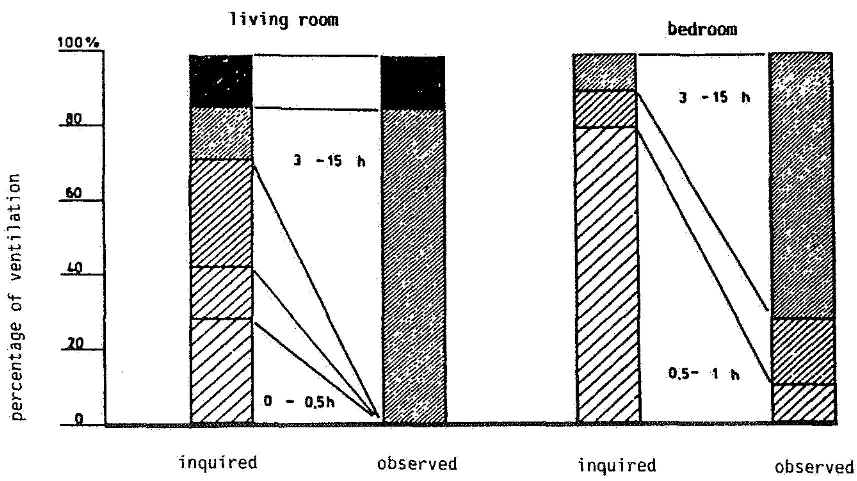

Figure 1: Comparison of inquired and observed window opening durations (results from Demonstration Project Berlin)

The inhabitants tend offen to underestimate their real windwo opening. The necessary window opening or closing remains undone, because of a lack of understanding of the ventilation effects, because of acting in traditional patterns etc. Also if the buildings were equipped with ventilating systems the window opening pattern followed the above mentioned scheme. To link indoor air quality requirements and energy conservation aspects with inhabitants' ventilation behaviour a better information and a higher degree of motivation is needed.

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