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'Blue Pages'

Welcome to the 'Blue Pages'. This is where the Editorial Advisory Panel for *Building Services Engineering Research and Technology* publishes state-of-the-art articles on developments in building services engineering practice and research. The articles are very short, on one theme of current interest, and are edited by a guest editor rather than going through the longer refereeing process for conventional research papers. This is to encourage consultants and contractors to discuss their latest developments in a non-commercial manner. Academics will also be asked to outline current research areas in universities and colleges. Without the constraint of full refereeing there is scope in the articles to provoke interest and to raise issues for discussion. Consequently the Editor of *BSER&T* is happy to receive and publish letters furthering the discussion of 'Blue Pages' articles. If you have a suggestion for an article or topic you would like to see included in the 'Blue Pages' please inform the Editor, Barry Copping. Comments on the 'Blue Pages' are also welcome. 'Blue Pages' will only succeed if readers of the journal wish the feature to succeed and contribute to its success.

Ventilation

Introduction

Martin W Liddament (Air Infiltration and Ventilation Centre)

Ventilation is of fundamental importance in securing a healthy indoor environment. It is essential for meeting the metabolic needs of occupants and for diluting and removing unavoidable pollutants emitted within a space. On the other hand, unnecessarily high rates of air change can present an excessive burden on heating (or cooling) needs, thus incurring a heavy energy penalty. The topic of ventilation is therefore pivotal in indoor air quality and building energy evaluation.

The objective of this issue of 'Blue Pages' is to highlight some of the ventilation research and application currently taking place in several of the participating countries of the Air Infiltration and Ventilation Centre. A diverse range of topics has been selected. From the United Kingdom, an account is given of a multi-zone test facility which may be used to verify the mathematical techniques needed to analyse tracer-gas data for interzonal air flow analysis. This is complemented by a contribution from Switzerland that describes current numerical techniques for air flow and ventilation prediction. Other articles include a review of recent ventilation and filtration developments in clean room technology from Denmark and the development of combined ventilation and floor heating systems from Germany.

As ventilation and heating systems become more complex, operational and maintenance needs become more demanding. A Finnish contribution looks at problems associated with the long-term reliability of ventilation systems incorporated into housing complexes in the early 1980s. Continuing with housing, a recent nationwide study on the ventilation performance of the Swedish housing stock is described, and from Belgium comes a report on the design and construction of a new generation of passive solar homes. The final paper comes from Italy and looks at the ventilation needs for room combustion appliances.It is hoped that this selection of articles will generate interest in current ventilation-related activities.

Ventilation rates and air tightness levels in the Swedish housing stock

J Kronvall (Technergo AB) **and C-A Boman** (Swedish Institute for Building Research)

1 Synopsis

This article reports the results from ventilation and air tightness measurements made in Swedish dwellings. The measurements were performed as part of the 1992 Swedish Energy and Indoor Climate Survey (the ELIB study) in which the indoor climate in a random sample of 1200 single- and multi-family houses from the Swedish housing stock was investigated. The ventilation measurements were made, using a passive tracer-gas technique, over a period of one month in each house or flat. The air tightness of a sub-sample of 90 buildings was measured using a Swedish standard pressurisation technique. The main results are that the average ventilation rate is lower than 0.35 l $s^{-1}m^{-2}$ or 0.5 ac h^{-1} in more than 80% of all the single-family houses and more than 50% of all the multi-family houses. Approximately 50% of all the houses have a ventilation rate higher than 10 l s^{-1} $inhabitant^{-1}$. The influence of age, construction year, ventilation system, renovation status and geographical region can be traced by means of a scheme of relative-difference correction factors. The investigation of the air tightness of the houses showed that newer houses are less leaky than older ones and that the prescribed maximum n50-leakage value, given in the Swedish Building Code, is reached only by the newest multi-family houses.

2 Background

A nationwide energy and indoor climate survey, the ELIB study[1,2] has been carried out in Sweden. Several indoor air quality parameters, among them ventilation rate, were measured in a random sample of 1200 single- and multi-family houses from the Swedish housing stock. A sub-sample of 90 single- and multi-family houses was investigated in more detail[3]. Tests in these houses included air tightness measurements by whole building pressurisation.

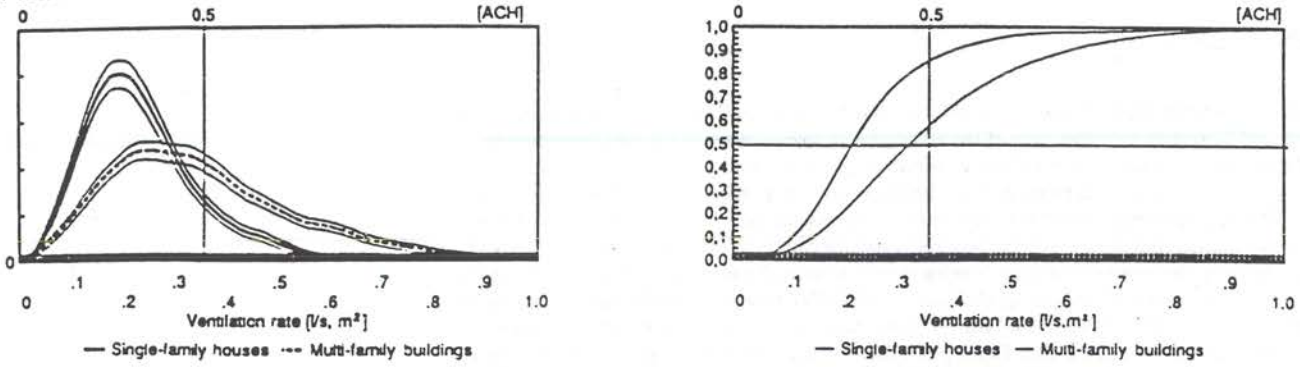

Figure 1 Frequency (left) and cumulative (right) distributions of the ventilation rate expressed as flow rate per square metre of the floor area and air change rate (ac h^{-1}) for single-family houses (full curve) and multi-family houses (dotted curve). Thin curves for the frequency functions show the upper and lower limits for the statistical uncertainty.

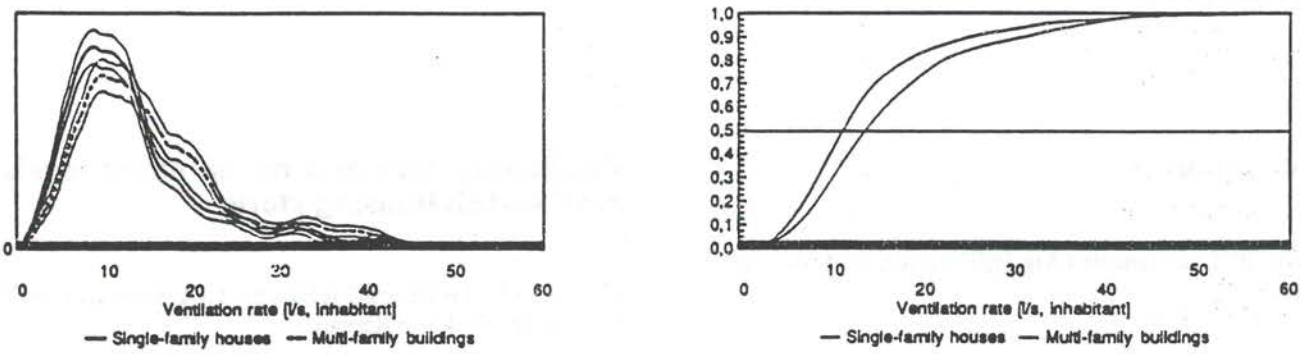

Figure 2 Frequency (left) and cumulative (right) distributions of the ventilation rate expressed as flow rate per inhabitant (ac h^{-1}) for single-family houses (full curve) and multi-family houses (dotted curve). Thin curves for the frequency functions show the upper and lower limits for the statistical uncertainty.

3 Ventilation rates

3.1 Measurement technique

Measurements using a 'passive' constant emission tracer gas technique (i.e. the PFT method using perfluorocarbon tracers) were undertaken. The further development of the method for this investigation, which was performed at the Swedish Institute for Building Research, is described by Stymne and Boman[4]. In this investigation, the tracer gas method has been applied as a single or (mainly in two-storey houses) as a two-zone model.

3.2 Results

The results of the long-term PFT measurements are summarised in Figures 1 and 2. The method used for estimating the distribution functions is described by Waller and Hogberg[5]. For each dwelling, measurements were taken for approximately one month in the period November 1991 to April 1992.

In Figures 3 and 4 the average ventilation rates in the Swedish housing stock are presented for different types and ages of residential buildings.

Based on these diagrams some obvious observations are as follows. The variation in average ventilation rates (expressed in l s^{-1} m^{-2}) is very large. It ranges from an average value of 0.20 for single-family houses built in 1961–1975 to a value nearly twice as large (0.38) for multi-family houses built up to 1940.

— The average ventilation rate for all single-family houses of all ages falls below the prescribed ventilation rate for dwellings of 0.35 l $s^{-1}m^{-2}$ given in Swedish Building Regulations from 1975 onwards. This is also the case for most multi-family houses, except for the group with the oldest houses and the group built in 1961–1975.

— Generally, the average ventilation rates in multi-family houses are higher than in single-family houses. There is no exception in any age group.

— When the average ventilation rate based on the number of inhabitants (l s^{-1} $inhabitant^{-1}$) is considered, the variation is small, both between different age groups of the same type of house and between different types of houses.

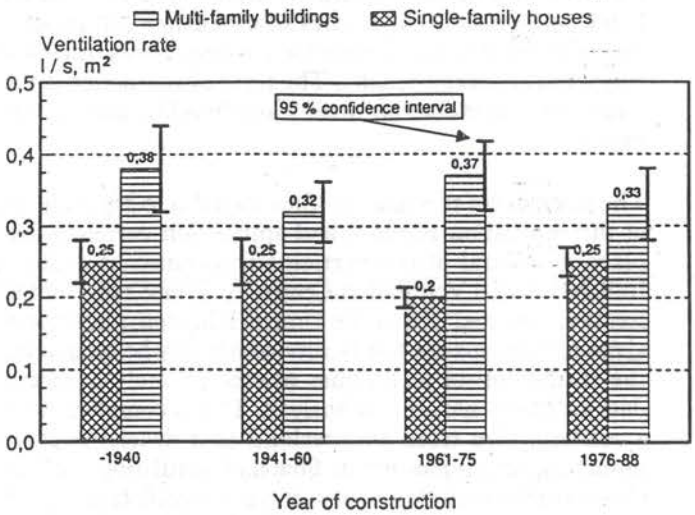

Figure 3 Average ventilation rate (l s^{-1} m^{-2}) in the Swedish housing stock by type of building and year of construction. 95% confidence intervals of the averages are indicated.

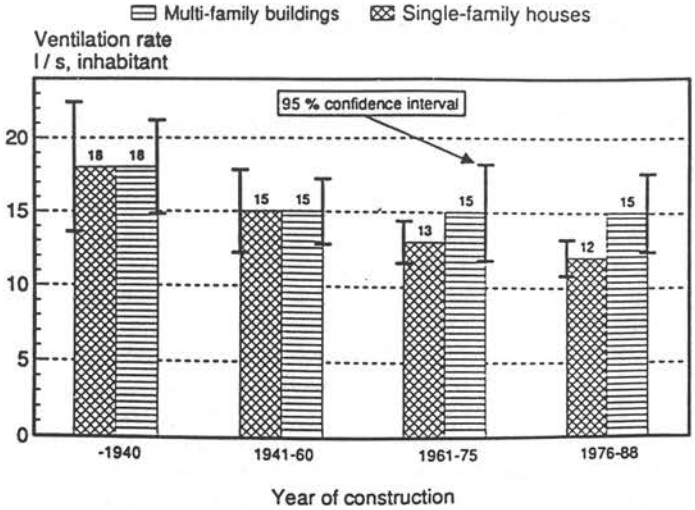

Figure 4 Average ventilation rate (l s^{-1} inhabitant^{-1}) in the Swedish housing stock by type of buiding and year of construction. 95% confidence intervals of the averages are indicated.

In order to analyse the extent to which specific factors such as age, ventilation system, renovation status and geographical region influence the average ventilation rate of dwellings, log-linear regression analyses were performed. The results are summarised in Tables 1 and 2[2].

Here it is assumed that the average ventilation in a group of residential buildings can be written as the product of a reference value and factors representing age, renovation status, ventilation and geographical region. Thus the average ventilation in a group of buildings can be roughly estimated by multiplying the reference value by the actual relative differences. Consider, for example, the group comprising all naturally ventilated, non-renovated single-family houses built in or before 1960 in central Sweden. Table 1 can supply the following estimate of its average ventilation in litres per second per person: $12 \times 1.10 \times 1.02 \times 1.04 = 14.4$.

4 Air tightness

4.1 Sample and measurement technique

The sub-sample of 90 single- and multi-family houses was drawn from the random sample of 1200 houses used in the main investigation. The sub-sample is identical to the sample chosen by the Swedish Institute for Building Research for quality control purposes relating to the subcontractors hired to inspect the houses in the main investigation. Practical aspects, such as availability, travel optimisation etc. may have influenced the choice of houses for the sub-sample, which means that it is not a truly random sample. However, the houses in the sample represent a wide variety of buildings in different geographical regions.

Table 1 Ventilation in single-family houses by construction year, renovation status, ventilation system and geographical region. Relative differences for significant factors are given in bold type. Single-family houses dating from or before 1960 with mechanical ventilation are not included in the analysis because too few observations were made.

(*a*) *Ventilation* (l $s^{-1}m^{-2}$); *Average relative difference (reference value = 0.22) according to:*

Construction year	Ventilation system	Renovation status	Geographical region
–1960 1.04	(Natural vent. 1.00)	Not renovated 1.05	Southern Sweden **1.01**
1961– 0.96	Natural vent. **0.78** Exhaust vent. **0.99** Supply-and-exhaust vent. **1.23**	Renovated 0.95	Central Sweden **1.07** Northern Sweden **0.91**

(*b*) *Ventilation* (l s^{-1}person^{-1}); *Average relative difference (reference value = 12) according to:*

Construction year	Ventilation system	Renovation status	Geographical region
–1960 1.10	(Natural vent. 1.00)	Not renovated 1.02	Southern Sweden **1.04**
1961– 0.90	Natural vent. **0.92** Exhaust vent. **0.98** Supply-and-exhaust vent. **1.11**	Renovated 0.98	Central Sweden **1.04** Northern Sweden **0.92**

Table 2 Ventilation in multi-family houses by construction year, renovation status, ventilation system and geographical region. Relative differences for significant factors are given in bold type. Multi-family houses dating from or before 1960 with mechanical ventilation are not included in the analysis because too few observations were made.

(*a*) *Ventilation* (l $s^{-1}m^{-2}$); *Average relative difference (reference value = 0.30) according to:*

Construction year	Ventilation system	Renovation status	Geographical region
–1960 1.04	Natural vent. **0.95** Exhaust vent. **1.05**	Not renovated 1.06	Southern Sweden **1.09**
1961– 0.96	Natural vent. **0.86** Exhaust vent. **1.01** Supply-and-exhaust vent. **1.13**	Renovated 0.94	Central Sweden **1.05** Northern Sweden **0.86**

(*b*) *Ventilation* (l s^{-1}person^{-1}); *Average relative difference (reference value = 13) according to:*

Construction year	Ventilation system	Renovation status	Geographical region
–1960 1.07	Natural vent. **1.00** Exhaust vent. **1.05**	Not renovated 1.03	Southern Sweden **1.07**
1961– 0.93	Natural vent. **0.86** Exhaust vent. **0.99** Supply-and-exhaust vent. **1.15**	Renovated 0.97	Central Sweden **1.06** Northern Sweden **0.87**

The pressurisation technique described in the current Swedish standard was used to assess the air tightness performance of the houses which were tested. The result of the test is expressed as the leakage rate at 50 Pa (average of leakage at over- and under-pressure) divided by the house or flat volume (unit: 1 h^{-1}). It should be noted that the figures relating to multi-family houses refer to individual flats, not the whole building. Due to limitations in the capacity of the measurement equipment, results from five single- and five multi-family houses are unavailable.

4.2 Results

The results of the air tightness measurements are summarised in Figure 5, from which it can be seen that:

— The standard deviations are rather large; this is due to the relatively small number of houses in each age-group.

— There is a clear trend which indicates that newer houses are less leaky than older ones.

— Multi-family houses have lower n50 values than single-family houses; this is due to a higher volume-to-leakage area relationship in the multi-family buildings.

— Compared to the prescribed maximum values of n50 given in the 1980 Swedish Building Code (3.0 for single-family houses and 1.0 – 2.0 for multi-family houses), only the newest multi-family houses (on average) seem to meet the prescribed level.

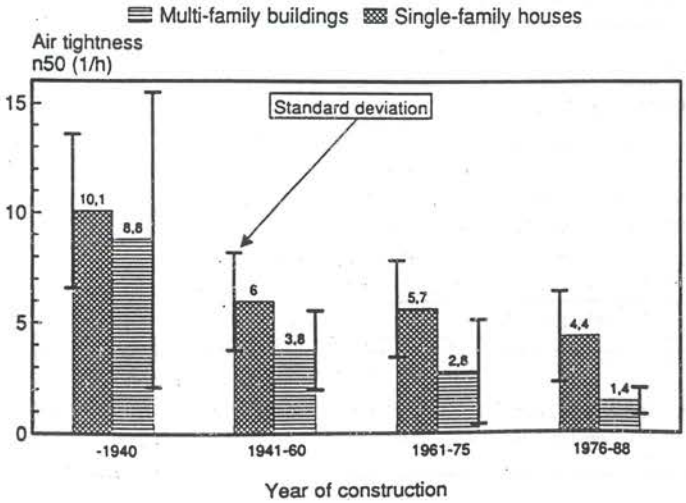

Figure 5 Air tightness of a sample of 50 single-family houses and 30 flats in multi-family houses of different ages in Sweden

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A four-zone ventilation test facility

C E Brouns and J R Waters (Coventry University, UK)

1 Introduction

The multi-zone theory of air flow is a well established method for determining ventilation and air flows in all types of building. This approach may be used to predict contaminant concentrations and to determine inter-zone air flows by interpreting the results of suitable tracer gas measurements. There is a large number of publications detailing the measurement of ventilation rates and interzonal air flows by tracer gas but only a small number describe validation methods in which tracer gas results are independently compared with direct flow meter measurement. The intention of this paper is to describe the four-zone test facility developed at Coventry University for the validation of tracer gas methods.

2 Design considerations for scale model test facility

Several design considerations are necessary as follows.

2.1 Number of zones

As much flexibility as possible is needed yet the system must be easy to handle. The minimum number of zones that can reflect all common recirculation and flow characteristics is four. A four-zone network gives twenty possible interzonal flows and sixteen independent flows.

2.2 Scaling factor

Previous experience has shown that relatively small volumes are adequate[6]. With this in mind and considering the limited space available, each zone was designed to have an internal volume of 1 m^3.

2.3 Time constants

An important scaling parameter is the time constant or the time taken for a complete zone volume of air to enter a zone. It has been shown from simulation studies, for example those of Heidt *et al.*[7] and Sutcliffe[8], that a minimum of two time constants of data are needed in the analysis procedure; these are the injection time of fresh air to a zone and the time taken for interzonal air transfer. Time constants should be of sufficient length to ensure an adequate number of data points. A system or fresh air time constant of 30 minutes was selected, giving a flow rate of 2 m^3s^{-1} of fresh air into each zone. The interzonal flow patterns of greatest interest occur when these flows are within a certain range on either side of the fresh air flow rate, typically between 1/10 and 10 times the fresh air flow rate. Below this range, the zones effectively behave independently, whereas above this range, the system approaches a fully mixed single zone enclosure. This gives a range interzonal air flows between 0.2 to 20 m^3h^{-1}.

3 Generating and measuring interzonal air flow

Air flows between two zones can be generated either by means of miniature fans or by means of air pumps. The choice is influenced by the method of flow measurement, these being:

— flow meters of the rotameter type

— orifice plates

— hot wire anemometers

— mass flow transducers.

Miniature fans require large-diameter pipes to achieve the desired flow rate. On the other hand, air pumps operate at much higher pressure and therefore have the advantage of requiring much smaller-diameter connecting pipes between zones. Rotameters can be used with small-diameter pipes and hence it was decided to select a combination of small-diameter diaphragm air pumps and rotameters equipped with flow control valves. The system must be designed so that the pressure in each zone remains close to atmospheric pressure and is not affected by the pressure changes in the interzonal flow paths. Firstly, each pump draws air from a zone, thus inducing a pressure rise in the flow path. Then, the air passes through the control valve, which has the effect of reducing the pressure in the system. Finally, the air passes through the flow meter and into the next zone where the pressure drops down to atmospheric. Manometers are used to check that each zone remains at atmospheric pressure. A schematic of two connected zones is illustrated in Figure 6. A bleed was inserted between the exhaust to the pump and the flow valve to improve control over the pumps and to prevent the overloading of their motor.

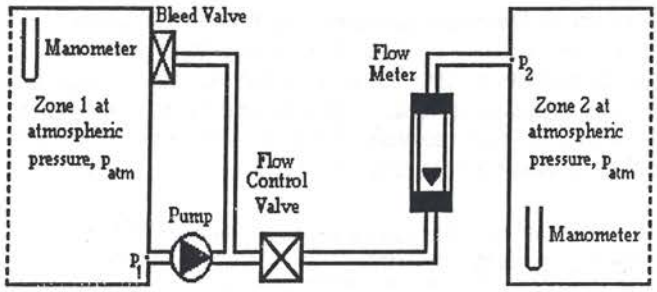

Figure 6 Schematic of typical flow path between two zones

4 Test facility construction

An 18 mm thick marine-grade plywood was used to construct each zone, which was then coated internally using a flexible and continuous chlorinated rubber paint. The joints between each panel were sealed using a latex solution and a coat of varnish was applied on the outer surface of each zone.

5 Validation measurements

The objective of the validation tests was to compare numerical methods used to analyse tracer gas estimates of flow rates between zones with the method of direct measurement under the carefully controlled environment provided by the test cell structure. The test programme was designed to explore the effects of errors due to:

— changing the interzone air flow pattern

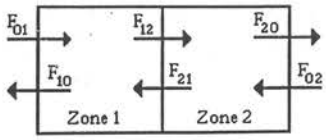

Figure 7 Schematic of two-zone model

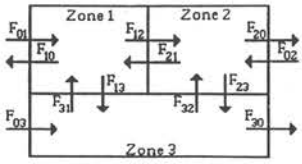

Figure 8 Schematic of three-zone model

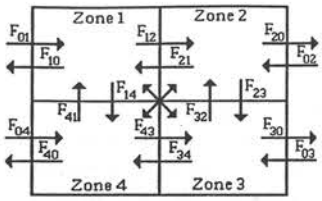

Figure 9 Schematic of four-zone model

— increasing the number of zones

— tracer gas seeding strategy

— analysis routine

— the method of analysis.

Tracer gas tests were carried out on two-zone (Figure 7), three-zone (Figure 8) and four-zone (Figure 9) configurations. Seeding strategies included tracer decay, multiple step-up tests and multiple pulse experiments. Before carrying out any experiments, the actual flow was carefully set to ensure that the pressures throughout the system were equalised, thus that the flow pattern was well balanced.

6 Results and conclusions

This test facility was found to perform reliably and has been used for a wide range of validation studies as described by Brouns[9]. Examples include the comparison of interzone air flows derived from measured tracer gas concentrations, using several analytical techniques, with those made by direct air flow measurement. Two main conclusions can be drawn from the present results. Firstly, interzonal air flows may be reliably determined from tracer gas analysis using non-negative least squares or singular value decomposition solution techniques. Other methods were found not to be as reliable. Secondly, the overall air change rate is most reliably determined from tracer gas decay testing. These conclusions become more clearly defined as the number of zones increase.

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The PLEIADE dwelling: An IEA Task XIII low-energy dwelling with emphasis on internal air quality and thermal comfort

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1 Introduction

International Energy Agency (IEA) Solar Task 13 is concerned with the design and construction of passive solar, low-energy dwellings. The aim is for each participating country to build a dwelling that, by the years 2000–2010, would represent a realistic, cost- and energy-efficient solar home. An important boundary condition is that the techniques to be applied, while not necessarily cost-effective at present, should have a reasonable prospect of being so as developments in building technology progress over the next 10–15 years. Fourteen countries are involved: Austria, Belgium, Canada, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom and the United States. Each building is to be monitored for energy and environmental performance. Currently construction has commenced in Belgium, Canada, Germany, the Netherlands and Norway. This paper reviews the Belgian contribution to this activity.

2 The Belgian PLEIADE dwelling

In support of this project, the Belgian participants have designed and are in the progress of constructing the 'PLEIADE' (**P**assive and **L**ow **E**nergy **I**nnovative **A**rchitecture **DE**sign) dwelling (Figure 10). This is a two-storey row house located in Louvain-la-Neuve, some 30 km south-east of Brussels. It has a width of 9 m and a depth of 10 m with some attic space and a basement. The rear facade is orientated south-west. An office is included in the design in anticipation of increased home working. An important objective of participation was to overcome problems associated with earlier Belgian low-energy developments, including overheating and poor durability. To accomplish this, the following design criteria were established:

- low energy demand for space heating
- good thermal insulation (Table 3)
- good all-year thermal comfort conditions
- good daylighting
- very good airtightness (< 1 ac h^{-1} at 50 Pa)
- good indoor air quality
- appealing design
- application of realistic technology
- compliance with existing Belgian Building Regulations

Table 3 U-values of various building components in the PLEIADE dwelling

Component	*U*-value (W $m^{-2}K^{-1}$)
Walls	0.14-0.20
Inclined roof	0.12
Floor above basement	0.19

- construction techniques must be acceptable to traditional builders.

Many organisations within Belgium are sponsors to this project. During construction, monitoring instrumentation was installed to allow for performance assessment. Initially the building will be unoccupied, during which time energy measurements under summer and winter conditions will be compared with predictions from design calculations. The building will be formally occupied in 1995, allowing for the effect of occupants to be evaluated.

3 Building construction

Walls, roofs and floors are insulated to well in excess of current Belgian Building Standards. The *U*-values are given in Table 3. Envelope construction is focused around the need to accommodate approximately 250 mm thickness of thermal insulation. Cavity masonry construction is used, with structural support offered by the inner leaf. The external wall is essentially non-structural. A continuous internal air-vapour barrier prevents moisture ingress from the occupied space into the construction and provides for the high airtightness specification.

4 Heating and ventilation

Gas warm-air heating is provided, combined with a four-zone temperature control system. For comparison purposes an electrical radiator system is also installed. Air quality is maintained by balanced mechanical supply and extract ventilation with air-to-air heat recovery. This is sized to meet current Belgian ventilation requirements (Table 4).

Table 4 Nominal air flow rates for the various rooms of the PLEIADE dwelling as given in NBN D50-001[10]

Room	Air flow rate ($m^3 h^{-1}$)	Remarks
Bedrooms (3.6 $m^3h^{-1} m^{-2}$)		
Bedroom 1	34	Outside air
Bedroom 2	34	Outside air
Bedroom 3	34	Outside air
Bedroom 4	34	Outside air
Office	22	Outside air
Living room	134	Recirculated air
Kitchen	50	Air extraction
Bathrooms (2)	50	Air extraction
Toilet (2)	50	Air extraction

Domestic hot water is provided by combined gas heating and solar collectors. An advanced energy management system is used to control heating, ventilation, lighting and security.

5 Design calculations

5.1 Ventilation

Advanced calculation techniques have been used to evaluate building performance. Ventilation and air quality analysis were simulated using VENCON as developed by TNO-BOUW[11]. This is a multi-zone air flow and pollutant concentration model. The building was represented by 17 zones, thus enabling the total air change rate and the flow rate of air between individual room to be predicted. An internal temperature of 20°C was assumed, while the wind pressure

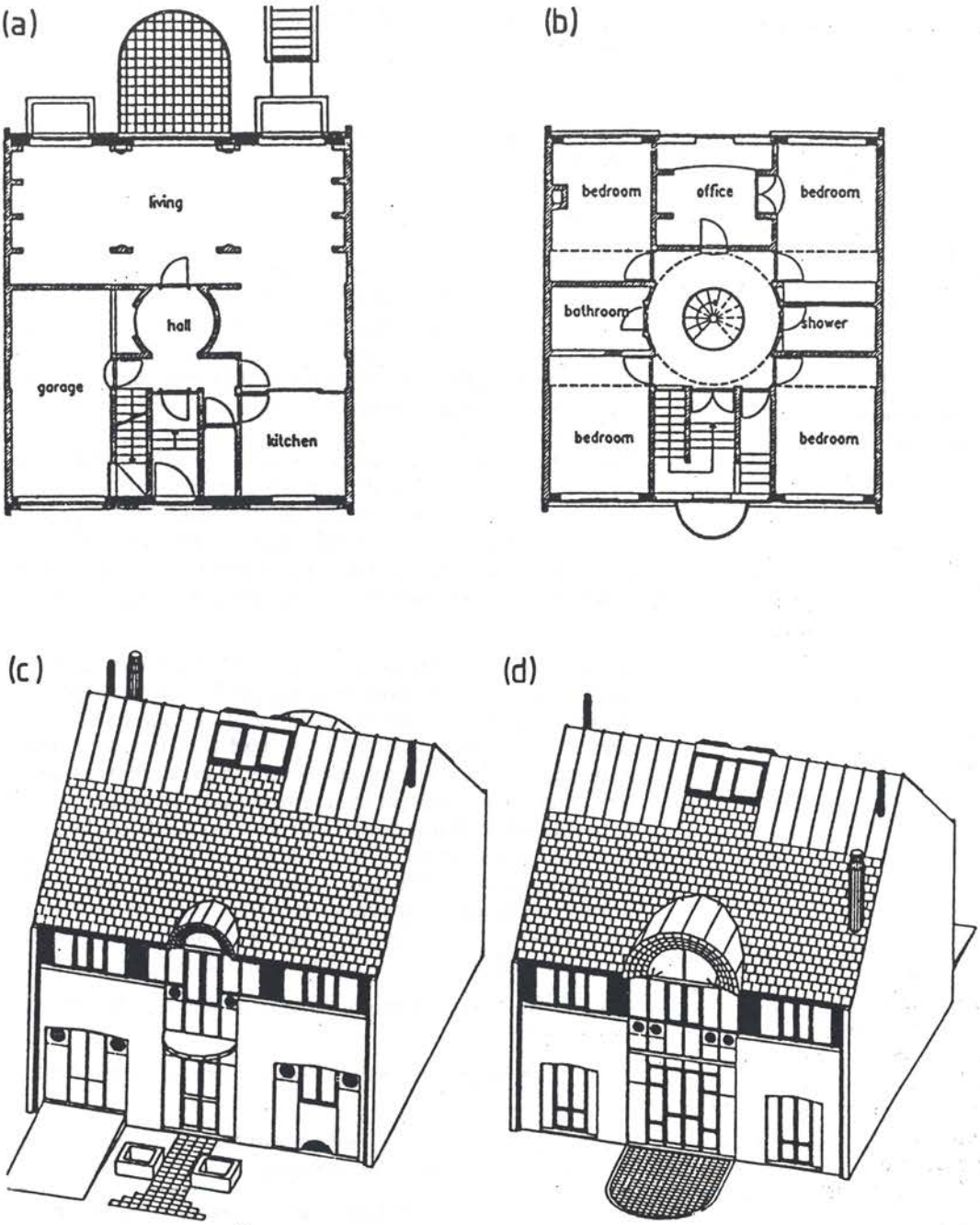

Figure 10 PLEIADE dwelling: (a) ground floor; (b) first floor; (c) front facade; (d) rear facade

distribution was based on the assumption of the building being surrounded by obstructions equal to the height of the building. The total air change rate for a range of wind and temperature conditions is given in Table 5. These results indicate that provided airtight construction is achieved, an essentially weather independent air change rate is possible.

It is common in Belgium to incorporate an extracting cooker hood in the kitchen with an extract rate of 300 $m^3 h^{-1}$. Calculations indicated that, without additional supply air, the fan would either not provide the desired air flow rate or a pressure difference of 50 Pa would be created during operation of the hood fan. To avoid this a cooker hood with a built-in heat exchanger and separate air supply is being incorporated.

Table 5 Total air change rates (ac h^{-1}) for mechanical air flow rates and transfer openings dimensioned according to NBN D50-001

Temperature (°C)	Air flow rate (m s^{-1})				
	0	4		10	
	0°	0°	180°	0°	180°
15	0.52	0.52	0.51	0.57	0.54
0	0.51	0.52	0.51	0.57	0.54
−10	0.51	0.51	0.50	0.57	0.54

The building design allows for a combination of shading and night cooling to provide acceptable thermal conditions during the Summer. Simulations of air change for night cooling were based on:

(*a*) three openings, each of 0.25 m^2 in the living room

(*b*) openings of 0.25 m^2 in each bedroom

(*c*) two openings each of 1 m^2 in the attic space.

Each of configurations (*a*)–(*c*) was simulated (i) with internal doors closed and (ii) with internal doors open.

For average summer windspeeds of 1 ms^{-1}, ventilation rates of between 6 and 8 ac h^{-1} were predicted with little difference between results for closed and open internal doors. At a less common higher windspeed of 4 m s^{-1}, much greater ventilation rates of up to 35 ac h^{-1} were predicted when internal

doors were open. These high levels were associated with cross-ventilation.

5.2 Thermal modelling (summer conditions)

Thermal modelling was accomplished using the dynamic multi-zone thermal model, MBDS[12]. This was used to assess the benefit of shading and ventilation rate on internal air temperature during periods of extreme Summer heat. Example configurations and results are summarised in Tables 6 and 7. The maximum predicted air temperature under optimum conditions of shading and high ventilation was estimated to be 25°C, as compared with an outdoor maximum of 32°C.

Table 6 Total air change rate (ac h^{-1}) for the whole dwelling and lowest ventilation rate in one of the bedrooms, $T_i = 25°C$, with bedroom doors closed

v ($m\ s^{-1}$)		T_i(°C)			
		20		15	
		n_{tot} (h^{-1})	n_{min} (h^{-1})	n_{tot} (h^{-1})	n_{min} (h^{-1})
1	0°	5.9	2.8	8.2	3.7
	180°	6.1	2.8	8.3	3.6
4	0°	13.1	3.1	14.1	3.8
	180°	13.1	3.0	13.6	3.8

Table 7 Total air change rate (ac h^{-1}) for the whole dwelling and lowest ventilation rate in one of the bedrooms, $T_i = 25°C$, with bedroom doors open

v ($m\ s^{-1}$)		T_i(°C)			
		20		15	
		n_{tot} (h^{-1})	n_{min} (h^{-1})	n_{tot} (h^{-1})	n_{min} (h^{-1})
1	0°	6.5	5.4	8.6	3.2
	180°	6.7	9.1	8.8	8.9
4	0°	17.6	32	18.5	33
	180°	17.5	34	17.6	35

6 Conclusions

The purpose of the PLEIADE dwelling is to achieve an energy-efficient, architecturally attractive building with good thermal comfort and optimum indoor air quality. These must be accomplished within a realistic and modest budget. This building is currently under construction with monitoring about to commence.

Acknowledgements

The authors wish to thank the Walloon Region for financial and moral support. They also wish to thank Electralabel and its laboratories Laborec; ARGB, COMITA, BCD as well as the sponsors to the project.

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Long-term performance of residential ventilation systems

M-L Pallari and M Luoma (Technical Research Centre of Finland)

1 Introduction

During the 1980s several demonstration buildings were constructed in Finland which incorporated novel technical solutions aimed at saving energy and improving indoor air quality. Warm-air heating systems and ventilation heat recovery units were installed in multi-storey and single-family buildings, and mechanical supply and exhaust air and heat recovery units were retrofitted into two multi-storey buildings. The performance and energy consumption of the systems were monitored and the opinions of occupants were obtained. These systems were intended to give occupants more opportunity to influence thermal comfort and ventilation. However, because the systems were complex, they were prone to malfunctions and had increased maintenance requirements (Figure 11).

A follow-up study was carried out in 1992–3 on nine of these buildings with the purpose of assessing the long-term performance of the residential ventilation and heating systems. As part of this follow-up, the energy and ventilation systems were examined and exhaust air flows and pressure conditions were measured. Changes in long-term energy consumption were estimated. Maintenance staff were asked about the malfunctioning and repair of the devices and also about regular maintenance work. The latter included changing filters every three to six months, vacuum cleaning the heat recovery units every twelve months (for single-family units only) and cleaning ducts and air terminal devices as necessary.

The heating and ventilation systems included in the follow-up study were:

- two air heating systems in multi-storey residential buildings
- two mechanical supply and exhaust air systems in multi-storey residential buildings
- one solar and earth-heat pump system in a single-family house
- one solar heating system in a terraced house
- one air heating system in a terraced house
- two heat recovery systems in multi-storey residential buildings installed during renovation.

The energy and ventilation systems were more complicated than those in normal use (Figure 11) and contained the newest technology. None of the systems had been altered since installation, although additional electric heaters had been installed in some of the air-heated terraced dwellings, and the solar heat unit of the solar and earth-heat pump system had not been in use since 1984.

2 Energy consumption

Generally, the total energy (heating of buildings, hot water and domestic electricity) consumption in Finland rose by approximately 12% between the period 1982–5 and the period 1989–90[13]. In comparison, the heating energy consumption

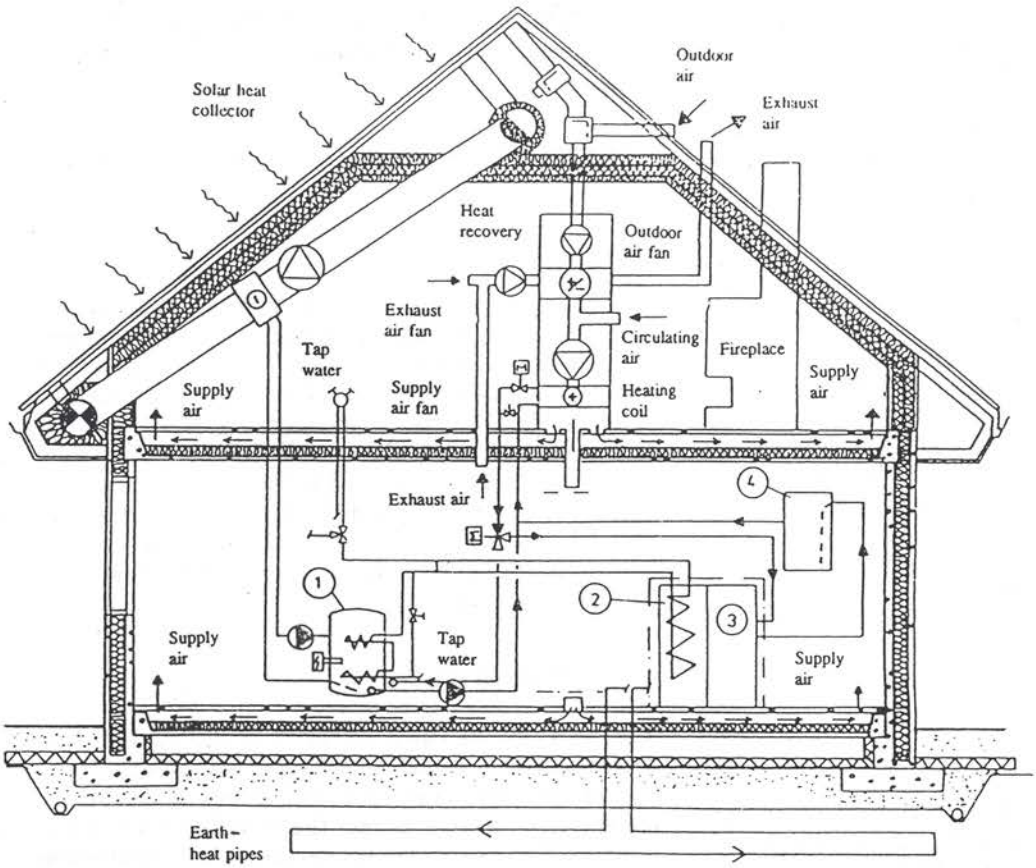

Figure 11 Demonstration building with solar energy, earth-heat pump and warm-air heating systems. This example illustrates a complicated heating and ventilation system. Too many new units should not be examined at the same time. 1 Storage of solar heat; 2 Storage of hot tap water; 3 Heat pump; 4 Storage of heating energy

of the demonstration buildings rose by between 2–39%, except for the air-heated multi-storey building, where it fell by 7%. The heating energy consumption (30 kWh $m^{-3}a$ – 57 kWh $m^{-3}a$) of the demonstration buildings was, however, lower than that of corresponding Finnish residential buildings (63 kWh $m^{-3}a$), due to the energy efficiency measures.

Changes in occupant behaviour[13] and falling energy prices affected energy consumption in the demonstration buildings. The increase in energy consumption was greatest in the fuel-oil heated terraced house, where the energy consumption in 1990 was 39% more than in 1979. This correlated with the fall in the real price of fuel oil as compared with other energy sources.

Ageing of the heating and ventilation systems in the longer term were also associated with increased energy consumption. For example, the study found that some control valves did not function as designed and that energy meters had not been calibrated after installation.

3 Ventilation rate and indoor air quality

In this study, the measured ventilation rates were low (0.02-0.71 ac h^{-1}). Only two dwellings, from the 21 measured, reached the minimum ventilation rate of 0.5 ac h^{-1} as specified by Finnish Standards. By comparison, a study of 251 typical Finnish dwellings showed that 52% did not fulfil the minimum ventilation rate (measured using the ptf method)[14]. In almost every measured demonstration building, the exhaust air flows had fallen by 15–94%. In one multi-storey building the exhaust air flows had increased by 9% in the flats on the ground floor but had decreased in the upper floors. Air flows and pressure conditions tended to change in the long term, for example because of occupant interaction and dirty ventilation components. Although the measured ventilation rates were low, the supply air distribution could be considered good in seven demonstration buildings where the supply air was distributed to the bedrooms and living rooms. In one building supply air was distributed to the halls and in another to the stairways.

Five demonstration buildings had warm-air heating with air circulation. In three of these buildings, occupants were asked about dust levels in the indoor air. Of those interviewed, 33%, 52%, and 72% considered that the amount of dust in their home was greater than usual.

4 Facilities for occupant control of the systems

Occupants were often unable to control ventilation devices either because control panels were unavailable to them or because use and maintenance instructions had disappeared, for example when new occupants moved into a dwelling.

In six demonstration buildings the control panels of the ventilation and air circulating devices were located in the dwellings, but in only three of them were occupants able to increase the air flow. This often, however, failed to improve thermal comfort because the outdoor air flow rate increased with the air recirculation rate. In one building the control system was broken. In two of the air-heated buildings, occupants were unable to control air flows or supply air temperatures. In one of these buildings occupants complained of draughts.

5 Maintenance

The heating and ventilating systems were maintained either by service staff or by the occupants themselves. In one

demonstration building where maintenance was the responsibility of service staff, gaskets were worn out and the exhaust air filter was not fastened properly. This resulted in a high proportion of the exhaust air entering the heat exchanger without being filtered. The measured exhaust air flow had fallen by 39% since 1980 and the supply air flow had fallen by 13%. In an air-heated building maintained by service staff the fans and filters were found to be dirty. One reason for the poor quality of servicing was that not enough time was allocated for maintenance work.

Occupants were responsible for maintenance in the air-heated terraced buildings. In these buildings, parts of the system, such as those located in the ceiling, were found to be very dirty. This was probably due to the inaccessibility of the components which made cleaning and maintenance difficult. Often, for example, bathroom air terminal devices were located in the ceiling above the bath, making cleaning difficult and even dangerous. A lack of understanding about the importance of cleaning and maintenance also contributed to poor servicing. Generally occupants had no suitable cleaning tools e.g. for cleaning fans. Even the cleaning of vents can be troublesome.

6 Conclusions

This follow-up study showed up areas of concern regarding the long-term performance of heating and ventilating systems. These systems developed in the 1980s were very complicated in design and contained prototype components. This led to difficulties during the installation and commissioning phases and with the control of the installed systems. However these problems can now be avoided with careful design and installation.

In Finland the type approval of ventilation system components was instigated in 1983. Type-approved products are quality controlled and this procedure has considerably improved the quality and performance of ventilation equipment. Current systems are also much simpler than those designed in the early 1980s.

In order to ensure the proper use of ventilation devices, the instructions should be installed on the devices. It is important, especially in air-heated systems, that occupants are able to control the supply air temperature. To keep the ventilation systems in good condition in the long term, regular maintenance work is needed and broken parts should be repaired as soon as possible. Occupants should not be responsible for cleaning and maintenance, because they lack suitable cleaning equipment and because the components requiring cleaning and maintenance are often sited in inaccessible places.

Regular inspections guarantee that the air flow rates do not change too much and the energy consumption does not rise due to malfunction of the heating devices in the long term.

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Development and investigation of a combined ventilation and floor-heating system

F Steimle and B Mengede (Universität Essen, Germany)

1 Introduction

A continuing reduction in building thermal transmission loss is adding to the overall significance of ventilation heat loss, particularly in residential buildings. While improved ventilation energy efficiency is achievable by using mechanical ventilation with heat recovery, much greater potential is possible by combining the ventilation and heating systems into one unit. The aim of the work described in this article was to develop a marketable system for the distribution of heat and ventilation air, based on a floor distribution system. The operation and performance of three potential systems are described and compared.

2 Description of systems

These systems are based on warm air distribution which is characterised by ease of control, rapid adjustment of heat levels and low-temperature operation. Moreover, warm air heating systems can incorporate the benefits of air-to-air heat recovery. Each of the systems developed is integrated into the flow design. They share a common approach to central filtering, preheating and heat recovery. Differences occur in the secondary heating of the air and in the balance between air heat distribution and surface heat distribution.

3 System 1

A single heating stage is employed in which the supply (ventilation air) is heated to 50°C by a water/air heat exchanger in a central boiler. This warmed air is distributed to the floors of each room by a series of well insulated ducts. Ducting runs through the floor from the direction of internal to outside wall. The preheated air is introduced into floor ducting at the internal wall end. The ducts terminate in a cavity of length 1 m, to equalise temperature and air velocity gradients. This supply air then flows into the room through outlet grilles placed along the inside face of the external wall. With this configuration, the fraction of heat transmitted to the room through the floor is quite small. In highly insulated homes, sufficient warmth is transmitted by the air volume necessary to meet basic ventilation needs. For poorly insulated buildings, higher air flow rates are needed to distribute an adequate amount of heat than is needed for ventilation air quality requirements alone, and hence recirculation of the supply air is necessary.

4 System 2

Heating is applied in two stages. Firstly, the air is preheated to 20-40°C, according to the heat capacity required. This air is injected into a layered floor at the internal wall end of the room in which the layer is separated by a matrix of cones (Figure 12). Room air grilles are placed along the external wall. The supply air gradually imparts its heat to the upper floor layer and steadily cools to near room temperature. Before it reaches the air supply outlet grilles to the room, it is

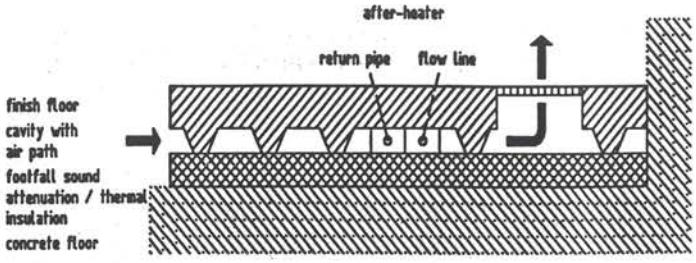

Figure 12 Second variant with floor-integrated after-heater

reheated by an embedded hot water system. This reheating enables sufficient heat to be supplied to the room in moderately insulated buildings without the need to recirculate air.

5 System 3

A conventional hot water floor heating system is placed in the upper floor layer above the supporting cones of the previous system (Figure 13). Heat from the hot water system is transferred to both the floor above and to the ventilation supply air below. This approach combines the benefits of a uniform room temperature and low supply temperature of a conventional floor heating system with the added benefits of air heating. This combination permits the use of even lower water temperatures, thus enabling low-temperature heating systems such as heat pumps to be considered.

6 Comparison tests

An extensive series of measurements was carried out so that an energy analysis of each of these systems could be made. To accomplish this each of the systems were installed in identical test rooms. The first system was chosen as a reference case against which the performance of the other systems could be compared. The main characteristic of system 2 was the rapid cooling of the preheat air before it reached the after-heater. The proportion of the heat transferred through the floor compared with that transferred by the emitted air stream is illustrated in Figure 14. When half the heat is supplied by preheat and the remainder is supplied by the after-heater, 57% of the heat to reach the room is transferred directly by the supply

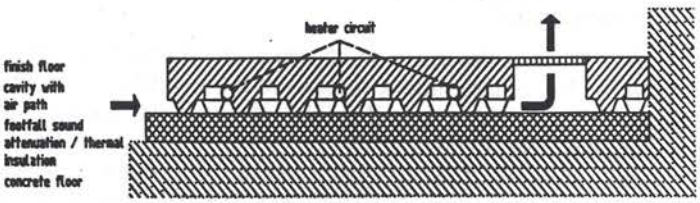

Figure 13 System 3

air. This share of the heat is directly coupled to the proportion of the heat flow supplied by the after-heater. This heating system, therefore, is easy to control by adjusting the heat output of the after-heater. The fraction of the heat supplied directly by the preheater is almost completely transmitted through the floor. Approximately 72% of the preheat is supplied to the room by radiation and the remaining 28% by convection.

By contrast with the first two systems, the air in system 3 is heated during its passage through the floor cavity. Therefore, when the air reaches the supply grille it is significantly warmer than the average room air temperature. Additionally,

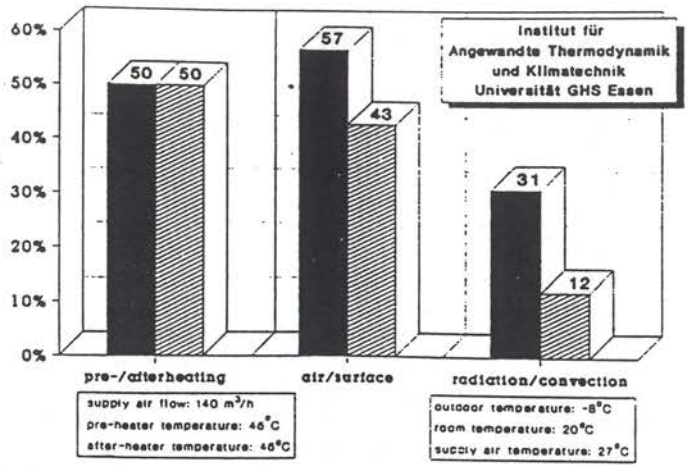

Figure 14 Second variant: Percentage of different heat flows

the temperature distribution over the surface of the floor was found to be homogeneous. The heat transfer characteristics are illustrated in Figure 15. Because the surface temperature of the floor is relatively high, the fraction of heat transferred through the floor is significantly greater than with the previous system. 90% of the entire heat flow was found to be transferred through the floor surface, 75% of which was through radiation. Assuming an air change rate of 1 ac h^{-1}, 10% of the heat transfer is through the supply air. Analysis showed that the temperature of the supply air remained almost independent of the air supply rate.

7 Conclusions

The measurements carried out under operating conditions were found to be in accordance with mathematical prediction. Both simulation and measurements showed that the heating systems developed meet the demands of thermal comfort and energy efficiency. Components had to be developed or improved to meet the special needs arising from the development of these systems.

Acknowledgement

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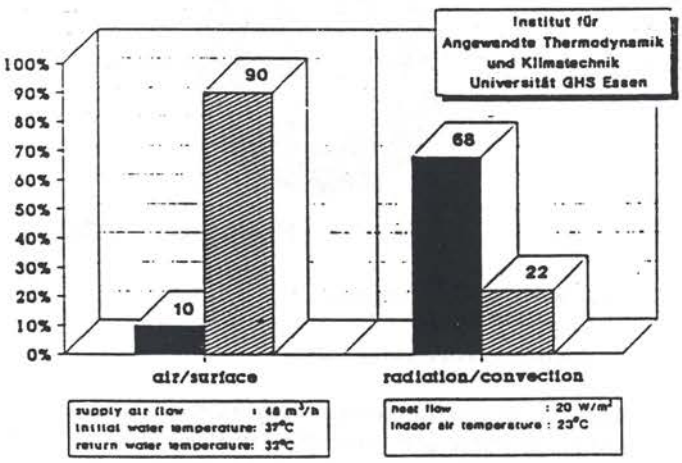

Figure 15 System 3; temperature gradient in flow direction. Supply air flow 48 m^3h^{-1}; initial water temperature 24.3°C; return water temperature 22.8°C

Clean room technology

J Pederson (Birch & Krogboe, Consultants and Planners, Denmark)

1 Introduction

Clean room technology for the control of particulates is essential for certain industrial processes. Examples include the medical, micro-electronics, mechanical equipment production, and food industries. This technology has its origins in the nuclear defence industry but developed into wider industrial applications during the 1950s and 1960s. While not providing a universal solution, it provides a tool which succeeds in reducing both particulate and microbiological contamination. The purpose of this article is to outline the need for clean room technology, to review the development of standards and to focus on design principles.

2 Needs

The primary need of the pharmaceutical and food industries is to minimise micro-organisms, whereas, for the electronics industry, the need is to avoid particulates. Frequently inert particles act as carriers to living organisms (i.e. bacteria, spores and fungi) and thus the fundamental need is the same.

Principally clean room technology is needed to perform the following functions:

— to prevent surrounding particulates from affecting production

— to prevent the spread of contaminants to the production zone.

— to prevent dangerous substances from affecting personnel.

— to prevent cross contamination from one product or zone to another.

Figure 16 illustrates the factors influencing clean room production.

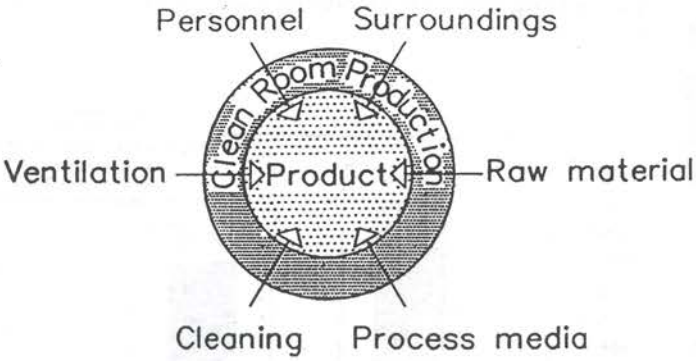

Figure 16 Clean room production

3 Definition of clean room

Often the expression 'clean room' suggests ultra-clean surroundings where personnel work in space suits. In reality it applies to a wide range of cleanliness levels. There are many definitions but probably the most frequently used is taken from Danish Standard FED-STD–209E which defines 'a clean room' as 'A room in which the concentration of airborne particles is controlled and which contains one or more clean zones'.

4 Standards

Standardisation for clean room technology is becoming both nationally and internationally harmonised. In this context the term 'standard' is applied as a general term covering a wide spectrum including:

— Standards

— Technical Orders

— Recommended Papers

— Recommendations.

International standardisation has helped in establishing a uniform terminology for users, designers and producers. Standards can primarily be divided into two main groups:

— pharmaceutical standards

— engineering standards.

An important pharmaceutical standard within the European Community is Good Manufacturing Practice[15]. The requirements indicated in this standard are aimed at ensuring a uniform quality throughout much of Europe for production, exporting and consumers. Table 8 presents an example of maximum particulate concentrations for various quality classes.

Table 8 EC-GMP[15] air classification

Class	Max. concentration of particles per m³		Max. no. of micro-organisms per m³
	0.5 μm	5.0 μm	
A (laminary airflow)	3 500	0	<1
B	3 500	0	5
C	350 000	2 000	100
D	3 500 000	20 000	500

The food processing sector currently has only a limited number of standards although experience suggests that requirements similar to those adopted by the pharmaceutical industry are applied.

Standards in the engineering sector are primarily concerned with class of cleanliness, measurement methods, control procedures and filter classification. Most of the industrialised nations have Standards, many of which are based on Fed. Std 209 (1963)[16]. This has been regularly updated; the most recent version (Edition E) has been in force since 1992. STD 209 has a good chance of becoming a worldwide standard. Particulate concentration is classified by an index M given by:

$$\text{No of particles per m}^3 = 10^M(0.5/d)^{2.7}$$

where d is the particle diameter (mm)

Table 9 presents the M classification for particles of size > 0.5 mm.

5 Design principles

Many parameters influence the quality of the finished product, as follows:

Table 9 Clean room classification in accordance with FS 209E

No. of particles per m3 ≥ 0.5 μmm^{-3}	FS 290E classification
10	Class M1
100	Class M2
1000	Class M3
10000	Class M4
100000	Class M5
1000000	Class M6
10000000	Class M7

5.1 Ventilation

A good ventilation system is one of the most important methods for keeping out and removing contamination. The selection of ventilation approach must be based on a careful evaluation of requirements and needs. Factors controlled by ventilation include:

— room purity. Air change is calculated on the basis of purity and on the infiltration of contaminant into a room.

— air movement patterns. The need for either laminar or non-laminar systems must be identified. In general requirements of M4 and above normally demand laminar systems. Pollutants should be removed at source.

— pressure conditions. To maintain the purity in a room, clean room facilities are normally designed as a 'room within a room'. A pressure difference of typically 15 Pa is maintained between rooms. The purest zone is maintained at the highest pressure. When contamination from a process is to be avoided, the pressure condition is reversed. Air locks and pressure regulation equipment may also be necessary.

The most common techniques for clean rooms are illustrated in Figure 17. Mixing or displacement ventilation may be applied where requirements are not very high. Laminar flow systems with recirculation are used where purity needs are high. For optimum air quality and economy, it has become common for traditional ventilation to be used to provide controlled 'background' ventilation and for laminar flow to be used to provide one or more 'clean' zones.

Air inlets and outlets must be located to reflect the buoyancy characteristics of air and the sedimentation of heavy particles. 'Dead zones' in which ventilation is reduced should be avoided to prevent the deposition of particles.

In biological areas, it may be necessary to protect both the process and the operator against the risk of contamination. Isolation modules may be used, including small glove boxes or larger enclosures accommodating a person.

5.2 Filtration

Filtration is a vital part of the ventilation system. The most damaging particles in the pharmaceutical and food industries tend to have a diameter greater than 0.3 μm. These must be controlled by means of high-efficiency filters (HEPA) incorporated within the ventilation system. For cost efficiency as much air as possible is recirculated through local ventilation units fitted with HEPA filters. Fresh air which has been conditioned for temperature and humidity is supplied through a recirculatory central ventilation system. A typical configuration for a laminar flow clean room design is illustrated in Figure 18.

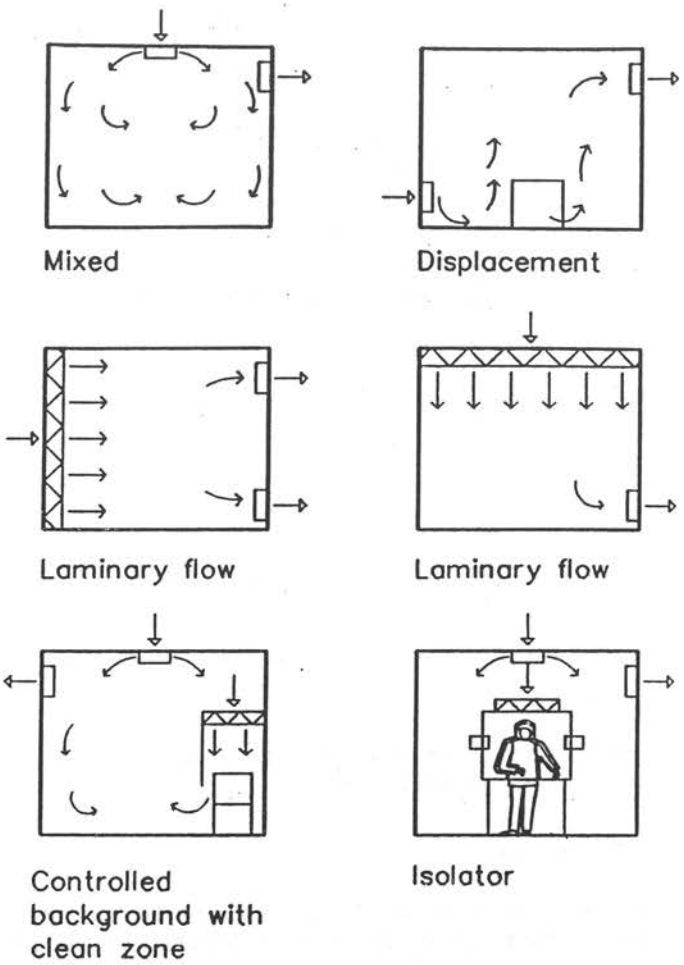

Figure 17 Ventilation principles

5.3 Building layout

It is important for the processing and person flow of the building to be designed in a rational way. An inventory must be established of raw materials, finished goods, packaging materials and personnel. Avoid the crossing of raw materials with finished goods. Cross-contamination between one product and another must be prevented.

5.4 Temperature and humidity

The production often specifies exact temperature and humidity conditions. If, however, there are no special conditions, then these should be set to satisfy occupant comfort criteria.

5.5 Utilities

Awareness of special provision for process requirements is essential. Examples include sterile vapour for humidification, sterile compressed air for processing purposes and sterile water for injection.

5.6 Equipment

Machinery must be designed and installed so that it can be accessed for maintenance without disturbing the clean room environment. Measuring equipment must be included to monitor the environment continuously. Operators must be completely confident with all instrumentation.

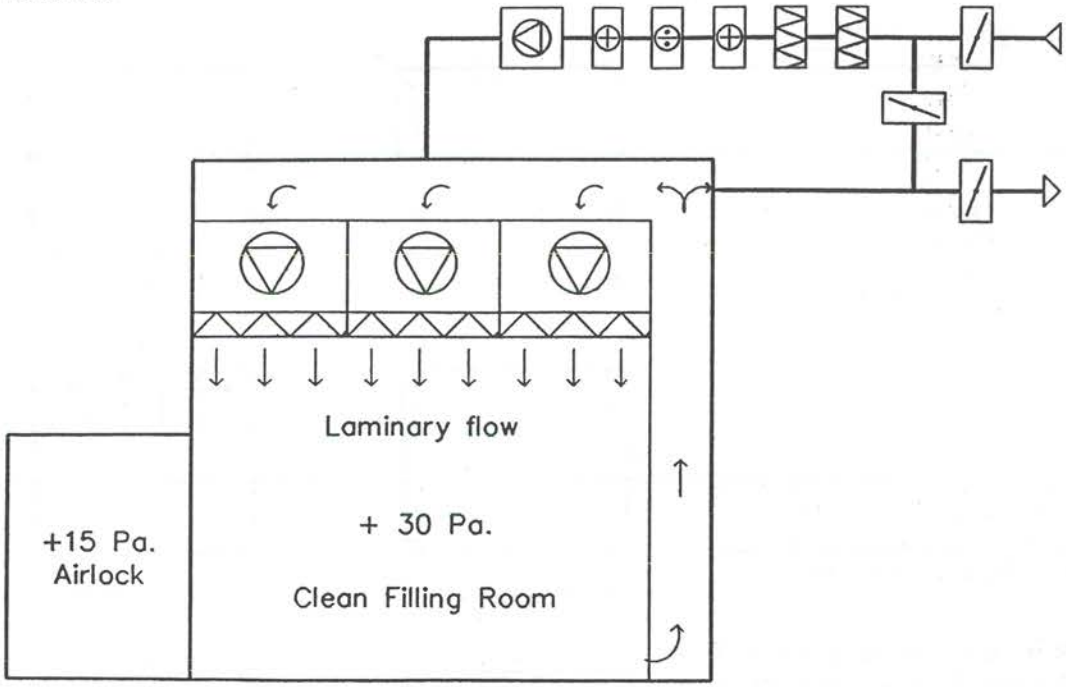

Figure 18 Room for aseptic filling

5.7 Cleaning technique

From the design stage, the cleaning methods and needs must be meticulously planned.

5.8 User training

Personnel must understand the rationale of clean room technology including knowledge of the contaminant sources and the exact requirements for the product in question.

5.9 Unambiguous output requirements

The user must be involved from the beginning of the planning facilities including room classification, compressed air purity, water quality etc.

6 Conclusions

Clean room design is evolving rapidly. Systems have a typical life of approximately ten years, therefore current technology is applicable only to the designs of today and, perhaps, tomorrow. Planning further into the future should await subsequent clean room developments.

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The influence of purpose-provided openings on natural ventilation of buildings equipped with gas-fired appliances

R Borchiellini, M Cali and M Masoero (Politecnico di Torino, Italy) **and M Girard** (ITALGAS s.p.a., Italy)

1 Introduction

In Italy, the spread of low-power gas-fired individual appliances for space heating and service hot water production, as well as concern about operational safety issues, have promoted interest in understanding ventilation mechanisms in dwellings equipped with such units.

Experimental work on gas appliances can be conducted in the laboratory[17], where individual systems or components can be characterised under strictly controllable and repeatable conditions, or in the field, when real installations are examined. The experiments described here use an intermediate approach. Measurements were conducted in one of the instrumented single-family buildings at the Italgas experimental facility in Venaria (Torino). The building, which is typical of those built in the residential sector in Italy, is very flexible in terms of the installation of thermal systems and is fully instrumented for monitoring relevant parameters such as ambient temperatures, meteorological conditions, combustion analyses, etc.

The investigations reported here are part of a research program started in 1990 and jointly developed by Politecnico di Torino and Italgas to investigate the interaction between energy performance, indoor air quality, and operational safety[18]. In Autumn 1992 a series of tracer gas measurements were made in the building during boiler operation. In each test the size of the ventilation openings and the cross section of the chimney were varied, in order to understand the influence of such factors on the overall system performance. The experimental set-up and results are described below.

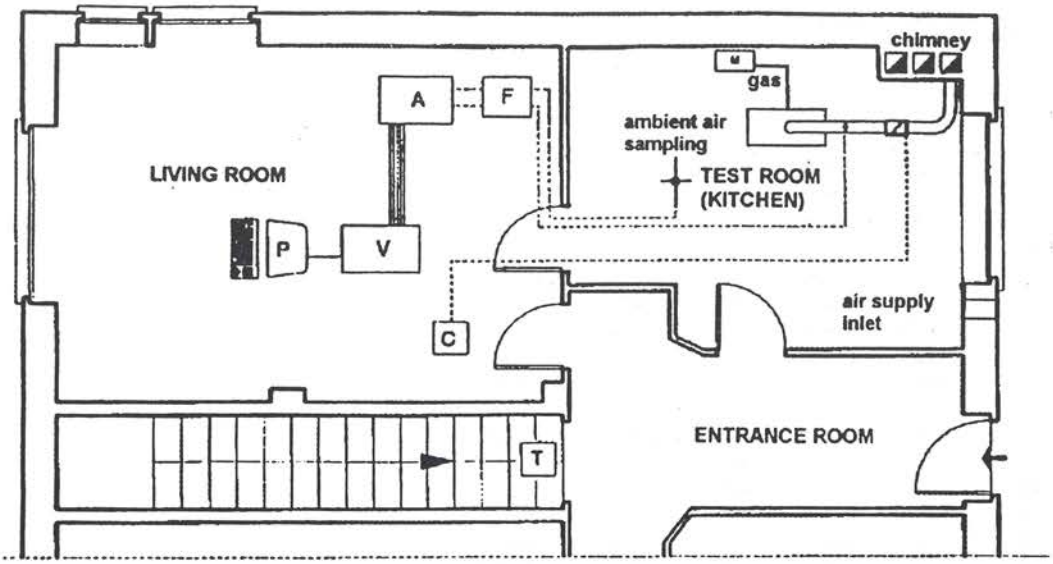

Figure 19 Plan view of test area: M gas inlet; P personal computer; F gas dryer; A gas analyser; V voltmeter; C motor-driven damper control; T tracer gas apparatus; – – – – –damper control line; . . . . . air/gas sampling line

2 Experimental set-up

The building consists of two storeys. The lower floor hosts the centralised service equipment and the data acquisition/processing system. Figure 19 is a plan view of the ground floor (in which the tests were performed) which has a floor area of 114 m². A 20 kW gas boiler for service hot water production was installed in the kitchen and connected to an existing vertical chimney (cross-section 18 × 20 cm, height 2.5 m). Combustion air was supplied by natural ventilation through a purpose-provided opening located in the lower part of the north facing external wall(under the window) sized according to Italian standard UNI-CIG 7129-72 (120 cm² in this case). During the experiment, the combustion gas exhaust conditions were adjusted by varying the cross-section of the duct connecting the boiler flue to the stack using a motor-driven damper. The supply air was also varied by obstructing the purpose-provided opening. The kitchen door was sealed with polyethylene film to minimise air transfer from the hall, but the window was usually kept closed and unsealed to reproduce realistic operating conditions.

A gas analysis system was installed in the living room. This was used to monitor the temperature and CO, CO_2, and O_2 concentrations of both the ambient air and the combustion gases. An automated multi-tracer gas apparatus developed at Politecnico di Torino[19, 20] was employed to measure air change rates. Air samples were taken at six different locations throughout the room using vertical plastic tubes radially perforated on the lateral surfaces. The air temperature was also measured at each site. Two fans were operated to achieve uniform tracer gas mixing and gas was injected immediately upstream of the fans. A laptop PC was used to control the apparatus, and for data acquisition and processing.

3 Experimental results

A summary of the experimental conditions in each test is given in Table 10. Four of the tests coded ST (special test) were aimed at selecting the most suitable experimental conditions, while the other nine tests (coded SxCy) correspond to all possible combinations of sizes of the purpose-provided opening and cross-section of chimney. Ambient air and flue gas analyses were also performed in parallel with the tracer gas measurements.

A comparison of average values and standard deviations of air change measured in each test is given in Table 11. Air changes were calculated in two different ways; firstly by assuming that the estimated parameters (i.e. flow rates) are constant in time; secondly by calculating the parameters at each time step, and then taking the average of such time dependent values. Time-dependent parameters were calculated with the Sequential Function Specification Procedure[21, 22], using a polynomial function in which the parameters are the coefficients.

Table 10 Summary of test conditions (The entrance door was sealed in all cases.)

Test code	Air supply opening (%)	Chimney cross section (%)	Tracer gas	Mixing fans operation	External window
S1C1	0	100	N_2O	On	Closed
S1C2	0	50	N_2O	On	Closed
S1C3	0	25	N_2O	On	Closed
S2C1	50	100	N_2O	On	Closed
S2C2	50	50	N_2O	On	Closed
S1C3	50	25	N_2O	On	Closed
S3C1	100	100	SF_6	On	Closed
S3C2	100	50	SF_6	On	Closed
S3C3	100	25	N_2O	On	Closed
ST1	100	100	SF_6	Off	Closed
ST2	100	100	SF_6	On	Sealed
ST3	100	50	SF_6	On	Sealed
ST4	0	0	N_2O	On	Closed

The effect on air changes of obstructing the air supply opening and throttling down the chimney cross section is shown in Table 12. The results clearly indicate that the overall air-change rate of the test room is markedly influenced by variation in air supply and/or gas exhaust conditions, with a variation trend that consistently reflects the opening/closing sequence.

Other observations can be made regarding the special test results. ST1 corresponded to S3C1, except for the absence of mixing fans. The time variations of airchanges were found to be very irregular and clearly depended on poor mixing rather than on variations in test conditions. Tests ST2 and ST3 (window closed and sealed) corresponded to S3C1 and S3C2 (window closed but unsealed) respectively. Comparison of the test results indicated that sealing the window did not significantly influence the results, since the variation in airchanges was approximately equal to 0.07 ac h^{-1} (i.e. is of the same order as σ). The results from test ST4 (total obstruction)

Table 11 Measured airchange values N_{ric} and standard deviation σ

Test code	Test length (s)	Time constant parameters		Time variable parameters					
		N_{ric} (l h^{-1})	σ(l h^{-1})	r	N_{ric} (l h^{-1})	σ(l h^{-1})	r'	N_{ric} (l h^{-1})	σ(l h^{-1})
S1C1†	2008	1.5177	0.0034	4	1.4932	2.0826	421	1.5642	0.0026
				10	1.4963	0.5673			
				20	1.5003	2.088			
				48	1.5110	0.0580			
S1C2	2020	1.1520	0.0015	48	1.1364	0.0422	428	1.1600	0.0018
S1C3	1870	1.0104	0.0009	48	0.9960	0.0344	397	1.0098	0.0016
S2C1	1814	1.7178	0.0021	48	1.6989	0.0456	382	1.7282	0.0024
S2C2	2320	1.2271	0.0010	48	1.2337	0.0405	487	1.2546	0.0015
S2C3‡	4244	—	—	48	1.1472	0.0535	897	1.1899	0.0008
S2C3A	3774	1.1748	0.0009	48	1.1630	0.0492	797	1.1972	0.0009
S2C3B	1897	1.2107	0.0007	48	1.2196	0.0347	399	1.2291	0.0017
S3C1	1824	1.9610	0.0019	48	1.9200	0.0599	395	1.9455	0.0030
S3C2	1983	1.6204	0.0013	48	1.5598	0.0587	418	1.5710	0.0027
S3C3	1893	1.5036	0.0017	48	1.4829	0.0527	400	1.5069	0.0025
ST1	2315	1.4279	0.0143	48	1.5943	0.0568	483	1.6618	0.0022
ST2	2945	1.8799	0.0012	48	1.8550	0.0872	621	1.8740	0.0022
ST3	1843	1.5526	0.0012	48	1.5274	0.0508	383	1.5148	0.0026
ST4	1906	0.6313	0.0018	48	0.6299	0.0356	402	0.6521	0.0016

†In test S1C1 the sensitivity of results to increasing r was investigated; since error decreases for increasing r, the results of the following tests were analysed with $r = 48$ only.

‡Since test S2C3 was over 1/2 hour longer than the others, three different times were considered in the analysis: ~1800 s as in the other tests; ~3774 s which corresponds to the maximum number of steps that can be processed by the time-constant parameter algorithm; actual test time.

Table 12 Effect of air supply-gas exhaust variations on overall airchanges

Air supply area (%)	Chimney cross-section (%)		
	100	50	25
100	S3C1 $N_{ric} = 1.9200 + 0.1032$ $Q_{ric} = 74.322 + 3.995$	S3C2 $N_{ric} = 1.5598 + 0.1761$ $Q_{ric} = 60.380 + 6.817$	S3C3 $N_{ric} = 1.4829 + 0.1581$ $Q_{ric} = 57.403 + 6.120$
50	S2C1 $N_{ric} = 1.6989 + 0.1368$ $Q_{ric} = 65.764 + 5.295$	S2C2 $N_{ric} = 1.2337 + 0.1215$ $Q_{ric} = 47.756 + 4.703$	S2C3B $N_{ric} = 1.1630 + 0.1041$ $Q_{ric} = 45.020 + 4.030$
0	S1C1 $N_{ric} = 1.5110 + 0.1740$ $Q_{ric} = 60.039 + 6.735$	S1C2 $N_{ric} = 1.1364 + 0.1266$ $Q_{ric} = 43.990 + 4.901$	S1C3 $N_{ric} = 0.9960 + 0.1032$ $Q_{ric} = 35.555 + 3.995$

showed that the test room was not perfectly airtight, since an airchange of about 0.6 ac h^{-1} still occurred.

The presence of a fully opened air supply caused an increase in airchanges ranging between 14 and 22 m^3 h^{-1} (depending of the area of the chimney), which corresponded to a 23–62% variation with respect to the complete obstruction case. However, a significant part of the air flow did not occur through the purpose-provided opening, but through adventitious openings. The latter could not be attributed to the window since the window sealed versus window unsealed data were virtually identical.

It appeared, therefore, that the test was influenced by the presence of adventitious openings other than windows, which had an airflow capacity of more than twice that of the purpose-provided air supply opening. Blower door pressurisation tests, performed a few days afterwards, confirmed this by identifying the presence of an air path connecting the test room and the adjacent living room.

Consequently, the results of the parametric test did not characterise the performance of the purpose-provided opening alone, and should therefore be interpreted in relative rather than absolute terms.

The combustion analysis data allowed the gas flow rate in the chimney to be estimated. By taking the measured concentrations of oxygen and carbon dioxide at the stack, and by estimating the natural gas flow rate entering the burner from the nominal power of the boiler (which was always operated at full load), the flow rate of combustion products was easily calculated from well known stoichiometric equations. Unfortunately, since the natural gas flow rate was estimated rather than measured, it was not possible to attribute a standard deviation to the chimney flow rate, as had been done for the measured airchange values.

Throttling of the chimney damper significantly affected the flow rate, which almost reduced to one half when the cross sectional area was reduced to 25% of the full value. In contrast, sensitivity of the results to variations in the air supply area was almost negligible.

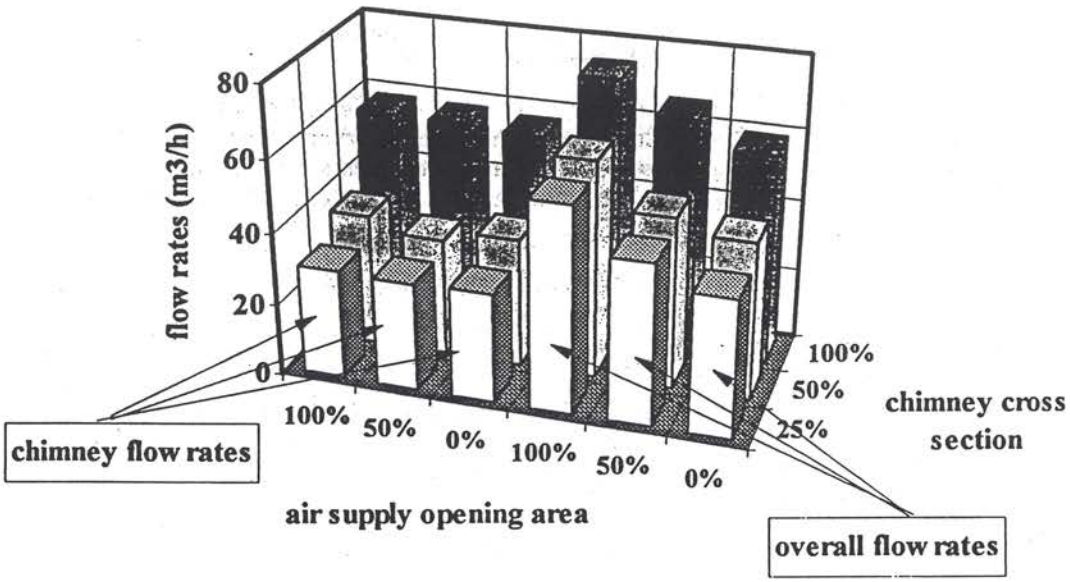

Figure 20 Overall airchange flow rates and chimney flow rates

The results of the tests are summarised in the three-dimensional bar graph of Figure 20, in which both the overall airchange flow rates and the chimney flow rates are shown. The graph indicates that the air supply area has a clear effect on overall airchanges, but does not affect the chimney flow, while throttling of the chimney does affect in comparable ways both airchanges and chimney flows. The influence of the supply opening on air changes is further confirmed by the results of ambient air quality measurements.

The CO_2 concentration increased from 800 to 900 ppm when the supply area was reduced to 50%, and increasingly higher values were attained with complete obstruction. The measured trends of CO concentration in ambient air were, on the contrary, not significant. No meaningful correlation was identified between test conditions and CO concentrations. Carbon monoxide conditions remained acceptable, even when the supply area was completely closed.

4 Conclusions

This study focussed on measuring the performance of gas-burning appliances which are installed in the living space, drawing combustion air directly from the space and exhaust combustion gasses outdoors through a chimney. Such a configuration is common in Italy, particularly in older buildings, although installation of the system does not always comply with safety codes. The results of these experiments confirmed the reliability of applying tracer gas techniques and pollutant concentration measurements to the performance assessment of such appliances.

The experiments also confirmed the hypothesis (based on evidence from several CO poisoning accidents and previous laboratory work carried out by Italgas) that the correct sizing of the chimney (cross section, height and shape) is the most crucial factor in achieving safe operation of the appliance. It is more important than correctly sizing the purpose-provided ventilation opening as prescribed by the codes. Purpose-provided ventilation openings may be extremely important in airtight buildings (e.g. post-energy crisis constructions, buildings in mountain areas etc.), while older dwellings are normally sufficiently permeable to guarantee an adequate supply of combustion air.

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Recent developments in building air flow modelling

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1 Introduction

Air flow modelling for buildings has become an important part of the integral design of buildings. This article gives a short outline of recent developments in both flow network (particularly multi-zone networks) and CFD (computational fluid dynamics) modelling, and also covers applications where the two types of models are coupled with each other and with thermal models.

2 Multi-zone models

Multi-zone modelling (MZM) is used to simulate air flow and pollutant transport between rooms or zones, and between the inside and outside of buildings. The multi-zone modelling of air flow is characterised by a network of nodes representing a volume of homogeneously mixed air interconnected by air flow components such as cracks, large openings, ducts or fans.

2.1 Applications

A number of different multizone models are currently used in the solution of a variety of problems[23]. Both steady-state and time-dependent cases can be treated. The basic application is the determination of infiltration and interzonal air flows due to natural and mechanically induced driving forces and the consecutive determination of room mean age and air change rate values. Design applications where MZMs can be used include

- the sizing of air flow inlets and outlets and of HVAC components, and the determination of the influence of building fabric leakage on system performance[24].
- energy problems such as the determination of seasonal ventilation heat losses. An example is the assessment of the energy impact of ventilation in residential buildings[25].
- the design of passive and active solar air heating systems.
- problems related to air quality including the study of contaminant spread within a building. Examples are the risk assessment of counterflows from kitchens or bathrooms back to the living rooms, the ingress of radon from the ground and reversed flow in furnace exhausts.
- the study of the transient infiltration of outdoor contaminants or of smoke propagation. Based on air flow and contaminant concentration results, the overall performance of the ventilation system may be determined using the concepts of multi-room ventilation efficiency.
- the derivation of health-related parameters such as accumulated dose figures for different occupants.

2.2 Recent developments

Many existing codes have been improved by developing user-friendly interfaces. Interactive input with mouse-driven menus and the selection of options is becoming more common.

A project of the International Energy Agency Conservation in Buildings and Community Systems Executive is dealing with the development and evaluation of a multi-zone program based on the COMIS model (Annex 23[26]. Within this, a graphical interface is being developed for the COMIS model. On-line output and links to graphical post processors are available in some cases. In other programs, flow results are shown directly on a floor plan of the building on the screen. In COMIS the user can select air flow components directly from a database based on the AIVC numerical database[27].

In some programs, vertical gradients for air temperature, humidity and contaminant concentrations can be defined for the characterisation of larger rooms such as atria. The modelling of large openings has been improved according to the newest research results[28]. For the simulation of occupant behaviour, stochastic models are implemented[29] and for the characterisation of contaminant sources adsorption effects can be taken into account.

In any simulation, the confidence intervals for the calculated results should be established and thus the propagation of input errors needs to be considered. In Annex 23, tools for on-line sensitivity and error propagation analysis are currently being developed[26].

2.3 Coupling with thermal models

For problems like natural ventilation and passive cooling of office buildings, multizone models have to be coupled with a thermal model. In some instances multi-zone models are used in conjunction with a thermal model (e.g. COMIS with TRNSYS[30]). Other thermal models, such as ESP, have an integrated air flow module[31].

3 CFD models

CFD models are essentially used to simulate the pattern of air flow and pollutant transport within a single space. In a CFD program, the whole volume under consideration is divided into a large number of cells (typically 10 000 to 100 000) and, for each cell, coupled transport differential equations for mass, momentum, energy and contaminants are solved in a multiple iterative process. Although computation costs and the level of expertise needed are far higher for CFD modelling than for MZM, the availability of modern workstation computing power and software facilities has promoted the increased use of CFD for room air flow in the last few years.

Flow in forced and natural convection is almost always turbulent in nature. Such flow is commonly assessed by a statistical approach where additional transport equations for quantities related to fluctuations around mean values are solved. For most purposes the 'κ–ε' turbulence model still offers the best trade-off between accuracy and computational effort. For higher accuracy, particularly in special situations such as regions with recirculation or strong streamline curvature, more advanced turbulence models, most of them still under development, have to be used[33].

Subtasks for the development of a CFD analysis include grid generation, which can occupy 80% of the work, and establishing appropriate boundary conditions, which are required for all variables for the complete surface of the computation domain. Simulation output includes field distributions of pressure, velocity components, turbulence quantities, temperature and concentrations of contaminants such as humidity, CO_2 or smoke. In most cases, energy flow through the building envelope is not determined, because this involves increased computational effort, but it is taken into account by appropriate boundary conditions.

3.1 Recent applications

CFD modelling is usually applied to one room only, but it can be extended to the flow field in the whole building[33]. Coupling with outdoor air through large openings with bidirectional flow is also possible[34]. From CFD raw data, additional comfort-related quantities such as the percentage of people dissatisfied because of draughts, thermal comfort or perceived air quality can be derived to help designers in the evaluation of ventilation systems[35]. Currently there is strong interest in calculating air flow in unusual large spaces such as atria, sports stadia, industrial halls etc.[36], IEA Annex 26 project[37].

3.2 Recent developments

Most codes use the finite-volume discretisation scheme and a structured grid, the latter imposing important constraints at the grid generation stage. More and more codes now offer opportunities for local grid refinement in regions of particular interest or which have high gradients: this avoids having a large number of cells in unimportant regions. Some codes offer numerical convergence accelerating methods such as the linked solving of continuity and momentum equations and multigrid techniques[32]. Very important in practice, particularly for non-orthogonal geometries, is the help of a CAD-type geometry and grid-generation pre-processor that has now become available. Increasingly, additional external programs are used to take into account surface radiation exchange and thermal coupling to the building[38].

For the use of CFD to become widespread, menu-driven easy-to-use interfaces are important. Such programs, adjusted for ventilation purposes, are now available.

9 Combined modelling

Two ways of combined modelling are possible, as follows.

MZM can be simply used to calculate the boundary conditions for the CFD simulation, e.g. for a special room in a full building with certain outside conditions. This method is particularly suited to 'pseudo-transient' simulations where stationary CFD solutions for three or four different sets of boundary conditions are obtained, rather than the full dynamic behaviour of the room air flow. This approach works because of the very different time constants of the air flow and the building mass.

CFD can also be used to enhance the accuracy of MZMs in many cases. In a MZM, each room is usually represented by one node with homogeneously mixed conditions. In real cases, however, temperature and contaminant concentrations vary throughout the space. The exchange to the neighbouring nodes is then strongly dependent on the local values of these variables near the flow paths within each zone. These local values are mainly influenced by the position of heat and contaminant sources and by the resulting air flow pattern.

Examples where local values have a strong influence on the multizone model predictions include:

— pollutant spread from a zone with a non-homogeneous concentration (i.e. a local source) into other rooms

— enclosures of large horizontal (e.g. open-plan offices) or vertical (e.g. atria, staircases) dimensions

— rooms with thermal stratification (e.g. displacement ventilation, open doors and windows) or generally complicated flows.

4.1 Recent developments

A combined method has recently been applied to the problem of contaminant distribution in buildings[39]. Instead of taking the room average concentration value for each flow path, a separate value from a CFD calculation is provided for each flow path connecting this node with other nodes. The general calculation procedure is as follows:

— A full-case multi-zone calculation is performed first (i.e. for the whole building).

— Flow path parameters are taken from this solution and transferred to the CFD program as input boundary conditions.

— The CFD code is then run for the single room.

— Variable values at the flow paths to the neighbouring rooms are transferred back to the multizone program.

In cases where the new multizone values affect the solution values which have been transferred previously to the CFD code as input boundary conditions, the whole procedure can be repeated as many times as necessary (two to three times is probably enough). This procedure could be called an external or 'manual' iteration or a 'ping-pong' technique.

A Swiss version of the MZM model COMIS was adapted for this special type of input. With such local values, time-dependent contaminant concentration distributions in the whole building can also be calculated under the assumption that the room air flow pattern remains unchanged.

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