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DISCUSSION PAPERS AND ADDITIONAL PRESENTATIONS

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SECTION 1: DISCUSSION FORMS

Discussion Papers from 17th AIVC Conference, September, 1996

SESSION 1: Optimum Air Distribution

PAPER: **Computerised Methods for Balancing Ventilation Systems**
AUTHOR: **B T Larsen, Norway**

Question: ***Fritz Steimle, Germany***

1. *To balance a supply and a return system you need mass flow balance and no volume flow balance.*

2. *Equation No.1 shows:* $P \sim Q^{2.0}$ *, but in turbulent flow in smooth ducts* $P \sim Q^{1.75}$. *Practically it is* $P \sim Q^{1.9}$

3. *What is it about your predicted balance, when caused by pressure, e.g. in filters the total air flow change?*

Answer:

1. In principle I agree with you, but in practise the temperature and humidity does not vary that much in comfort ventilation applications. Using volume flow is therefore perfectly applicable. The errors introduced by doing so are "second order" effects compared to measuring errors, etc.

2. We are not talking about ducts here. We are talking about pressure reducing devices like dampers and air terminals that are designed to reduce pressure most effectively, e.g. by creating fully turbulent flow.

3. Pressure drop in filters, etc. in the central air conditioning plant will reduce the total air flow. The air flow in all air terminals and duct branches will be reduced proportionally. i.e. 16% reduction in total air flow will give 10% reduction in air flow in all air terminals.

PAPER: **The Effect of Recirculation on Air Change Effectiveness**
AUTHOR: **C C Federspiel**

Question: ***V Dorer, Switzerland***

What is more important to the designer eventually: The flow pattern in the room (represented by ε_R*) or the absolute ventilation effectiveness?*

Answer:

The most important feature of the ventilation system is the outcome (e.g., age of air in the breathing zone). If the measured outcome differs significantly from the designed outcome, then one needs to know why it differs. The relative air change effectiveness, which is a quantitative measure of the flow pattern, will reveal whether or not the problem is with the space itself (e.g. configurations of supply/return grilles). the absolute air change effectiveness does not provide a quantitative measure of the flow pattern, so it cannot be used to diagnose a ventilation fault. Therefore, I think the relative air change effectiveness is more important.

Question: ***W F De Gids, Netherlands***
Why do you express a complex air distribution field in just one parameter? If you do that, it is logical that the type of definition of your effectiveness give different answers.

Answer:
The use of the mean age of air in the definition of relative air change effectiveness bounds it between zero and two. This bounding makes the measure more useful for diagnosing ventilation faults (e.g. undesirable flow pattern such as "short circuiting"). However, the age at a point could be substituted for the mean age. If this is done then the relative air change effectiveness at that point will be independent of the recirculation fraction but the maximum value may be much higher than two and will be difficult to determine analytically.

Question: ***F Steimle, Germany***
The remark of Viktor Dorer is very important because a mean value of the efficiency is not of interest, but the effectiveness in the occupied zone where comfort is necessary only. The ceiling does not need a good air quality.

Answer:
(Please also read responses to V Dorer and W De Gids). The use of the mean age of air in the calculation of relative air change effectiveness enhances its use as a tool for diagnosing ventilation faults because the measure is then bounded between zero and two with values greater than one indicating "displacement" flow and values less than one indicating "short circuiting" flow. I think that the age of air in the breathing zone is a better outcome measure than the effectiveness in the breathing zone.

PAPER: **How Effective is Natural Ventilation? A Study of Local Mean Age of Air by Modelling and Measurement.**
AUTHOR: **R R Walker**

Question: ***V Dorer, Switzerland***
How did the measurements compare with the calculations?

Answer:
The measurements were complementary to the modelling. As the building modelled was not used for the measurements no direct comparison was possible. However, in both modelling and measurements it was seen that ventilation rates can be less than the minimum

requirements. Also it was shown that conventionally calculated ventilation flow rates cannot be relied upon to indicate true freshness of air.

Question: ***H Karlsen***
What do you mean by saying automatic controls?

Answer:
Controls control system making an automatic opening and closing of windows determined from parameters, temperature, etc. We suggest a default of automatic control operated by a building management system using CO2 and temperature sensors as triggers to operate windows and louvered shutters. This is especially desirable in buildings with large spaces using stacks and atria as part of their ventilation strategy.

Question: ***B T Larsen, Norway***
Was the calculation of the office complex (the first shown) infiltration in addition to air exchange by mechanical ventilation?

Answer:
The building modelled is naturally ventilated.

PAPER: **The Effect of External Atmospheric Pollution on Indoor Air Quality**
AUTHOR: **V Kukadia, UK**

Question: ***J V Andersson, Sweden***
Before concluding which is the better system of the two, one has to know more about the systems. Location of the air intake for the mechanically ventilated building - was the system balanced or did it have an under pressure towards the outside etc. One of each is a rather small statistical population to be used as a basis for a decision.

Answer:
1. The location of the air intake for the mechanically ventilated building is shown on the site plan of the buildings monitored (Fig 1. of paper in proceedings) and attached.

2. The ventilation system was taken as found and it is known to be serviced regularly every 2-3 months. We believe that the system was balanced but we are checking this.

3. No decision has been made as to whether air-conditioning is better or worse than natural ventilation for office buildings located in urban areas with respect to external pollutants being drawn into the building. The paper only reports the findings of a pilot study. However, the study highlights problems which may occur with air-conditioned buildings. We will be monitoring other buildings in the next few months to look at this in more details.

Question: ***L Ekberg, Sweden***

1. *Where were the pollutant measurements located?*
2. *Did you compare the concentrations in the rooms facing the street to the concentrations in the rooms facing the backyard in the naturally ventilated building?*

Answer:

1. Measurements of the pollutants were carried out approximately in the centre of the offices about 1.5 - 2m above the ground.

2. The office monitored in the naturally ventilated building has sash windows at opposite ends of the room - one set faces onto the major road and the other on to a narrow open courtyard.

In future studies we will be monitoring separate offices - those facing major traffic roads and those facing what is regarded as "less polluted" backyards/courtyards. A comparison of the pollutant concentrations will be made.

Question: ***F Flourentzos, Switzerland***

Did you observe the occupant behaviour?

Answer:

The investigation was carried out in the winter period (one week in February 1996), the weather was cold and therefore the windows remained closed throughout the study. Only the door for the purpose of entering/leaving the office was opened/closed whenever necessary.

Question: ***J Sowa, Poland***

Have you taken smoking habits of users into consideration in your study? CO_2, CO or NO_2 are also products of tobacco smoking.

Answer:

In both buildings we studied there was a "No Smoking" policy so it was not necessary to take into consideration the products of tobacco smoking.

Question: ***M Byrne, UK***

Were there any sources from local power stations?

Answer:

There were no pollutant sources from power stations.

Question: ***P Ajiboye, UK***
If in mechanically ventilated buildings re-introduction of exhaust air is a problem does this indicate that additional filter media is required and how does this affect general ventilation rate within building?

Answer:
For the gases that we monitored, i.e. SO_2, CO, CO_2, NO_2, NO, it is unlikely that filtration would necessarily help in reducing the levels of these gases. Some absorption method however may help. Filtration is more likely to help reduce particle levels. However, this would increase the pressure drop and thus reduce the ventilation rate in the building.

Question: ***M Santamouris, Greece***
Could you give us some indication about the air flow rates in both buildings?

Answer:
The air flow rates in both buildings are given in the attached table.

Question: ***P J M Op't Veld, Netherlands***
1. *Information about the natural ventilation system?*
2. *The weather conditions during the measurements?*

Answer:
1. The naturally ventilated building had vertical sliding sash windows, some of which were double/secondary glazed. Ventilation was provided by simply opening these.

2. The measurements were carried out during February 1996 for a period of one week. Generally, it was very breezy with wind speeds usually above 5 ms^{-1}. There were periods of both rain and snow showers during the week. External temperatures ranged from 3-13 ^{0}C. Relative humidity ranged from 55-98%.

Question: ***W De Gids, Netherlands***
The air change rate measured are quite high, so what is the air leakage of the building?

Answer:
In this pilot study, the air leakage of the building was not measured.

SESSION 3: Ventilation Strategies

PAPER: **Residential Mechanical Ventilation System: Performance Criteria and Evaluations**
AUTHOR: **V Dorer, Switzerland**

Question: ***P J M Op't Veld, Netherlands***
Specific energy consumption for space heating and DMW. Does this also include energy for fans, pumps, etc?

Answer:
No, electricity is considered separately. Nevertheless, heat produced by the fans is considered in the space heating energy index.

Question: ***Tor Helge Dokka, Norway***
Could you describe the principle of the earth coupling system?

Answer:
This system provides preheating or precooling of the intake air, making in many cases, in systems with heat recovery, a separate heating unit for the supply air unnecessary. The intake air is led through a pipe buried in the ground or below the building floor plate before it enters the ventilation system.

Question: ***J Andersson, Sweden***
In your conclusion you pointed out the necessity to clean the earth coupling system. How is that achieved and how often has it to be done? (Bearing in mind that there are no filters on the air intake and that the pipe diameters are quite small).

Answer:

Cleaning How?:
- Big enough diameter
- Slope angle and provisions for rinsing and other cleaning methods.
- Accessibility at both ends, not too many bends.

How Often:
- Swiss project on microbiological effects in earth coupling system is ongoing (results end 1996). Answers are expected for this project.

Filter:
- At the end of the earth pipe, as the first part of the ventilation unit there are always filters (coarse and fine).
- No filters in the air intake terminal.

PAPER: **<u>Efficiency Characterisation of Various Ventilation Configurations</u>**
AUTHOR: **M-L Hanrion, France**

Question: ***P Ajiboye, UK***
In terms of establishing the most effective position of the inlet and exhaust devices, how important is pollutant type (which in part describes particulate size) in this investigation.

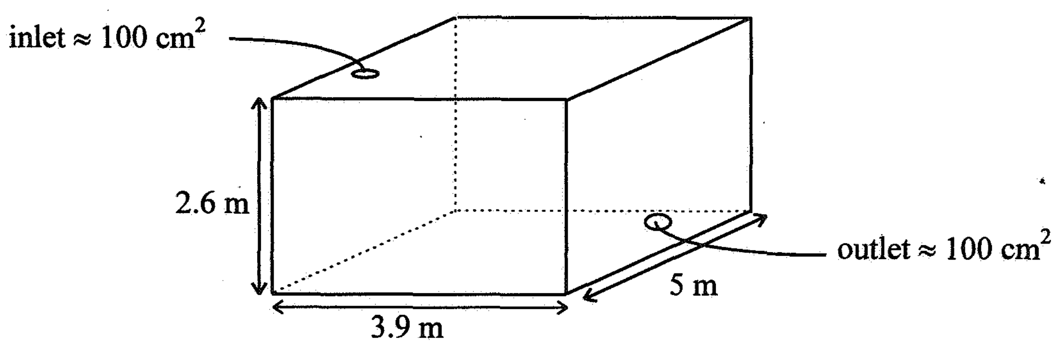
Answer:
We program the study of the influence of this parameter at the beginning of 1997 and we will analyse:
- the size of the source of pollution
- the position of the source of pollution
- the density of the pollutant
- the temperature of injection's of pollutant

For further information contact: M-L Hanrion, Tel:+33 01 49 22 56 87

Question: ***V Dorer, Switzerland***
Are the inlet/outlet and measurement points located in windplane? (yes)
Is it a pure 2-D case? (No)
Depth of test room? (l/m)

Answer:

TEST ROOM (3-D)



PAPER: **Ventilation in Houses with Distributed Heating Systems**
AUTHOR: **Denis Parent, Canada**

Question: ***M Byrne, UK***
I wonder about the contribution of outdoor sources to the resuspended particulate levels in the 30 dwellings which you studied: were the houses in urban or sub-urban areas, or a combination of both?

Answer:
All the dwellings were single detached houses in residential areas (suburbs) of a small city of 50,000 people.

PAPER: **French Ventilation System Performances in Residential Buildings.**
AUTHOR: **J Riberon, France**

Question: ***P Wouters, Belgium***
The η_{50} values on p.169 are very low for the "French" standard value, especially $\eta_{50} \leq 0.67\hbar$. Do you have information if such values are found for new French individual dwellings?

on p.169

Answer:
At present we have not a lot of information about the actual values of air leakage for the new French individual dwellings. However, some airtightness measurements have been carried out in new single family dwellings and have shown that the leakage value was in accordance with the French Standard DTU 68.1.

PAPER: **Residential Ventilation and Energy Characteristics**
AUTHOR: **M Sherman, USA**

Question: ***B T Larsen, Norway***
In the presentation a heat recovery efficiency of 70% was shown. What kind of heat exchanger is most popular in the US?

Answer:
Counter-flow or plate-type heat exchangers are probably the most popular type, but the total number is still quite small. The home ventilating institute in the US is the industry group that most closely follows the sales of these kinds of products.

Question: ***W De Gids, Netherlands***
How does another open window scenario affect your figures?

Answer:
Window opening behaviour has a low impact on both system selection and energy costs. While we assumed that windows would be closed when it would cause discomfort or an

energy penalty one might allow some window opening at other times such as when it is 10 degrees C outside. Under these conditions there would be an additional energy penalty. Furthermore, such an assumption would shift the optimal ventilation choice away from mechanical systems. Window opening assumptions are key in both standards and energy analysis. Issues such as security, noise, outdoor pollution and draught all compete with the perceived need for ventilation in considerations regarding window opening. Deciding on how much responsibility the occupants have regarding ventilation is often the determining factor.

Comment: ***D Stevens, USA***
Canadian HRV manufacturers are expanding into the US South to take advantage of cooling climate market interest - biggest growth area.

Answer:
This is not surprising given our results; the hot humid climates seem to get the most benefit from HRV's.

Question: ***F Steimle, Germany***
You mentioned the energy amount of 3,5 EJ. Is this oil, electricity or primary energy?

Answer:
The energy values in the text were net thermal loads. We did not convert them to resource energy or CO2 equivalent. The economic analyses took into account system efficiencies, fuel mixes and energy costs on a local basis. Prices, fuel availability and electrical generation basis varies substantially from region to region.

PAPER: **Ventilation Requirements in Non-Domestic Buildings and Energy Efficiency**
AUTHOR: **P Wouters, Belgium**

Question: ***P Ajiboye, UK***
The variation in Standards Guidelines is the problem identified in terms of energy demand variations. Are these figures devised from extensive health and comfort criteria?

Answer:
It depends what you mean by "extensive"!

Question: **R Cohen, UK**
You showed the required ventilation rate increases very significantly when a typical external air pollution level is assumed. Does this result take into account the presence of a filtration system?

Answer:
No, the outdoor air pollution level is especially important if Class A is taken since the target is then 1 dpol. In case of Class C the target is 2.5 dpol and then the outdoor pollution level is less critical.

Question: ***A Cripps, UK***
I would interpret your paper as advising delegates to vote against the proposed European Standard (Prenv1752). Is this a valid interpretation?

Answer:
The aim/objective is not to suggest to vote against the CEN proposal. The major

PAPER: **Ventilation Measurements in a Cinema**
AUTHOR: **Y Jin, Norway**

Question: ***C Federspiel, USA***
Why was the air exchange efficiency at sample point number 1 not reported?

Answer:
To have more channels for sampling means longer time interval for the tracer gas measurement. The time intervals were already long (>4 min) for 5 channels and we did not want to sacrifice that for adding more channels.

PAPER: **IEA Annex 27: Assessments on Noise**
AUTHOR: **P J M Op't Veld**

Question: ***M W Simons, UK***
When applying none reduction procedures to prevent inward transmission of outdoor noise, is frequency of significant importance? For example, do high frequency sounds results in greater sound penetration than lower frequency sounds?

Answer:
Frequency is of significant importance. If the noise reduction of a certain element is expressed as one value, then the noise reduction is weighted for a specific frequency characteristic (traffic, railways, aircraft). As an example normal double glazing (6/12/4 mm) has an A-traffic weighted noise reduction of 28 dB(A) and an A-railway weighted noise reduction of 31 dB(A). Generally noise reduction is more difficult for low frequencies than for high frequencies (railway traffic has more high frequencies).

Question: ***V Kukadia, UK***
Where there any internal noise sources? If so, what were they and did you take them into consideration in your tests?

Answer:
All the allowable noise levels mentioned in the papers are for one source. Most of the standards in different countries take into account one source and not a composite of different sources (there are exceptions however, such as Sweden, I believe). Hence, if there are more sources (outdoor noise + internal noise) it can lead to a higher indoor noise level.. Another aspect is that if facade have an excellent soundproofing (no outdoor noise in room) the indoor sources become more critical (people notice them much earlier).

Question: ***Brian Webb, UK***
Do different types of draughtproofing or weatherstripping materials produce different sound reduction (i.e. rubber strip silicone sealants better than brush type).

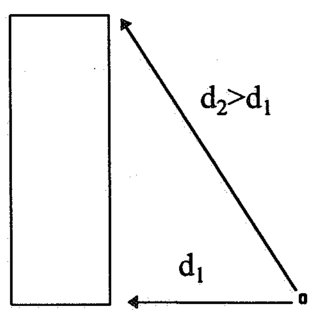
Answer:
Draughtproofing and weatherstripping materials can have different acoustic performances. A problem is how to express the "noise reduction" of weatherstripping as it is difficult to estimate the "surface area" of the weatherstripping (necessary in the calculations). This can be solved by introducing a reduction factor (*k*) without a surface area

So $Ra_A = -10(\log \frac{s_j}{s_{tot}} 10^{-R_j/10} + k)$

To return to your question:
Simple weatherstripping $R_{a\sim} 30...35dB(A)$
Good weatherstripping sealed in the corners: $R_A \sim 90dB(A)(\longrightarrow k = 10^{-9})$
Excellent weatherstripping: double and sealed in corners $95 = -50dB(A)(\longrightarrow k = 10^{-9.5}...10^{-5})$

Question: ***Paul Ajiboye, UK:***
How does altitude effect sound levels generated at a road site levels?

Answer:
The noise level on the facade mainly depends on the distance from the source to the facade. So on higher altitudes noise levels decrease. Another aspect is the sound absorption of the ground. Sound absorbing effects of the soil, vegetation, etc.. reduces noise. this effect is stronger on the ground than on higher levels. There are transfer models to calculate noise levels (taking into account distance, altitude, sound absorption, sound shielding, etc..).



SESSION 5: Calculations and Measurements

PAPER: **Calculation Methods for the Determination of Air Flow Rates in Dwellings**
AUTHOR: **A Cripps, UK**

Question: ***G Nelson, USA***

1. *On Page 381, you list many required input data, some of which (leakage distribution, number of facades exposed to wind, ventilation flows and times) must be estimated by user. Won't two people often assume very different values for these inputs and won't this still result in large variations in outputs?*

2. *In the examples, there were no data on these parameters. How were they estimated?*

3. *Why don't you use the Palmiter fan interaction model (in ASHRAE Fundamentals) instead of adding in quadrature. It is a simple and has been shown to agree much better with measurements. (EPRI's measured US predicted infiltration studies by Ecotope & LBL).*

Answer:

1. Different assumptions/estimates may be made by different people, but there must be set down clearly according to the standard. The aim is to minimise variation between users.

2. These parameters were used within the factors used in the examples when they apply (e.g. no fan leads to no fan flow rate!). There is not space here to give details. Please refer to the draft standard.

3. The stack and wind driven flows are added in quadrature. The fan flows are added using a method close to that proposed by Palmiter.

PAPER: **Does the Power Law Rule for Low Pressure Building Envelope Leakage?**
AUTHOR: **I S Walker**

Question: ***B Webb, UK***

What wind speed was your high windspeed test carried out at? (Reference your last slide)

Answer:

The high wind speed test was at an average of 11 m/s (@ 10m above ground) with a range of 5 to 17 m/s over the test period.

Question: ***B T Larsen, Norway***
What was the exponent of the Power Law shown in the diagrams?

Answer:
In the figure showing all three models (Power Law, Parallel & Series) the exponent was 0.65. In the figure showing measured data the exponent was 0.66

PAPER: **Improve Train Tunnels: A Dynamic Ventilation Model**
AUTHOR: **H Phaff, Netherlands**

Question: ***J V Andersson, Sweden***

1. *Would you say that the size (20m^2) of the ventilation openings is optimal or would a larger size have led to a lower power consumption for the fans?*

2. *Is the tunnel a single or double track tunnel?*

3. *Have you got any complaints from the train passengers due to the fluctuating pressure in the train cabins (and/or noise complaints)?*

Answer:

1. The size of the openings results from an earlier study on fire safety. So we could not change the size of all the openings. Two extra openings of 80m^2 each did not solve the problem. We cannot give any answer in the case of using fans about the effect of larger openings on the power consumption.

2. The tunnel is a double track tunnel with connections between the tubes at the station.

3. We know that people are complaining due to the pressure pulse at the moment the train enters the tunnel. The fluctuating pressure in the train going through the tunnel are a well known feature. We know about complaints but have no quantitative data.

PAPER: **Multizone Calculations and Measurements of Airflows in Dwellings**
AUTHOR: **A Blomsterberg, Sweden**

Question: ***V Dorer, Switzerland***
What kind of measurement results did you consider in the calculations?

Answer:
The outside climate was monitored during the measuring periods outdoor air temperature at the site, wind speed and wind direction at a nearby weather station. The indoor climate was measured (hourly). The airtightness was measured and the airleakage was evenly distributed over the building envelope. In the naturally ventilated dwellings the crackage around the

interior doors were measured. For the mechanically ventilated dwellings the air flows in the supply and exhaust air flow rates were measured. After the simulations were done no adjustments were made to the simulations to fit the measurements.

Question: ***Martin White, UK***
You carried out 3 passive tests per dwelling. Did you carry out 3 constant concentration tests as well?

Answer:
No, in the passive stack and exhaust ventilated buildings our intention was to do two or three different measurements at different outdoor climates. For the ps. ventilated dwellings we have made two measurements on each object, except for the one-family house where a complimentary measurement is being done during the late summer. For the exhaust ventilated apartments the additional measurements were unfortunately stopped by the occupants. The balanced ventilated dwellings were considered very airtight and the system so reliable that additional measurements were not necessary.

PAPER: **<u>Probabilistic Analysis of Air Infiltration in a Single Family House</u>**
AUTHOR: **K Pietrzyk, Sweden**

Question: ***W De Gids, Netherlands***
Can you not do this same type of analysis using a deterministic model and real weather data, including the change in leakage distribution.

Answer:
It is possible to do the same type of analysis using the weather data instead of results of pressure difference measurements.

Question: ***M Santamouris, Greece***
Could you give us the density probability functions of both wind speed and temperature differences you have considered? Is it possible to give us the joint probability you have considered for both parameters?

Answer:
1. We have estimated the probability density functions for both wind speed and temperature difference (external-internal) on the basis of the data measured during an 8 month period. For wind speed: two-parameter Weibull distribution with the shape parameter of 2.5 has been fitted to the measurement data. For temperature difference, normal distribution has been estimated.

2. We have not done the analysis of the joint probability considered for both parameters, but it is possible to do this.

SESSION 7: Energy Efficient Ventilation

PAPER: **Summer Cooling for Office Type Buildings by Night Ventilation**
AUTHOR: **M Kolokotroni, UK**

Question: ***V Dorer, Switzerland***
Measured Building: Can you give details on solar shading and solar heat gains? Were the solar heat gains quite identical in Floor 1 and Floor 3?

Answer:
There was no external solar shading. The double glazed curtain walling was low E glass with UV and IR reflective coatings. Internal venetian blinds (Black) with small holes. Solar gains identical on Floor 1 and 3. No shading by other buildings. We reversed the floors with vents open and closed - there was no bias in temperatures or night cooling effect.

SECTION 2: ADDITIONAL PRESENTATIONS

Optimum Ventilation and Flow Control in Buildings
17th AIVC Conference, Göteborg, Sweden
17-20 September, 1996

A Tool for Evaluating Domestic Ventilation Systems' Ability to Provide an Acceptable Indoor Air Quality

L-G Månsson✳, J-R Millet✦, J-G Villenave✦, J Kronvall¤

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✦ CSTB, Marne la Vallée, France.
¤ J&W Consulting Engineers, Malmö, Sweden

Synopsis

This paper is describing the first results of the Annex 27 work aiming at developing simplified tools for evaluating domestic ventilation systems by using sofisticated simulation programs studying pollutant concentration either for each person or in an individual room. Assumptions based on previous research works are set up for a number of parameters. The total number of combinations are about 17 500 and have been reduced to 174 by the statistical method "fractional factorial analysis". With this reduction it is possible to make all the runs even with sofisticated multicell models. The result is presented as coefficients for the various pollutants.

Background

The rate of outdoor air supply as well as comfort aspects associated with air distribution and the ability of the systems to remove pollutants are important factors to be considered at all stages in the building lifecycle. As distinct from a work place, residents can vary across a wide span from an allergic infant to a well trained sportsman, from active outgoing people to elderly confined to a life indoors.

During the lifetime of a building the resident's pattern vary. This results in a varying need for supply air to obtain acceptable indoor climate and to avoid degradation of the fabric. Emissions from building materials are also time dependent. When the building is new or recently refurbished it may be necessary to dilute the emissions by extra outdoor air. In standards and codes the outdoor air needed in a dwelling is generally based on the maximum number of persons living in the dwelling, defined by the possible number of beds contained therein.

Dwellings represent about 25 - 30 % of all energy used in the OECD countries. In the near future domestic ventilation will represent 10 % of the total energy use. Thus even relatively small reductions in overall ventilation levels could represent significant savings in total energy use. Improvement of residential ventilation is of concern in both existing and future buildings. The functioning of the ventilation system may deteriorate at all stages of the building process and during the lifetime of the building. Research in the recent years and in particular the IEA annexes now makes it possible to formulate methods to evaluate domestic ventilation systems.

Objectives

The objectives of the IEA Annex 27 are: **to** develop tools to evaluate domestic ventilation systems; **to** validate the methods and tools with data obtained from measurements; **to** demonstrate and evaluate ventilation systems for different climates, building types, and use of the dwellings. The methods, tools, and systems are intended for existing and future residential buildings, that require heating. The target group is composed of standard and policy makers, developers in industry, and ventilation system designers.

With this general objectives the Annex is divided in three subtasks:

1. State of the Art,
2. Development and Validation of Evaluation Methods, and
3. Evaluation, Demonstration, and Application of Current and Innovative Ventilation Systems.

Introduction

With the above objectives and scopes of the three subtasks the Annex started in April 1993 and has today eight participants: Canada, France, Italy, Japan, Netherlands, Sweden, UK, and USA. Based on the subtask "State of the Art" assumptions have been set up to develop simplified tools for:

1. Indoor Air quality (reported in this paper)
2. Energy
3. Noise
4. Thermal Comfort
5. Life Cycle Cost
6. Reliability
7. Building and User aspects.

With the State of the Art Review, ref 1, it is possible to give realistic assumptions of the most frequently used ventilation systems, the design of the dwellings, how many residents there usually are, the behaviour, and the time spent in dwellings. With these assumptions we can cover about 90 % of all possible cases, that are influencing the need of outdoor air supply. The usual levels of different pollutants in the dwellings are also given based on the review. The review report is based on and giving references to about 400 reports.

The 14 OECD countries studied have 700 million inhabitants, 280 million dwellings with a floor space of 32 000 million m^2. The habitable space varys greatly and goes from 65 m^2/dwelling (Italy) to 152 m^2/dwelling (USA). There is also a great variation between the countries weather the dwelling is in a single family house or in a multi family building.

The number of persons/dwelling goes from 2.1 (Sweden) to 3.2 (Japan, Italy). Combined with the dwelling area it gives a floor space from 27 m^2/person (UK) to 61 m^2/person (USA). The crowdiness is defined by the number of persons/bedroom. From data can be seen that in 35 % - 50 % of all dwellings, there is less than 1 person/bedroom and in nearly all (90 - 95 %) less than 2 persons/bedroom. Moving frequency studies show, that after 35 years of age the family has settled and will remain living in there.

A very important trend is that the number of one-person household is increasing. Today it goes from 20 % (Japan) to 40 % (Sweden). This trend has been observed during the last 45 years in all countries. A majority of the households have only two persons, except Japan (40 %). In the future it can be expected that we will have even more 1- and 2-person households as the number of persons older than 60 years during the next 40 years is growing from about 20 % today to 30 % of the population.

A survey amongst the AIVC countries gave that the most frequent ventilation system is either stack or simply window opening. However, in new constructions in most countries a fan is installed either for central exhaust or for local extraction in bath and/or kitchen.

Method

In order to develop simplified tools for the indoor air quality, a set of assumptions had to be made. Here is also included family pattern both for weekdays and weekends. Such assumptions are time schedule at home and in the individual rooms, for taking showers, cooking, smoking, window airing. In table 1 can be found the parameters the simulations are made for. The common way to do parametric studies are to vary one parameter and keep all the others constant. By this you will not get the extreme combinations. By selecting a representative number of the total combinations out of nearly 17 500, it is possible to make simulations for a statistically representative number of combinations of the parameters, "multi variant parametric study". The combinations of the values of the parameters are selected by the method "fractional factorial analysis". The number of runs is given by chosing the IVth resolution, see ref 2. Then the regression analysis of the result is giving coefficients, which can be applied on that specific case you are interested in.

This paper describes the results from the first complete 174 runs made by the semi-multicell program called SIREN developed by CSTB, France, see ref 3. The aim is to do the same with the true multi-cell program COMIS.

Here follows a short description of some of the assumptions. See also table 1.

Example dwelling: A number of dwellings were assumed, typically for the participating countries. Two type dwellings were selected as the assumed number of persons in each dwelling have the same area per person for the crowded case. The dwelling types selected are a 4-room flat either on the ground floor in a 4-storey multifamily building or on the top floor (D4a) and a 4 room detached single family house (D4c).
Ventilation systems: The four main systems are: **1** adventitious or natural window airing (Airing), **2** natural passive stack (Stack or S), **3** mechanical exhaust (Exh), **4** mechanical supply and exhaust (SE). All systems can be combined with local fans.
Family types: Three cases crowded (5 persons), average (4 persons), spacious (2 persons)

Table 1. Links between factors and high, medium, and low values used in the simulations

Factor	Level			Comments
	+1	0	-1	
Dwelling A (DWA)				
Dwelling B (DWB)				
Leakage (LEA) dwell. D4a dwell. D4c	5 (5) h^{-1} 10 (5) h^{-1}	2.5 (2.5) h^{-1} 5 (2.5) h^{-1}	1 (1) h^{-1} 2.5 (1) h^{-1}	( )in brackets mech supply and exhaust
Occupancy (OCC)	Crowded	Average	Spacious	
Window airing (WIN)	Climate depending	50 % climate depending	Closed windows	
Climate (CLI)	Cold, Ottawa	Mild, London	Warm, Nice	
Supply area (SUP)	410 cm^2 400 cm^2	205 cm^2 200 cm^2	0 cm^2 0 cm^2	Vent. systems 1 Vent. systems 2 & 3
Flow rate (FLR)	60 l/s	45 l/s	30 l/s	Mech. ventilation
Local fan, kitchen hood (LKF)	On, 100 l/s		Off	
Local fan, bath (LKB)	On, 25 l/s		Off	

Leakage: Three cases are given with more airtight envelope if mechanical supply and exhaust ventilations system is used. Tighter for flats.
Window airing: Assumed to take place only in bedrooms. Three cases are given **1** closed window, **2** opening pattern depending on the outdoor temperature and wind speed, and **3** a medium case with 50 % of the opening area depending of the climate.
Clothes washing and drying: Base case with no water vapour.
Indoor temperature: +20 °C
Body washing: All residents are taking a 10 min shower every day in the morning
Tobacco smoking: The woman is smoking in the living room when at home after 13.00 h

In table 1 is indicated the level which is purely used when interpreting the combination given by the fractional factorial analysis and here **"+1"** indicates that the high value is to be used in the calculation, **"0"** the medium value, and **"-1"** the lower value. By combining columne DWA and DWB the type dwellings are selected to be D4a on ground floor or on top floor in a 4-storey building or the detached house D4c. In table 2 is given the number of factors for each parameter and the number of runs for each of the ventilation systems.

Table 2 Number of factors and how many levels

System	DWA	DWB	LEA	OCC	WIN	CLI	SUP	FLR	LKF	LKB	Factors	Number of runs.
Airing	2	2	3	3	3	3	3	-	2	2	9	$2^{9-4}+2\times5+1=43$
Stack	2	2	3	3	3	3	3	-	2	2	9	$2^{9-4}+2\times5+1=43$
Exh	2	2	3	3	3	3	3	3	2	2	10	$2^{10-5}+2\times6+1=45$
SE	2	2	3	3	3	3	-	3	2	2	9	$2^{9-4}+2\times5+1=43$
Total												Total 174 runs

Results

The regression analysis have given a set of coefficients for each of the indoor air quality factor and for each system. The first preliminary results for supply and exhaust ventilation systems have just been produced. The approach is illustrated in table 3.

The results of the complete simulations will give for each case the following indoor air quality and energy parameters.

1. Pollutant 1. Is a pollutant constantly emitted (eg. building material)
2. Pollutant 2. The number of hours that the most exposed person is exposed for a CO_2-level above 700 ppm or 1400 ppm. (Here 1400 ppm is never reached
3. Pollutant 3. Exposure for cooking products, e.g. water vapour, CO, NO_2
4. Pollutant 4. Exposure for tobacco smoke, passive smoking.
5. If the dwelling has a too high or too low pressure difference it might give a risk for radon, combustion spillage, and interstitial condensation.
6. Humidity. Relative humidity (RH) in each room, number of hours RH>75 % indicating a risk for mould growth. As it is nearly impossible to have water vapour content < 7g/kg all the time. We have checked if there is a 4 week period during the heating season with lower values giving a chance to recover from house dust mite.
7. Outdoor air change rate in the individual habitable rooms
8. Energy both for heating the outdoor air and for the fan energy

The pollutant production is assumed to be constant when smoking. The presence in the dwelling varys and is depending on which case that is selected. For the crowded and average cases is given41 h/week and for the spatious case only 27 h/week.

This first presentation of the results are given as factors for some some of the above parameters, see table 3. As the code, SIREN, is a semi-multicell computer code the result is given for all the habitable rooms together or the most exposed person. Both additative and multiplicative regression analysis has been tested and the best fitted is selected.

Discussion

This first presentation of some of the pollutants for one ventilation system is indicating the proceedure of the work within Annex 27 to predict the indoor air situation for a very large number of combinations. By using simulation technique it is possible to run a statistically selected number of combinations representing the total number of combinations. As it is too expensive to do a simulation run on an individual dwelling for each case with a number of assumptions, the final aim is to give possibilities to evaluate all ventilation systems in an easy way for a variety of pollutants.

The first analysis indicates that a regression based on multiplying or adding factors is a possible way. Runs with the code SIREN, that has a short running time for each combination, will be compared with the true multicell model COMIS. The results will also be compared with detailed measured dwellings in the participating countries.

Usually there is no time or money to make detailed computer simulations for ventilation systems in the residential sector during the design process. The simplified tools make it possible to predict the indoor air quality for a lot of different parameters for many ventilation systems. The tool can be used for proposing systems in new houses or when renovation is proposed. It can also be a tool for a first check if any complaint has been made by the residents.

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2. Montgomery D C. *Design and Analysis of Experiments*. 3rd edition 1991. Arizona State Univ. John Wiley & Sons. ISBN 0-471-52000-4
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Table 3. Factors for IAQ. Exhaust and supply air system									
Parameter	**Lev-el**	**CO2> 700 ppm. h**	**Cook h**	**Smok, h**	**Dry, h**	**Low press, Pa**	**Cond ens h**	**Energy kWh**	**Vent, ach**
Basis value		**18**	**1692**	**936**	**813**	**-7.9**	**174**	**2250**	**0.93**
Add +/-; Mult *		+/-	*	*	+/-	*	+/-	*	*
Detached		0	1	1	0	1	0	1	1
Ground fl		-53	0.99	1.08	620	1.08	87	0.97	1.02
Top floor		-12	0.98	1.09	+654	1.51	+100	0.95	1.01
Leakage	Low	+22	1.00	1.03	+30	1.35	+22	0.81	0.91
	Ave	0	1	1	0	1	0	1	1
	High	-58	0.99	0.94	+65	0.88	-1	1.30	1.14
Occupancy	Low	-100	0.81	0.68	-102	1.21	-126	1.03	1.01
	Ave	0	1	1	0	1	0	1	1
	High	+186	1.19	1.00	-357	1.10	+67	0.99	0.99
Window	No	-30	1.01	0.99	+44	0.63	-6	0.90	0.96
airing	Ave	0	1	1	0	1	0	1	1
	High	-6	0.99	1.00	+41	0.71	+28	0.98	0.99
Climate	Mild	-44	0.69	0.66	-299	1.08	-66	0.58	1.04
	Ave	0	1	1	0	1	0	1	1
	Cold	+6	0.97	0.95	+187	1.92	-62	1.83	1.04
Air flow	Low	+273	1.09	1.19	-214	1.13	+104	0.77	0.72
rate	Ave	0	1	1	0	1	0	1	1
	High	-89	0.94	0.87	+218	1.18	-58	1.25	1.29
Kitchen fan	used	-5	0.68	0.99	+24	1.47	-63	1.05	1.07
	not	0	1	1	0	1	0	1	1
Bathr fan	used	-25	1.01	0.99	+18	1.16	-103	1.02	1.04
	not	0	1	1	0	1	0	1	1

OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS
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Passive Cooling, Simulations and Experiences from Realized Projects in Sweden

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Passive cooling, simulations and experiences from realized projects in Sweden.

Abstract.

The use of computers for simulating building thermal behavior started early at the Royal Institute of Technology in Stockholm, Sweden. The first example of such use dates from a 1957 study of an exterior wall exposed to solar radiation.

The simulation program, later named BRIS, has gradually evolved with regard to the users and growing computer capacity. It has been used since the early sixties for research projects, design work and development of new systems, among others the ventilated hollow-core slab (Thermodeck) system.

In 1990 the originators of BRIS recieved Swedish Great Energy Award for "distinguised contributions in the field of energy conservation". The jury stated that the knowlege we got from the simulations has lead to an annual saving of energy worth 100 millions Swedish Crowns.

BRIS contains different installation- and control components representing generic models rather than specific implementations. The components can be combined freely to correspond to the principal operation of any HVAC system.

The control strategy is based on a sequence of restrictions on the possible sources for heating, cooling or heat recovery. The restrictions are relaxed successively within each time step in the building model until a solution is found. The order in which the restrictions are to be relaxed may be varied, the capacity intervals can be open ended on one side, etc.

By combining loads and systems minimum energy strategies can be defined and found by the program. When limiting the installed capacities the building dynamics will be more active in the control process which has shown to give a surprisingly high potential to reduce peak power problems and energy use.

We now have experience from over 300 buildings using the Thermodeck system for passive cooling. Some of theese experiences are reported and commented in this paper.

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Background.

Many load calculation methods or computer programs cannot be directly employed for thermal storage systems. In Sweden research has been focused on the technique of using building mass since the late fifties. A computer program, BRIS, was developed at the Royal Institute of Technology in Stockhom with support from the Swedish National Board of Building Research. The program was based on fundamental physical relationships and finite difference techniques (Crank - Nicolson) were used to solve the Fourier equations and the boundary conditions were treated in detail. BRIS has been developed continuosly with regard to the users and growing computer capacity.

The control strategy is based on a sequence of restrictions on the possible sources of heating, cooling and ecomomizer cycles. The restrictions are relaxed successively within each time step in the building model until a solution is found.

By combining loads and systems minimum energy strategies can be defined and found by the program. When limiting the installed capacities the building dynamics will be more active in the control process which has shown to give a surprisingly high potential to reduce peak power problems and energy use without sacrificing (maybe rather improving) the comfort.

Among serious consultants BRIS is a natural tool in the design process today and we have seen about one thousand results in the shape of real buildings.

Significant energy savings have been realized and in 1990 the originators of BRIS recieved the Swedish Great Energy Award for "distinguised contributions in the field of energy conservation".

Passive technology is a well known concept today, but still many buildings with very complicated and oversized HVAC systems are built. Energy costs and peak - power problems now lead to a wakening need to improve the competence and reintroduce the physical laws in the design process.

Now the next generation of BRIS, called IDA, is being developed.

This is a modular system for applications on different complicated processes. For description of the mathematical component models a special format, the Neutral Model Format (NMF) has been developed. NMF models are program neutral and can be automatically translated into the formats required by a number of different simulation environments such as IDA, TRNSYS, HVACSIM+ and SPARK. Based on NMF, environment independent application libraries can be established. ASHRAE has assumed the responsibility of maintenace.

Experiences from realized projects.

There is a large potential in utilizing the building dynamics together with installed equipment for climatisation. The basic philosophy is to work with nature instead of against it.

Accordingly the experience from buildings where BRIS has been used in the design work (most governmental, official and private business buildings downtown Stockholm) is that high comfort can be provided even with very low installed capacities for cooling (1/2 or 1/3 compared to buildings where more conventional design tools have been used). Also in hot, arid climates considerable savings have been done.

However, the utilization of building dynamics is poorly understood in practice today. Also modern, advanced control systems seem to have recoiled upon the ambition to maintain constant temperatures or to force the temperature to follow special schedules. If there are large capacities for heating and cooling available this could lead to peak power problems and a tremendous waste of energy. On the other hand, effective climate control often can be achieved with modest capacity and much less energy if passive techniques and the building mass are incorporated in the control policy. This is shown in the following example:

Example.

Office 10 m^2, surrounded by similar rooms:

Exterior wall:	12.5 cm brick
	12 cm of mineral wool
	10 cm of concrete
Partitions:	2*13 mm of plaster board
Floor-	
ceiling slab:	20 cm of concrete,
Window:	1.8 m^2 (glass area), three panes of ordinary window glass. Venetian blinds between the outer panes.
Outdoor	
temperature:	19±6 °C max. at 3 PM.
Air flow rate:	5 ACH.
	Remark: From the energy efficiency point of view this is a very high value. More common today is 0.5 ACH compensated by fancoils or cooling panels for heat extraction. Due to the sick building problem the supply air flow rate is now being discussed, and will probably increase in the future.
Infiltration:	.2 ACH

Solar (Stockholm July South) and internal heat gains during the office hours are shown in Fig. 1.

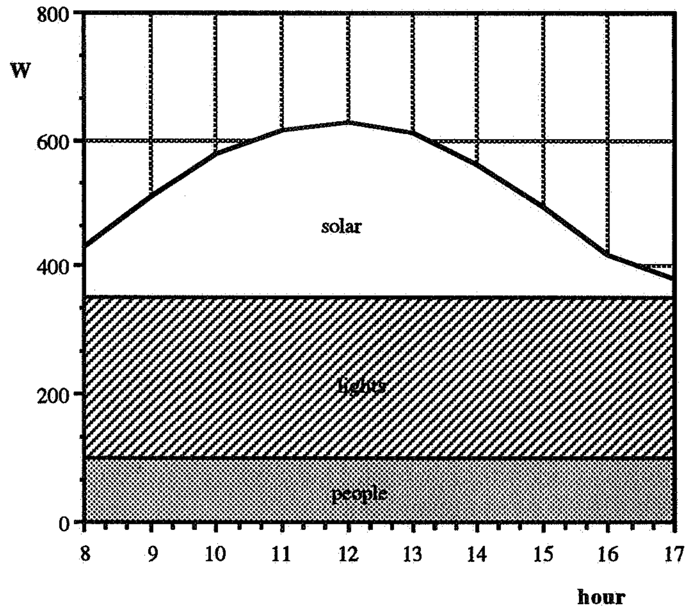

Fig. 1. Heat gains. Maximum value = 626 W.

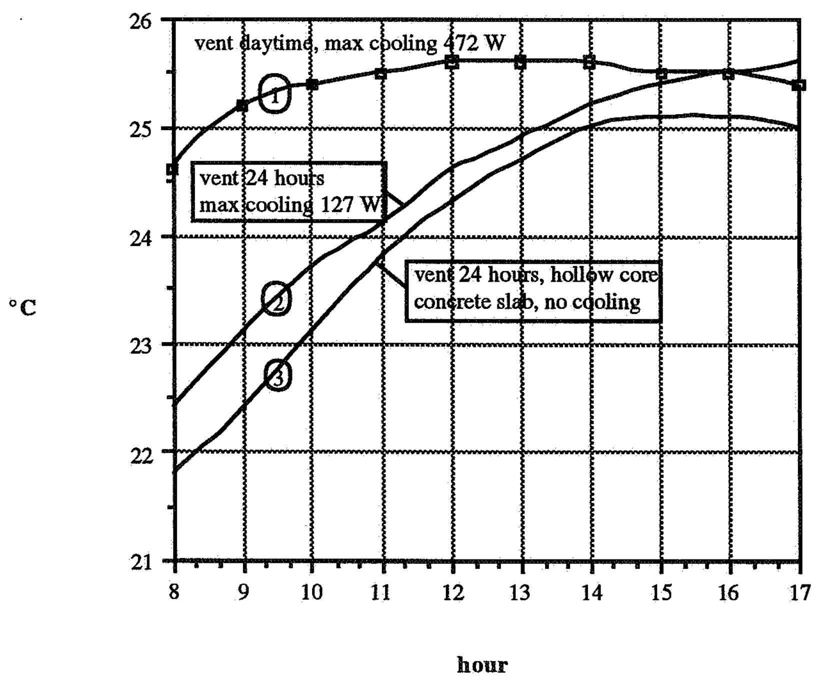

Fig. 2. Effective temperatures during the office hours using different control strategies.

Curve 1: Here we see a control policy typical in many modern buildings. The cooling system is operating only during occupied periods, and the control system is designed to maintain constant, 25 °C, room air temperature. The effective temperature is higher due to radiation. The cooling coil load is large, 472 W. Daily energy for cooling: 3.11 kWh + fanpower 0.50 kWh = 3.61 kWh.

Curve 2: Now we operate the equipment continuously. Space effective temperatures are cooler in the early occupancy hours due to lower surface temperatures, but still well within comfort range. These lower surface temperatures also mean lower capacity and energy required for cooling throughout the day. Also, since the additional hours are mostly during cooler hours, some of the cooling can be provided with outdoor air (economizer cycle). To see if we can go further with this strategy, we have stepwise reduced the installed capacity to 27 % of the original, and use a 22 °C set point. We see that we still are well within comfort conditions throughout the occupied period. Daily energy for cooling 1.66 + 1.09 = 2.75 kWh (76 % of the original).

Curve 3: Finally we reduce the cooling coil capacity to 0 and compensate by letting the supply air pass the holes in hollow core concrete slabs (Thermodeck). The stronger thermal coupling between the air and the mass gives a better use of the thermal capacity. The comfort is better without cooling than in the original case. Daily energy use for cooling 1.09 kWh (only fanpower).

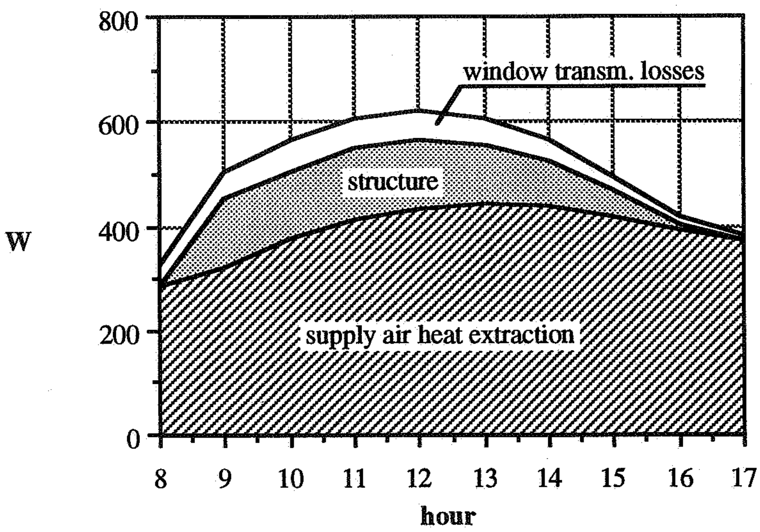

Fig. 3. Negative items in the room heat balance when the cooling system operates only at daytime. Set point 25 °C. The major part of the heat gains are extracted by the

zone supply air (maximum 442 W). Only 136 W is stored in the structure (coming back at night). Required cooling coil capacity is 472 W. The effective temperature exceeds 25 °C during more than 8 of 9 office hours, see curve 1 in Fig. 2.

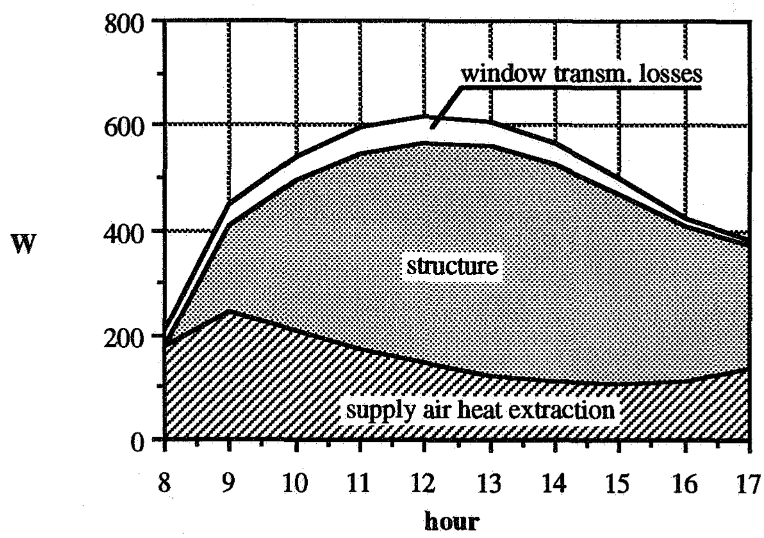

Fig. 4. Negative items in the room heat balance when the cooling system operates continuously. Set point 22 °C. A smaller part of the heat gains are now extracted by the supply air (maximum 243 W) and 435 W is stored in the structure. Required cooling coil capacity is reduced to 127 W (27 %). Still the comfort is improved, see curve 2 in Fig. 2.

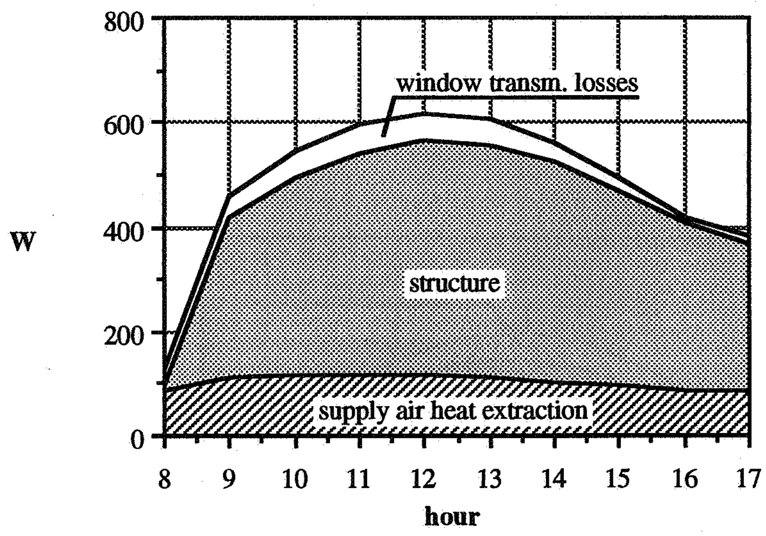

Fig. 5. Negative items in the room heat balance when using ventilated hollow core concrete slabs and no cooling. The structure is fully utilized and takes care of more than 75 % of the gains in the afternoon.The comfort is better than in the original case, see curve 3 in Fig. 2.

A simple one-mass model for estimating the performance of ventilated hollow core slabs.

Energy saving in modern Scandinavian office buildings is a matter of storing excess heat from daytime to cover heat losses during the night. The heat capacity of concrete slabs is mostly sufficiently high to store and emit enough energy to keep rooms within a comfortable temperature range.

However, the slabs are not always available for heat storage, due to soft carpets and suspended ceilings which introduce thermal resistance at the surfaces.

A Swedish system called the Thermodeck system utilizes hollow core slabs to reach the storage capacity from the inside. The supply air passes through the holes in the concrete before it enters the room. Laboratory measurements have shown that the temperature gradients along the slab are small compared to the temperature difference between the incoming and outgoing air. To show how different parameters affect the performance of this system a simple one-mass analytical model is used.

The mass is supposed to be concentrated in a thin sheet with a uniform temperature.

The incoming air varies sinusoidally:

$$\upsilon_{in} = a \cdot \sin(\omega t)$$

where

a is the amplitude, °C

ω angular velocity, h^{-1}

t time, h

(for a 24-hour oscillation $\omega = \pi/12$)

The mass temperature and outgoing air temperature are damped and delayed

$$\upsilon_{mass} = \frac{a}{Z_m} \cdot \sin(\omega t - \phi_m)$$

$$\upsilon_{out} = \frac{a}{Z_{out}} \cdot \sin(\omega t - \phi_{out})$$

The air temperature along the slab is assumed to change exponentially towards the slab temperature.

With $\alpha = exp(-\frac{hA}{V\rho cp})$

and $\beta = \frac{V\rho cp}{MC}(1-\alpha)$

the solution of the differential equation that this model gives rise to

is:

$$\phi_m = arcsin\left(\frac{\omega}{\sqrt{\beta^2 + \omega^2}}\right)$$

$$Z_m = \frac{1}{cos(\phi_m)}$$

$$\phi_{out} = arctan\left(\frac{cos(\phi_m)\, sin(\phi_m)\, (1-\alpha)}{cos^2(\phi_m)\, (1-\alpha)+\alpha}\right)$$

$$Z_{out} = \frac{sin(\phi_{out})}{cos(\phi_m)\ sin(\phi_m)\ (1-\alpha)}$$

Here

V = air flow, m^3/h

ρ = air density, kg/m^3

c_p = specific heat capacity of air, Wh/kg,°C

M = slab mass, kg

C = specific heat capacity of the slab material Wh/kg,°C

h = film coefficient, W/m^2,°C

A = area, m^2

The unknown parameter in this model is the film coefficient h. To examine how it affects the time lag and the damping we now chose a 10 m^2 slab ventilated by 100 m^3/h as an example. The mass is supposed to be 4600 kg (20 cm of concrete, C = 0.24 Wh/kg,°C).

When $hA = 0$ the mass temperature is constant, and the outtgoing air temperature follows the incoming air temperature. With an increasing hA-value the air temperature variation is more effectively damped and delayed. The mass temperature starts varying sligtly with a delay close to 90 ° (= 6 hrs), the highest possible value for a 24 - hours swing.

The time lag and damping of the outgoing air temperature variation are plotted in fig. 6 and 7 respectively.

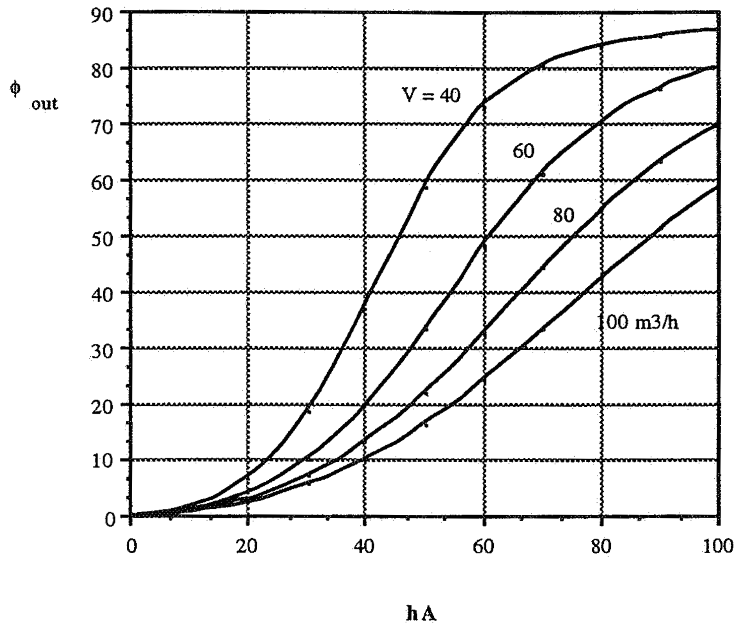

Fig. 6. Time lag in outgoing air temperature. 90° = 6 hours.

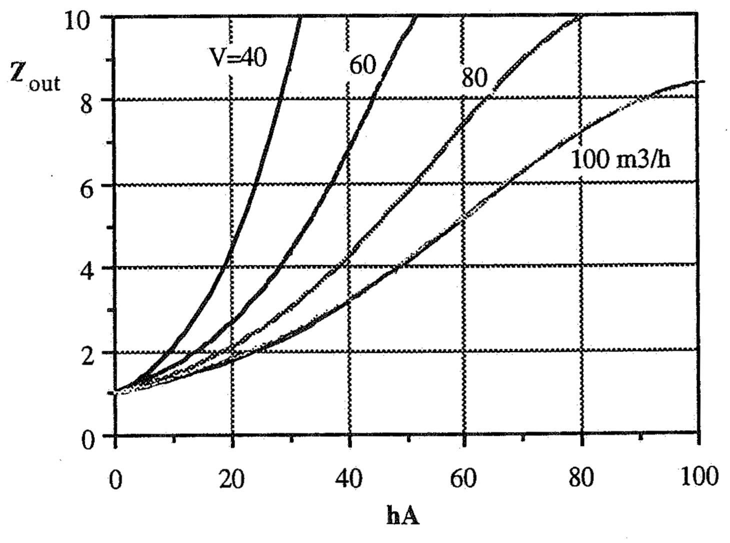

Fig. 7. Damping of amplitude incoming/outgoing air temperature.

It is obvous that the value of hA has a strong influence on the performance of this system. This value depends on the hole diameter, the number of holes, and the air velocity.

The film coefficient for straigt channels can be obtained from the expressions

$Nu = 0.032*Re^{0.8}*Pr^{0.30}*(D/L)^{0.054}$

for turbulent flow and

$Nu = 0.578*Re^{0.5}*Pr^{1/3}*(D/L)^{0.5}$

for laminar flow.

We use the equations on the following standard element which is manufactured in many countries:

length $L = 5$ m

breath 1,2 m

thickness 0,28 m

5 holes diam. $D = 0,18$ m

The holes are connected in series.

For this element we get the results shown in Figs 8- 9.

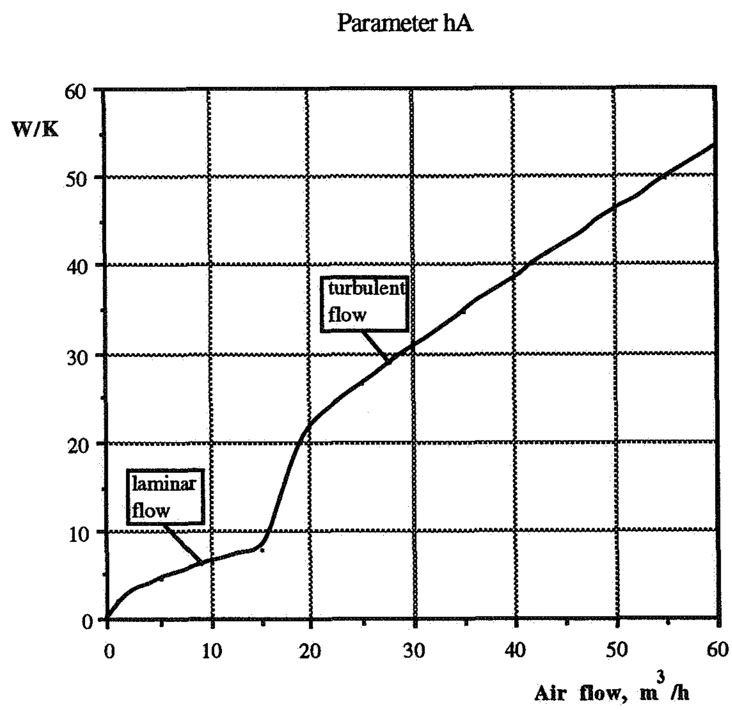

Fig 8. Convective heat transfer inside the holes. Hole diameter 0.18 m.

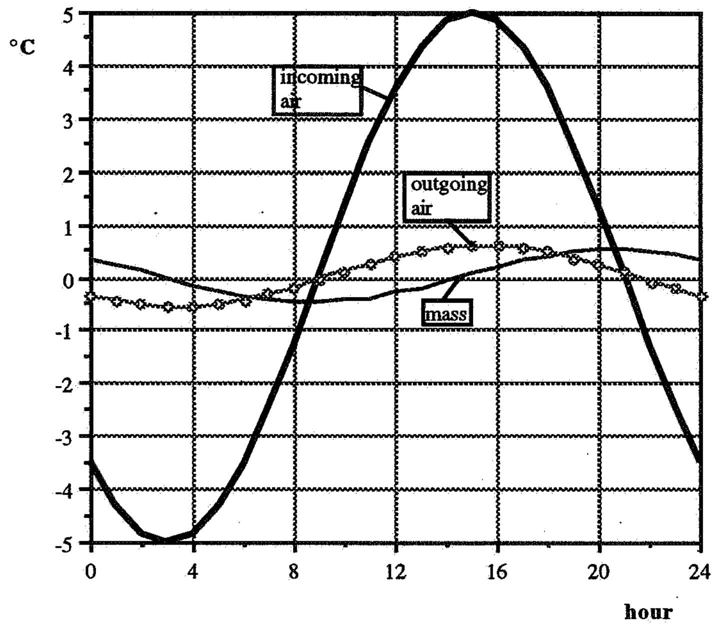

Fig. 9. Temperature variation of incoming - outgoing air and mass. Air flow rate 40 m^3/h.

In a building any element is exposed to disturbances by heat exchange from the room via the floor- and ceiling surfaces, and in the BRIS program the model presented above defines the boundary conditions on the inside of the holes.

Conclusions.

It is now time to use simulation programs and knowledge from the use of these tools not only for the design of systems meeting requirements from an uninformed builder, but also to convince him what poorly formulated requirements will cost him.

More cooperation with the control engineers is also necessary. Computerized control systems have a high potential, and could be used not only for prompt compensations, but for advanced smoothing and forecasting techniques. Energy supply or extraction could then be made using low powers during long periods, for instance during the night hours, to prepare the building for the next morning. Peak periods can be avoided until it is necessary. In between, the building takes care of itself.

A proper use of simulation programs will show how the building dynamics can be utilized and result in much more energy and power efficient buildings in the future.

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Ventilation Measurements in a Cinema

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VENTILATION MEASUREMENTS IN A CINEMA

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SYNOPSIS

This paper reports on the ventilation measurements in a cinema using the tracer-gas technique. Both the local and room air exchange efficiencies were measured. The two tracer-gas methods, "step-up" and "step-down (decay)", were used alternately when the cinema was in use to enable a continuous measurement of air-exchange efficiencies under various occupancies. The air exchange efficiencies were found to be very close to that for a perfect mixing, with little influence from the occupants. This might be due to that the cinema had a downward mixing ventilation with a large air change rate. The air exchange efficiencies were found to be lower with the decay method than with the step-up method. The results also show that the decay method was more stable than the step-up method for evaluating the local air exchange efficiencies. However, both are stable for evaluating room air exchange efficiencies.

Other parameters such as the CO_2 concentrations and temperatures were also measured. Due to good mixing in the cinema, the thermal stratification was found to be small. However, the difference between the CO_2 concentrations in the occupied zone was found larger with higher occupancy. The CO_2 concentrations were found to be higher in the occupied zone than the room-average ones.

1. INTRODUCTION

The main objective of ventilation is to achieve good air quality for the occupants. How the fresh air is distributed to the occupied zone and the pollutants are removed from the space are of particular interest for HVAC engineers. The introduction of the "age of air" and the development in experimental methods with tracer-gas technique facilitate the study of the air distribution and flow pattern in a ventilated space.

The mean-age of air in a room is the time it takes, on an average, to replace (exchange) the air present in the room. Its value can be used to determine whether the space is well ventilated or whether there are stagnant zones present. However, to determine whether the stagnant zone is located in the occupied zone requires the measurement of the local mean age of air. With a multi-channel tracer-gas equipment, the flow situation in a room can be examined.

In this study, a small cinema was chosen for the measurement of the air exchange efficiencies. In addition, the temperatures and CO_2 concentrations were also measured.

2. EXPERIMENTAL SET-UP

The cinema being investigated was located in the centre of a town in northern Norway. It had a floor area of about 120 m^2 and a seating capacity of 60 persons. The effective volume was about 340 m^3. Figures 1 and 2 show schematically the cinema.

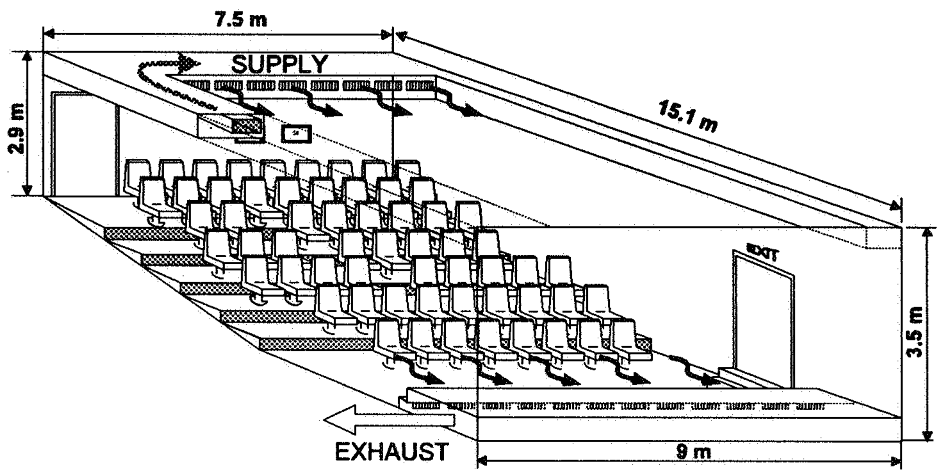


Figure 1. Illustration of the cinema.

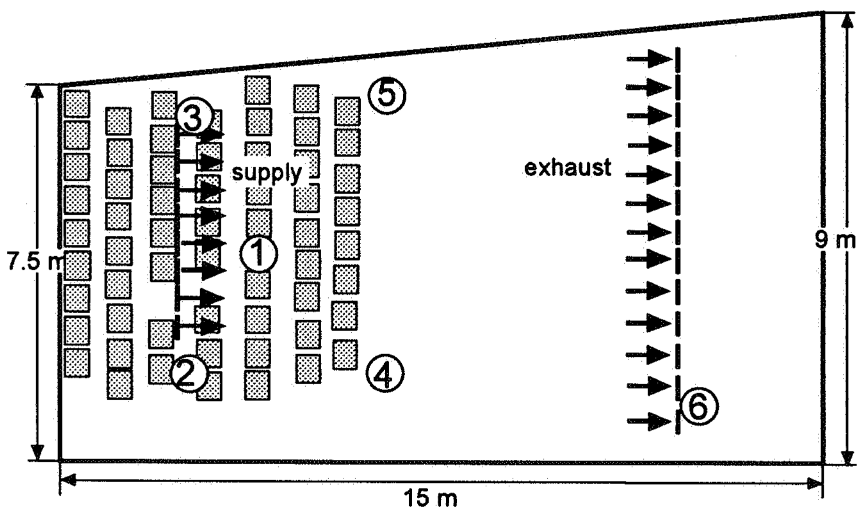


Figure 2. Plan of the cinema and sampling locations.

The cinema was situated underground, so the outdoor climate had little influence on the indoor climate. It had a downward mixing ventilation system, and no heating or cooling devices were used within the cinema. There were eight rectangular air terminal devices used at the supply and 13 at the exhaust, measuring 0.1×0.5 m (height × width) each. Figure 3 shows schematically the ventilation system for the cinema.

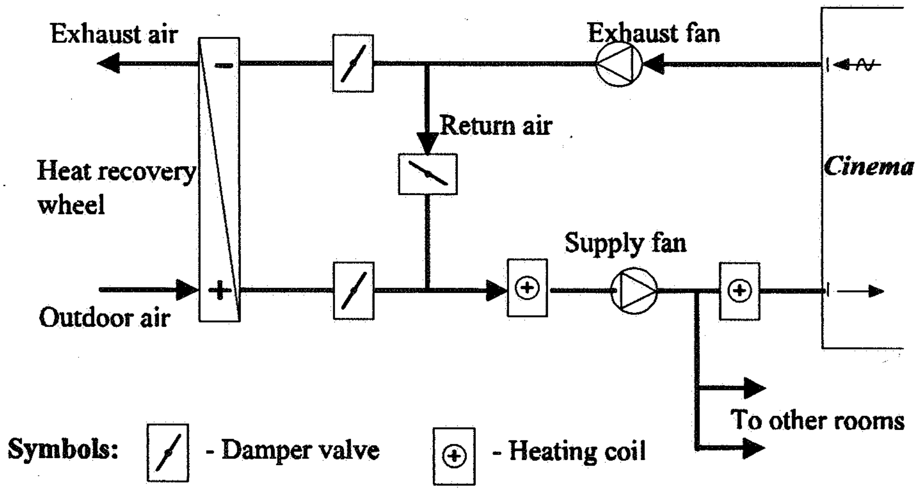


Figure. 3. Schematic diagram of the ventilation system for the cinema. The return-air damper was closed during the measurement.

The measurements were carried out at six sampling points. The locations of the sampling points and the parameters measured can be found in figure 2 and table 1. The tracer-gas used was SF_6 (sulphur hexafluoride).

Table 1. Parameters measured at various sampling points

Sampling points	Height over the floor (m)	Measured parameters		
		Temperature	CO_2 conc.	SF_6 conc.
1	0.8	yes	yes	no
2	1.6	yes	yes	yes
3	1.6	yes	yes	yes
4	1.6	yes	yes	yes
5	1.6	yes	yes	yes
6 (exhaust)	0.2	yes	yes	yes

The temperatures were measured continuously at all six sampling points with thermal couples. Additional five thermal couples were placed vertically near sampling point 4, spaced evenly between the heights 0.5 m and 2.5 m for determining the vertical temperature gradient. These thermal couples were all calibrated with a precision thermometer.

CO_2 concentrations were measured at all the six sampling points. At sampling point 1, a portable CO_2 monitor manufactured by Fläkt, Sweden was used. At sampling points 2 to 6, both CO_2 and SF_6 concentrations were measured using a multi-gas monitor together with a multipoint sampler and doser (Brüel and Kjær model 1302 and 1203). They can provide a maximum of six channels for sampling and analysis of six different gases at the same time, of which five were used during the measurement. Descriptions of these instruments and the application software for data acquisition are given in (1,2).

The measurements were carried out during two consecutive evenings. Two films with a length of 1.5 to 2 hours were shown during each evening. There was a 20 to 30 minutes pause between the two films. Measurements started a couple of hours prior to the first film. The occupants were 2 respectively 9 the first evening, and 22 respectively 16 the second evening.

3. TRACER STEP-UP AND STEP-DOWN (DECAY) METHODS

The theory on the age of air and air exchange efficiency has been well established, and they can be determined by the two commonly used methods: the tracer step-up and tracer step-down (decay) methods (3,5,6). The local mean age of air at a particular point p, $\bar{\tau}_p$, can be determined using these two methods (see figure 4):

$$\bar{\tau}_p = \frac{\int_0^\infty [C(\infty) - C(t)]\mathrm{d}\,t}{C(\infty)} = \frac{\text{Area above the step-up curve}}{C(\infty)} \text{ (for step-up method)} \quad (1)$$

and

$$\bar{\tau}_p = \frac{\int_0^\infty C(t)\mathrm{d}\,t}{C(0)} = \frac{\text{Area under the decay curve}}{C(0)} \text{ (for decay method)} \quad (2)$$

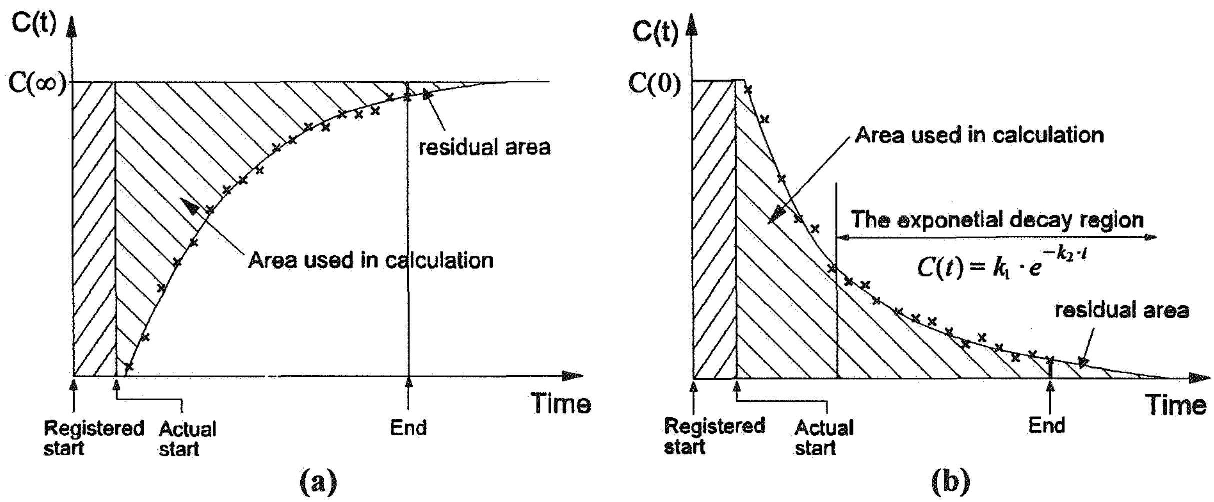


Figure 4. (a) Step-up method, and (b) Step-down (decay) method.

The areas used both in equations 1 and 2 consist of two parts: the first part is obtained using the measured data sets; the second part is the residual part, which can be obtained using the extrapolation method with the exponential functions (2,4).

Notice that the length of the dosing and sampling tubes will cause a time delay during the measurements. This time delay is the one for tracer to be transported in the tubes. The areas used for calculation should be the ones from the actual start time.

The local air exchange efficiency at point p, ε_p, is

$$\varepsilon_p = \frac{\tau_n}{\tau_p} \times 100\% \tag{3}$$

where τ_n is the nominal time constant, $\tau_n = V/q_v$, V is the room volume and q_v is the ventilation flow rate.

The air exchange efficiency for the room, ε_a, is defined as (3)

$$\varepsilon_a = \frac{\tau_n}{2 < \bar{\tau} >} \times 100\% \tag{4}$$

where $< \bar{\tau} >$ is the room mean age, which can be calculated from

$$< \bar{\tau} > = \frac{1}{\tau_n} \int_0^{\infty} t \cdot \left(1 - \frac{C_e(t)}{C_e(\infty)}\right) \mathrm{d}\, t \qquad \text{(for step-up)} \tag{5}$$

and

$$< \bar{\tau} > = \frac{\int_0^{\infty} t \cdot C_e(t) \mathrm{d}\, t}{\int_0^{\infty} C_e(t) \mathrm{d}\, t} \qquad \text{(for decay)} \tag{6}$$

where C_e is the tracer concentration at the exhaust.

4. RESULTS AND DISCUSSION

4.1. Air exchange efficiency

The measured tracer concentrations at five sampling points 2-6 are shown in figure 5.

The ventilation flow rate can be measured accurately using the tracer-gas technique (7). With a constant dosing method and the measured downstream concentration, the ventilation flow rate, q_v, is

$$q_v = \frac{\text{dosing rate}}{\text{downstream tracer concentration}} \tag{7}$$

The measured downstream tracer-gas concentrations in the supply duct to the cinema are shown in figure 6. The supply air flow rate was found to be 2150 m^3/h with very small variations with time. This gives an air change rate of 6.3 h^{-1}. By measuring the upstream concentration, the amount of return air or short-circuiting air through the heat recovery wheel can be also be determined. The short-circuiting air was found to be less than 3% the fresh air, thus no considerations were taken on the background tracer concentration in the supply air.

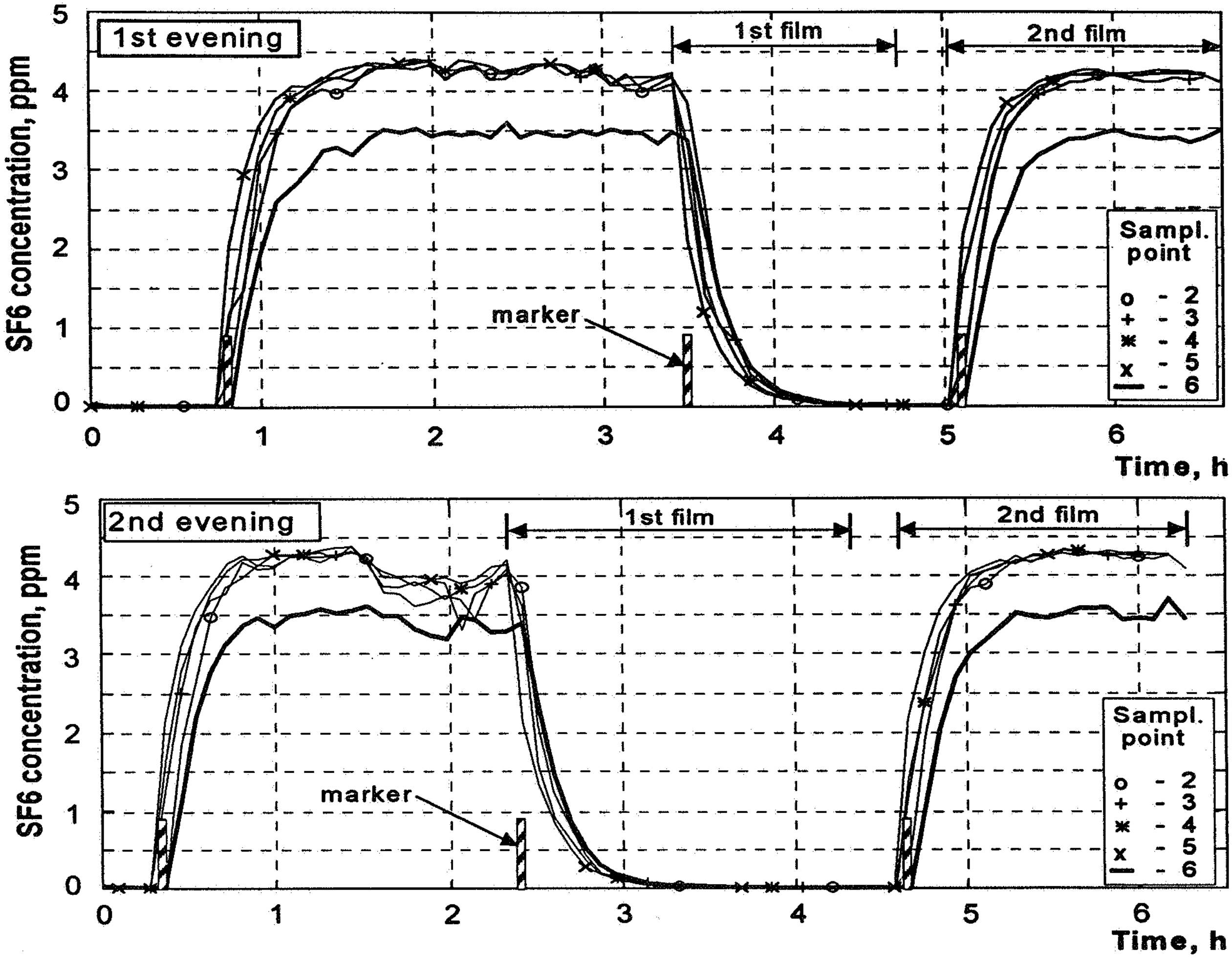


Figure 5. Variations of SF_6 concentration during the step-up and step-down measurement. The actual start time is marked by the marker.

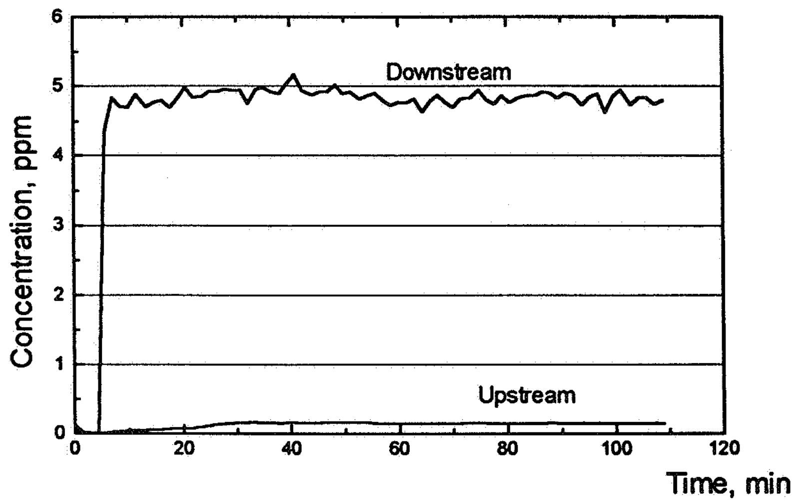


Figure 6. The measured concentration in the upstream and downstream of the dosing point in the supply duct.

The measured air exchange efficiencies are summarised in table 2.

Table 2. The measured air exchange efficiencies.

No. of occupants	1st evening			2nd evening		
	0	2	9	0	22	16
Method	*Step-up*	*Decay*	*Step-up*	*Step-up*	*Decay*	*Step-up*
Local		ε_p			ε_p	
Point 2	54%	52%	53%	56%	46%	55%
Point 3	45%	45%	54%	49%	47%	46%
Point 4	55%	44%	44%	48%	42%	46%
Point 5	47%	39%	43%	44%	38%	45%
Room		ε_a			ε_a	
	53%	50%	52%	52%	48%	53%

We can see that the decay method gave lower air exchange efficiencies than those with the tracer step-up method. The air exchange efficiencies for the room were 2 - 5% lower with the decay method than with the step-up method. This might be due to the fact that no mixing fans were used at the start of the decay. The measured local air exchange efficiencies were found more stable with the decay method than those with the step-up method. However, the mean air exchange efficiencies were equally stable for both the step-up method and the decay method, which is different from the conclusion as given in (8).

The measured air exchange efficiencies with various occupancies were found all to be very close to 50%, which is the air exchange efficiency for perfect mixing. The occupants had little influence on the air exchange efficiency due to the downward mixing ventilation and the large air change rate in the cinema.

4.2. Temperatures and CO_2 concentrations

Figure 7 gives an example of the vertical temperature profiles at the beginning and end of a film. The temperatures in the cinema increased about 1°C due to the heat loads from the occupants, but the temperature gradient remained nearly the same. The temperature difference between the heights 0.5 m and 2.5 m was less than 1°C, which was also true for all the other cases, even when the cinema was unoccupied. This might be explained by the downward mixing ventilation with a high air change rate.

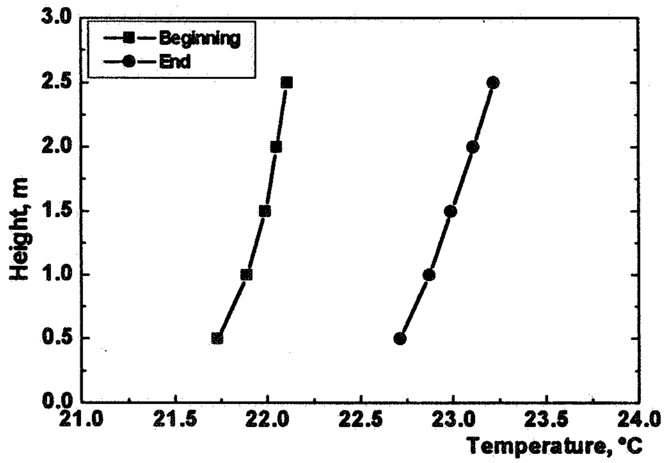
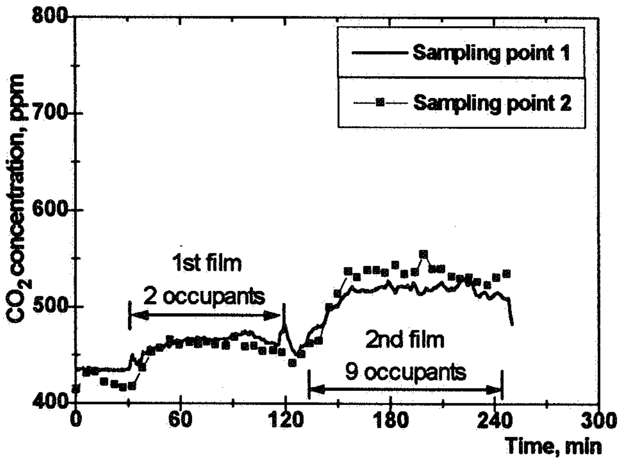
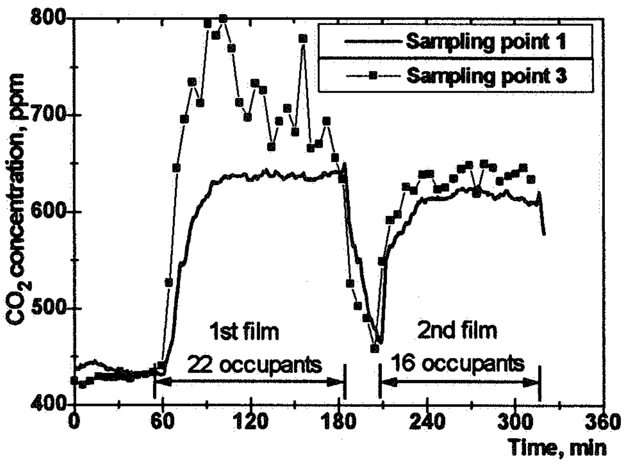


Figure 7. Vertical temperature profiles at the beginning and end of a film with 22 occupants.

Figure 8 shows the variations of CO_2 concentrations at sampling point 1 at a height of 0.4 m and the sampling point with the highest CO_2 concentration among sampling points 2 to 6 at a height of 1.6 m.



(a)



(b)

Figure 8. The variations of CO_2 concentration with time, (a) first evening at sampling points 1 and 2, (b) second evening at sampling points 1 and 3.

There are two possible reasons why the highest concentrations occurred at the sampling point 2 during the first evening and sampling point 3 during the second evening: 1) both of them are located at the back of the cinema below the air supply. As the air was distributed horizontally towards the stage, the CO_2 brought by the convective currents from the occupants might not be diluted directly. 2) the difference in CO_2 concentrations might also depend on the different occupancy densities below these sampling points.

The CO_2 concentration stabilised some 30 minutes after the beginning of the film. The mean values of the increase in CO_2 concentration between 30 minutes after the film began and the end of the film are calculated and plotted against the number of occupants in figure 9.

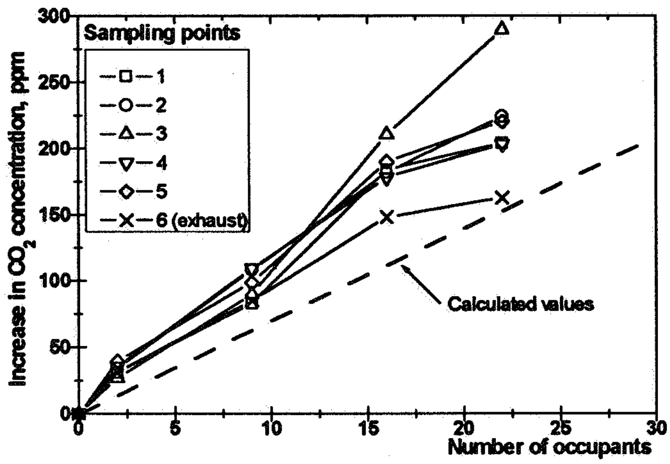


Figure 9. The variations of increase in CO_2 concentration with number of occupants at all the six sampling points. The dashed line represents the calculated values of the mean CO_2 concentration in the cinema at perfect mixing.

As the air exchange efficiencies approach very much that for a perfect mixing, the increase in CO_2 concentrations, ΔC_{CO_2}, can then be estimated by

$$\Delta C_{CO_2} = \frac{n \cdot V_{CO_2}}{q_v} \tag{8}$$

where n is the number of occupants, q_v is the ventilation flow rate, and V_{CO_2} is the CO_2 generation rate per person, which can be calculated using (9)

$$V_{CO_2} = 0.25 \cdot M \ \text{(liter / min)} = 15 \cdot M \ \text{(liter / h)} \tag{9}$$

where M is the metabolism rate, for a sitting person M = 1 met.

The calculated mean increase in CO_2 concentrations are plotted in figure 9.

The CO_2 concentrations were lowest at sampling point 6, which was located at the exhaust. The difference between the CO_2 concentrations are greater with larger number of occupants. At sampling points 2 to 5, the differences in CO_2 concentrations may be explained by the different occupancy densities below these sampling points. As can be seen, the CO_2 concentrations are higher in the occupied zones than the mean in the cinema space.

CONCLUSIONS

The air exchange efficiencies were measured in a cinema with tracer step-up and decay methods alternately. The measured air-exchange efficiencies are close to that for a perfect mixing, with little influence from the occupants. This might be due to the downward mixing ventilation with a large air change rate. The measured air exchange efficiencies with decay method were found 2-5% lower than with the step-up method. Even though the built-up concentrations were stable at the end of the step-up measurement, a mixing fan should still be used to reduce the errors in the coming decay measurement. The decay method gave more stable values than the step-up method for the local air exchange efficiencies. For the room air exchange efficiencies, it seems that both methods were equally stable.

The increases in CO_2 concentrations were found to be linear with the number of occupants. In the occupied zones, the increases were larger than the mean values. The temperature gradients were small due to the mixing type of ventilation.

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OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS

17th AIVC Conference, Gothenburg, Sweden,
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(Title) CONTAM96: A Multizone Airflow and Contaminant Dispersal Model with a Graphical User Interface

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CONTAM96
A Multizone Airflow and Contaminant Dispersal Model with a Graphic User Interface

Abstract

The latest version in the CONTAM family of airflow and contaminant dispersal models, CONTAM96, has recently become available. CONTAM96 is an easily-used contaminant analysis program combining state-of-the-art algorithms for modeling airflow and contaminant dispersal in multizone buildings. CONTAM96 employs a graphical interface for entering data and viewing the output of a simulation. The interface is based on a SketchPad upon which the user draws building floor plans and places various symbols representing building features relevant to the calculation of airflow and contaminant dispersal. The SketchPad is used to establish the geometric relationships of the relevant building features, producing a simple illustration of the building that represents the underlying mathematical model. This illustration describes the connection between building zones using icons to represent the zones, openings between zones, ventilation system components, and contaminant sources and sinks. The SketchPad brings up data entry screens used to define the mathematical characteristics of various building features, e.g., leakage areas of openings and contaminant source strengths. After performing a simulation, the flows and pressure drops at each opening are presented on the SketchPad. Transient contaminant concentrations can be displayed as separate graphs. In contrast to previous versions of CONTAM, CONTAM96 has the following new features: the ability to perform year-long simulations and exposure analysis, and a duct model. CONTAM96 requires a 386-class (or higher) PC-compatible computer with a math coprocessor, VGA graphics and MS-DOS. The program can also run in a DOS window under Microsoft® Windows95.

Introduction

Over the past several years, NIST (the National Institute of Standards and Technology - formerly NBS, the National Bureau of Standards) has developed a series of public domain computer programs for calculating airflow and contaminant dispersal in multi-zone buildings. The earliest such program was ASCOS (Analysis of Smoke Control Systems) (Klote, 81). Another program, TARP (Thermal Analysis Research Program) (Walton, 83), used multizone airflow calculations to estimate the portion of building thermal load due to infiltration and perform a simple contaminant migration analysis. Programs developed specifically for the study of contaminant dispersal include CONTAM86 and CONTAM87 (Axley, 87 & 88). NBSAVIS/CONTAM88 (Grot, 91) added multizone airflow analysis capability based on TARP and a menu-driven interface to CONTAM87. Improvements in the airflow calculation algorithm were implemented in the AIRNET (Walton, 89) program. CONTAM93 (Walton, 94) combined a new graphic interface with the contaminant simulation capabilities of CONTAM88 and the airflow analysis method of AIRNET. The application of this program to a residential IAQ modeling study was discussed at the 15th AIVC Conference (Emmerich, 94 & 95). In CONTAM96 the user interface has been extensively improved, the simulation capabilities expanded, and the separate interface and computation programs of CONTAM93 combined into a single executable program.

The fundamental assumption in CONTAM is that the building can be modeled by some number of zones of well-mixed air. Over the years many methods have been developed to compute the building airflows which are necessary for the contaminant analysis. Feustel and Dieris (1992) report 50 different computer programs for multizone airflow analysis. Note than "zones" go by many other names in these programs, e.g., nodes, cells, and rooms are common alternatives.

The calculation of airflows is based on a quasi-steady analysis at each time step where conservation of mass provides the convergence criterion for the Newton-Raphson solution of the non-linear algebraic equations.

A simple implicit scheme is used to solve the first-order differential equations that model the contaminant dispersal in trace concentrations throughout the zones. Details of the airflow and contaminant migration models are given in the CONTAM93 (Walton, 94) report.

Building Idealization

CONTAM96 supports the analysis of whole building systems *idealized* or *modeled* using collections of control volumes or *zones* linked by air flow paths - doors, windows, ventilation fans, cracks or leakage paths in the building construction, etc. These airflow paths are, in turn, modeled by so-called *flow elements*. As such, CONTAM96 is a *macroscopic* analysis tool - a term used to distinguish the modeling approach used from *microscopic* analysis based on computational fluid dynamics that are useful for modeling the details of flow and contaminant transport within individual rooms or connected spaces. At this point, we will address the problem of transforming a real building, existing or proposed, into an idealization suitable for macroscopic analysis with CONTAM96.

The manner in which a building is idealized as a number of zones depends on the layout of the building, the zoning of the ventilation system and the reason that the user is performing the analysis, that is the question at hand. One could include every conceivable zone in a building idealization, down to every room and closet. Fortunately, it is unlikely that such a detailed idealization is necessary. Depending on the building and the purpose of the analysis, the zones may be building floors, groups of floors, or individual rooms. Floors may be grouped together if they are served by a common ventilation system, or are assumed to have common air leakage and pollutant source characteristics. For example, an office building with an underground garage could be modeled as two zones (the garage and the rest of the building) if a user is trying to understand the transport of motor vehicle exhaust from the garage to the rest of the building. Instead, if they are trying to understand airflow between the floors of the building, a single zone idealization of the occupied floors will not be appropriate, and the building will need to be divided into a number of zones.

To make the discussion more concrete consider the *"real"* building sketched below in plan and perspective drawing - a four story apartment building with two units on each floor, an access stairway, and a four-story light shaft.

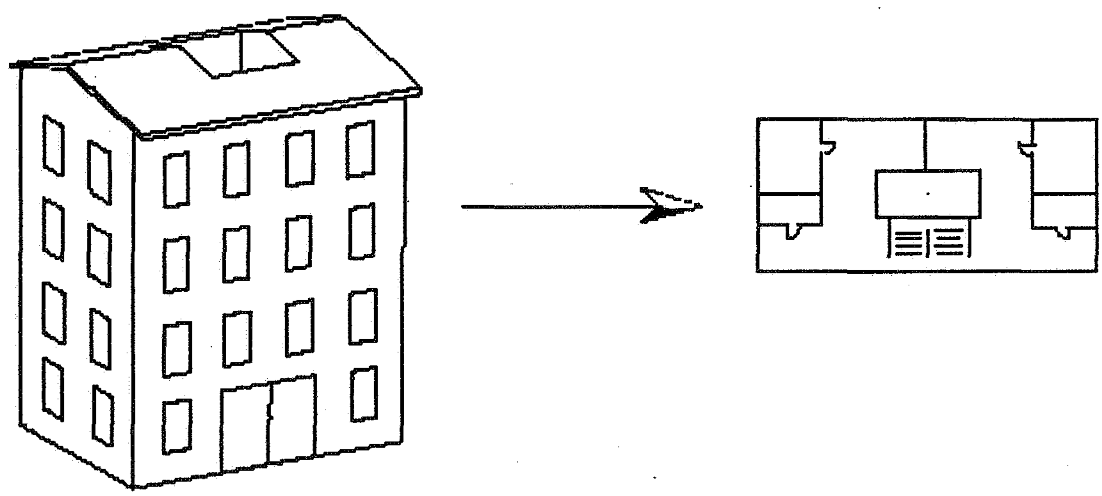

Figure 1. Example building

To form an idealization of this real building suitable for macroscopic analysis we must represent it as a collection of zones. At this point there are many ways to do this some clearly reasonable and useful, and some that are not. For example, we could *model* the apparent building as a single zone. This might be appropriate if we need only to get a rough estimate of indoor air pollutant concentrations when air flows freely between all eight units within the building - not likely to be a common occurrence. Alternatively, we could *model* each living unit in the building as a single control volume and the stairway shaft as an additional single control volume as sketched below. This idealization would allow us to predict airflows into, out of, and between units and to estimate average air contaminant concentrations within units.

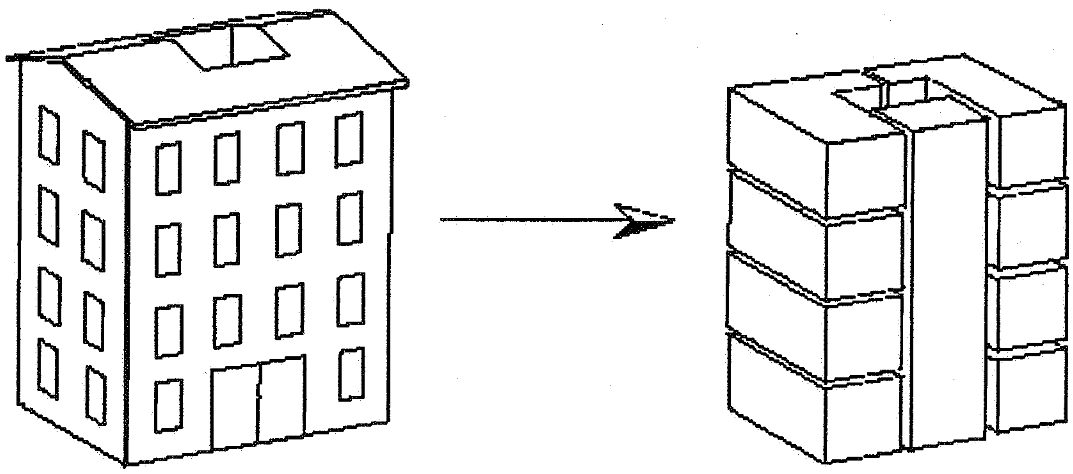

Figure 2. Simple Model

Finally, we could *model* each room in each living unit as three separate zones and the stairway shaft as a vertical stack of zones as sketched below. This idealization would allow us to predict airflows into, out of, and between rooms and units, to estimate average air contaminant concentrations within rooms, and to account for vertical distributions of contaminants in the stair shaft.

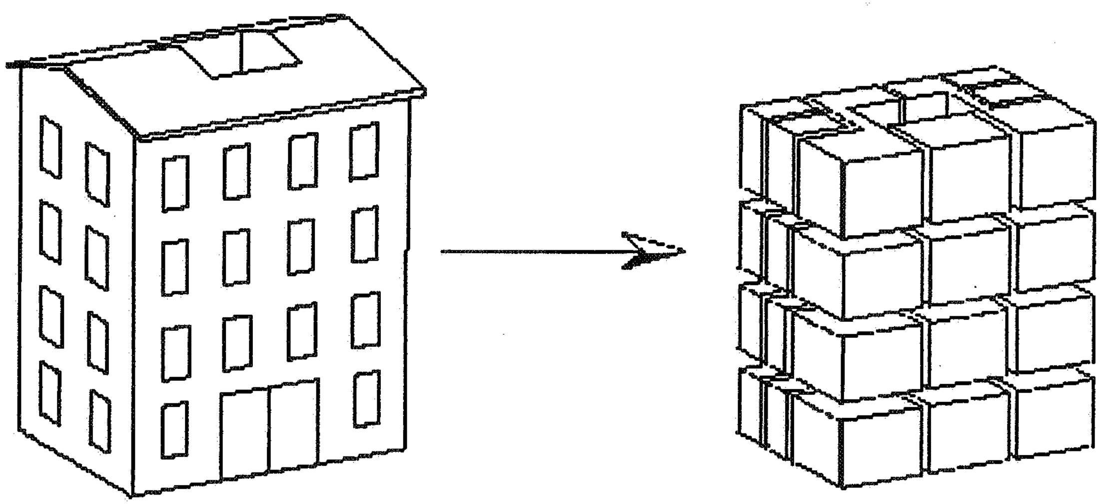

Figure 3. More Detailed Model

As indicated in the sketches above, it is natural for most buildings to organize these zones by building level. We, therefore, *represent* modeled zones in CONTAM96's sketchpad using plan views of the zones on each building level. While the *sketchpad* convention uses a 2D enclosed region to represent a zone it is important to keep in mind that each 2D region actually corresponds to a 3D volume.

Graphic Interface

The description of the building is created or modified via the SketchPad. The SketchPad consists of an invisible array of small cells into which the user places various icons representing building features relevant to the calculation of airflow and contaminant dispersal. This produces a simple illustration which has been chosen intentionally to represent the simplicity of the underlying mathematical model. The SketchPad is used to establish the geometric relationships of the relevant building features. It is not intended to produce a scale drawing of the building. Instead, it is used to create a simplified model where the walls, zones, and airflow paths are topologically similar to the actual building. The SketchPad allows the entry and display of the data in an intuitive manner. The SketchPad brings up various data entry screens needed to define the mathematical characteristics of the various building features (e.g. leakage areas and contaminant source strengths). After performing the simulation, the flows and pressure drops at each opening are presented on the SketchPad. Transient contaminant concentrations can also be displayed as separate graphs. Context sensitive, on-screen help is always available.

The CONTAM96 SketchPad is designed to simplify the data input and analysis processes for a multi-zone airflow and contaminant dispersal simulation. It is still up to the user to decide how best to idealize the building as a multizone system based on the building layout and the objectives of the simulation. The user must also determine which contaminant dispersal processes are important and appropriate input values for the building being simulated. The required input values can be numerous and include the following: airtightness of exterior envelope and interior partition components, ventilation system airflow rates, wind pressure coefficients, ambient weather and contaminant concentrations, indoor contaminant source strengths and sink characteristics, contaminant reaction rates, and filter efficiencies. Values of these quantities can be estimated from the published literature and field measurement.

Once the user has decided how to represent the building as a multizone system and has determined appropriate input values, the building data is entered into the SketchPad. Building data is organized by levels with data entry beginning at the lowest level. A level would typically be a building floor, but a suspended ceiling acting as a return air plenum or a raised floor acting as a supply plenum may also be treated as a level leading to multiple levels per floor.

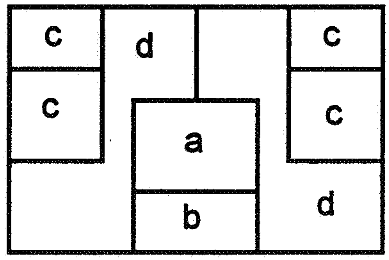

Figure 4. Draw Walls

Each level is divided by walls into separate regions of uniform air temperature, pressure, and contaminant concentration called zones. Walls include the building envelope and internal partitions with a significant resistance to air flow, and are drawn as either horizontal or vertical lines. Figure 4 shows the walls for the first level of the building. This sketch includes the lightshaft (a), the stairwell (b), and the two apartments which are each divided into two individual rooms (c) and the well-mixed remainder (d).

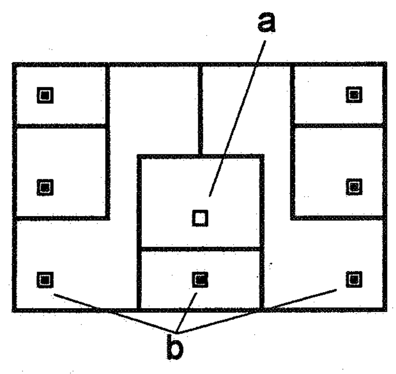

Figure 5. Add Zone Icons

Some additional information is needed to complete the description of each zone. This is done in two steps. First one zone icon is created in each walled area by moving the cursor to the desired position and pressing the key associated with the icon. The type (a) icon in figure 5 indicates an outdoor, or 'ambient' zone (there is an ambient zone around the outside of the building by default). The type (b) icons indicate 'normal' zones. There is also a 'phantom' zone icon which indicates that the area on the current level is actually part of the zone on the level immediately below. When these icons are first created they appear in a dark red color. After the appropriate data has been entered, they are black. The data includes the name of the zone (for output reports), the zone temperature, volume, and initial contaminant concentration if that is applicable

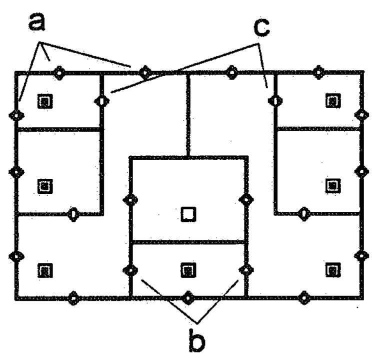

Figure 6. Add Flow Path Icons

An airflow path indicates some building feature by which air can move from one zone to another. In figure 6 the icons (a) have been placed on the walls represent leakage openings between the zones and ambient. It may be desirable to use several openings to represent the individual airflow features on each wall. The icons (b) indicate the closed doors between the stairwell and the apartments. The icons (c) indicate open doorways which can allow a two-way flow between zones with different temperatures. At the path icon the user enters data describing the flow/pressure relationship, the height of the path relative to the current level, and wind pressure data which will be used to convert wind speed and angle to pressure on envelope openings. A large number of flow/pressure formulations are provided. These include three forms of the powerlaw equation, $Q = C\ (\Delta P)^n$, $w = C\ (\Delta P)^n$, and $w = C \sqrt{\rho}\ (\Delta P)^n$, where Q = volume flow rate, w = mass flow rate, ΔP = pressure drop, and ρ = air density. The user may create a powerlaw model from a physical description of a crack, stairwell, shaft, or experimental data. There are two forms of the quadratic model, $\Delta P = aQ + bQ^2$ and $\Delta P = aw + bw^2$, which the user may also create from a crack description or measured data. There is a model for 2-way flow through a tall opening caused by a temperature difference in the two zones, and there are simple fixed flow rate fan models and a fan modeled by its performance curve.

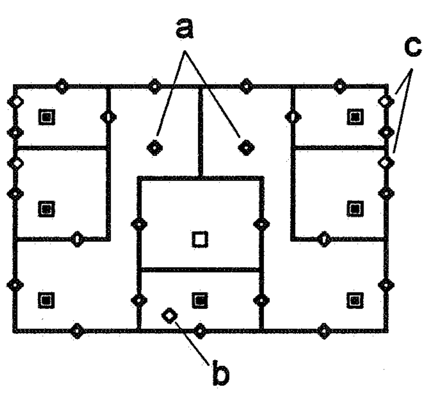

Figure 7. Add 2nd Floor Paths and Fans

Figure 7 shows the second level in the building. It was created by a single command that copied the first level and then was modified with a few additions. The icons (a) which are not on walls represent flow paths through the floor separating this level from the one below to allow an inter-level flow. Icon (b) in the stairwell has been set by the user to indicate a large opening betweens levels to indicate a low resistance to airflow. The icons (c) represent fans which can move air between zones according to a schedule. The icon is modified to indicate the direction of air flow, in this example out of the building to ambient.

A simple model of an air handling system is available with supply and return point symbols placed within the appropriate zones. Icon (a) in figure 8 represents the implicit supply and return nodes (zones) in such an air handling system, which are placed independent of the building zones. The supply zone is implicitly connected to all the icon (b) supply points, and the icon (c) return points are connected to the return zone. At the return zone some air may be exhausted and some recirculated; at the supply zone some outdoor air enters the system. All supply and return airflows follow user defined schedules. In this example a separate system has been created for each apartment.

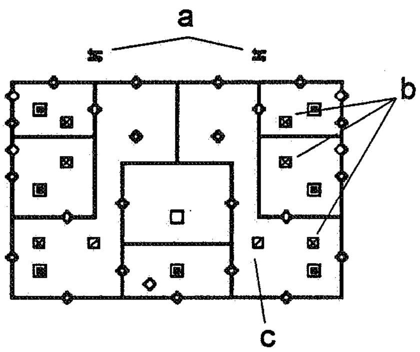

Figure 8. Add Simple AHS

Contaminant source (or sink) icons, (a) in figure 9, may be placed in any zone. These represent any feature which produces, removes, or adsorbs a contaminant. The basic model is the constant coefficient model, $S_\alpha = G_\alpha - R_\alpha \cdot C_\alpha$, where S_α is the contaminant α "source strength" computed from the generation rate, removal rate, and concentration in the zone. Other models include a pressure driven model, a cutoff concentration model, a decaying source model, and a boundary layer source/sink model. All source/sink icons include an optional schedule which varies the source strength as a function of time.

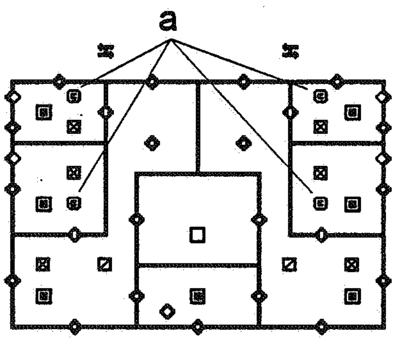

Figure 9. Add Contaminant Sources

A significant addition to the capabilities of CONTAM96 has been exposure analysis represented by the icons (a). In addition to just computing the transient contaminant concentrations in each zone, you can now easily determine the exposure of an individual as he moves to different zones as a function of time. You simply define the occupancy schedule which tells where the person is. In other cases you will be interested in exposure to contaminants generated by the occupants, and it will be critical that the generation schedule match the occupancy schedule. Here you can specify contaminant generation rates and schedules which will assigned to zones according to the occupancy schedule.

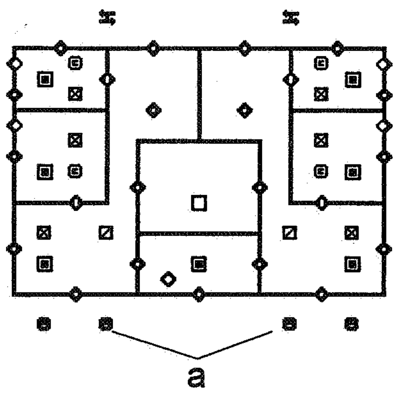

Figure 10. Add Exposure Icons

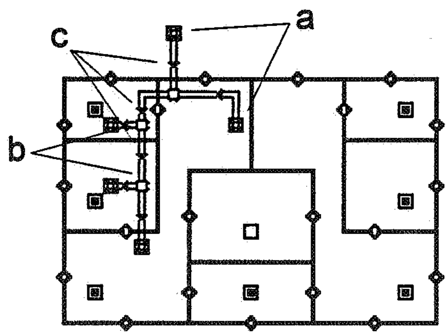

Figure 11. Duct Model

In addition to the simple AHS model of figure 8, CONTAM96 now provides a detailed model of ductwork shown in figure 11. The duct lines are drawn in much the same way as walls were drawn. Every duct line must terminate either in a zone as indicated by icons (a) or at a junction with other ducts shown by icons (b). When the flow characteristics of the duct segment are defined a small icon (c) is created which indicates the normal direction of flow (and the point at which the characteristics may be modified). The actual flow direction will be computed in the simulation. Special junction icons can be created which indicate that a duct segment is connecting junction on two building levels.

Other Capabilities

Flow elements, schedules, and wind pressure profiles can now be saved to "library" files and called into other project files which should reduce the amount of numeric input as the user develops his own personal libraries. CONTAM96 can now perform simulations for longer than one day -- actually, for up to one year. Since the detailed flow and concentration output files from such long runs could be very large, the program can produce summary statistics instead. These summaries consist of average, maximum, minimum, and standard deviations for age-of-air, contaminant concentrations, and exposures. The summaries can be used to determine critical days in the long simulation. A restart file is produced which allows the user to run individual days producing detailed output.

Future Extensions

Work is presently underway to develop a Windows NT version of the program. Theoretical approaches for non-linear contaminant chemistry and aerosol transport have been developed. Inclusion of non-trace contaminant analysis, simple thermal analysis, and simple data transfer to/from a wind pressure calculation program would also be desirable.

Requirements

CONTAM96 requires a 386 class (or higher) PC compatible computer with a math coprocessor, approximately 2 megabytes of RAM, VGA graphics, and MS-DOS. The use of a more advanced CPU chip (486DX or Pentium equivalent) is recommended for its faster computational performance. CONTAM96 is a DOS program which can also be run in a DOS window under Windows 3.1 and Windows 95.

Availability

CONTAM96 is available on diskette and the Internet. For a diskette, contact the

Indoor Air Quality & Ventilation Group
Building Research, Room A313
National Institute of Standards and Technology
Gaithersburg, MD 20899

It is faster and easier to get CONTAM96 by using the anonymous FTP process on the Internet. The FTP site is *ftp.nist.gov*. The latest upgrades will be posted here first. They will be described in the ASCII file CONTAM96.TXT which you should download occasionally to check for the latest modifications and fixes. Contact *gwalton@nist.gov* for instructions.

Acknowledgements

The financial support of NIST, the theoretical contributions of Jim Axley, and the feedback of Steve Emmerich, Stuart Dols, Mike Pantuik, and Lem Curran of the NIST IAQ&V group plus many other users are gratefully acknowledged.

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OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS

17th AIVC Conference, Gothenburg, Sweden

17-20 September, 1996

Efficiency Characterisation of Various Ventilation Configurations

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OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS

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EFFICIENCY CHARACTERISATION OF VARIOUS VENTILATION CONFIGURATIONS

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Synopsis

The study concerns the ventilation of a parallelepiped shape room by means of several systems whose supplying and extracting methods differ, so the different thermic conditions applied to limits. To qualify the efficiency of each of these systems in relation with the various current criteria, we carried out measurements by means of a tracer gas, both with a transitory and a permanent flow.

At the same time, numerical simulations were carried out by means of a CFD code which solves the equations of the fluids mechanic, material and heat transfers associated with flows. These calculations results, after measurements validation, enable to accurately know the air movements in the ventilated room as well as the tracer gas concentrations distribution in the tested configurations.

From these calculation results, was also demonstrated how the complex behaviour of each of these ventilation systems can be characterised owing to the possibility of identifying it to a simple model, using a reduced number of parameters. These typical parameters can in turn be used to implement the system performance evaluation criteria.

These criteria allow to compare the various studied ventilation systems and class them in performance order. It can be seen that this classification can be modified depending on the selected criterion as well as the chosen ventilated area.

The study results equally show the interest of the use of numerical simulation together with experiments, thus extending the range of results in order to generalise conclusions.

1. Introduction

In this paper, a methodology is described to determine the performances of different ventilation systems in a room with a local emission of pollutant. This methodology is based on numerical calculation of air flows and transfers. First of all, this simulation has been applied to a room where measurements were done, in order to validate the calculation.

Then the methodology was applied to four elementary ventilation systems in a room, in order to qualify their efficiency using performance criteria which are defined in this study.

It was shown that the methodology can be used to study and to qualify the efficiency of a defined ventilation strategy in a room.

The comparisons between the different studied configurations show that the performance classification strongly depend on the criteria and on the observation point into the room.

2. Measurements

The measurements used for comparisons with calculations were done in a parallelepipedic room represented in Figure 1.

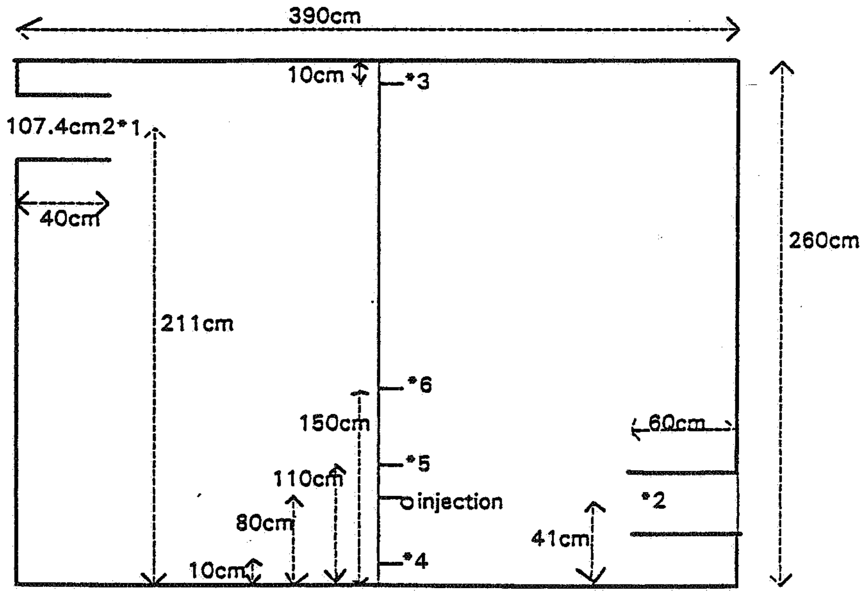

Figure 1 : Test room with concentrations measurement points

In the considered ventilation system, air is supplied on the top of one wall (middle of the wall) and extracted at the bottom of the opposite wall (middle of the wall).

The pollutant is N_2O ; it is generated with constant flow, in the center of the room, at a 0.8 m height.

This type of pollutant has been chosen because it is possible to measure low concentrations and because its density is the same that the CO_2 one, which represents one of the most common pollutant in occupied spaces.

The positions of the measurement points are shown on the same Figure 1 ; four points are on the vertical, at center and different heights ; one control point is in the air inlet, another is in the air outlet.

The experiment is divided in two periods : after establishing the ventilation scheme, the pollutant is generated, continuously, until constant concentrations are reached ; then the pollutant generation is stopped, and the ventilation goes on, until the initial zero concentration is get.

Measurements give the concentrations evolution during the different periods : continuous generation period, transitory increasing and decreasing periods.

3. Numerical simulation

The simulation consists in integrating Navier-Stokes equations in the studied field. The method of the finite volumes is used, with a three-dimensional representation of the space.

The FLUENT CFD is used. The turbulence is taken into account with a two equations model (k-e).

The pollutant diffusion in the air is also represented (molecular and turbulent diffusion) ; the buoyancy effect is also represented, and it induces different forces on the local concentration of pollutant which is denser than the air. The calculation were done in isothermal conditions, with adiabatic walls ; the pollutant is generated at the same temperature as the indoor air.

As in the experiments, the calculations were done for different specific periods : stationary period with continuous generation of pollutant, and transitory period representing the evacuation of N2O after a pollution period.

The Figures 2 and 3 show the comparisons between measurements and calculations for both periods.
Figure 2 shows the vertical profile of N_2O concentration at the center of the room.

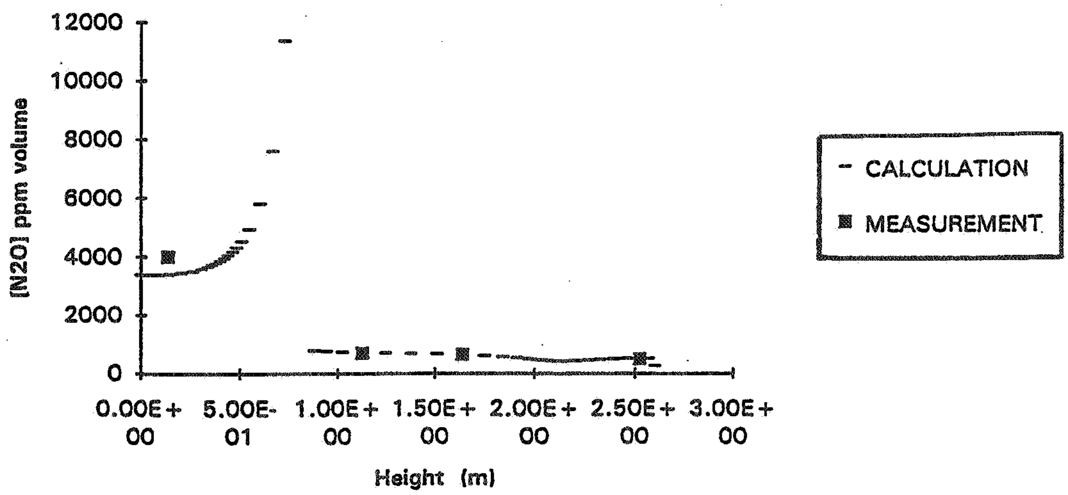

Figure 2 : Profile of concentration in the middle of the room

Figure 3 shows the decrease of the N2O concentration at different measurement points, during the time, after the end of the generation period.

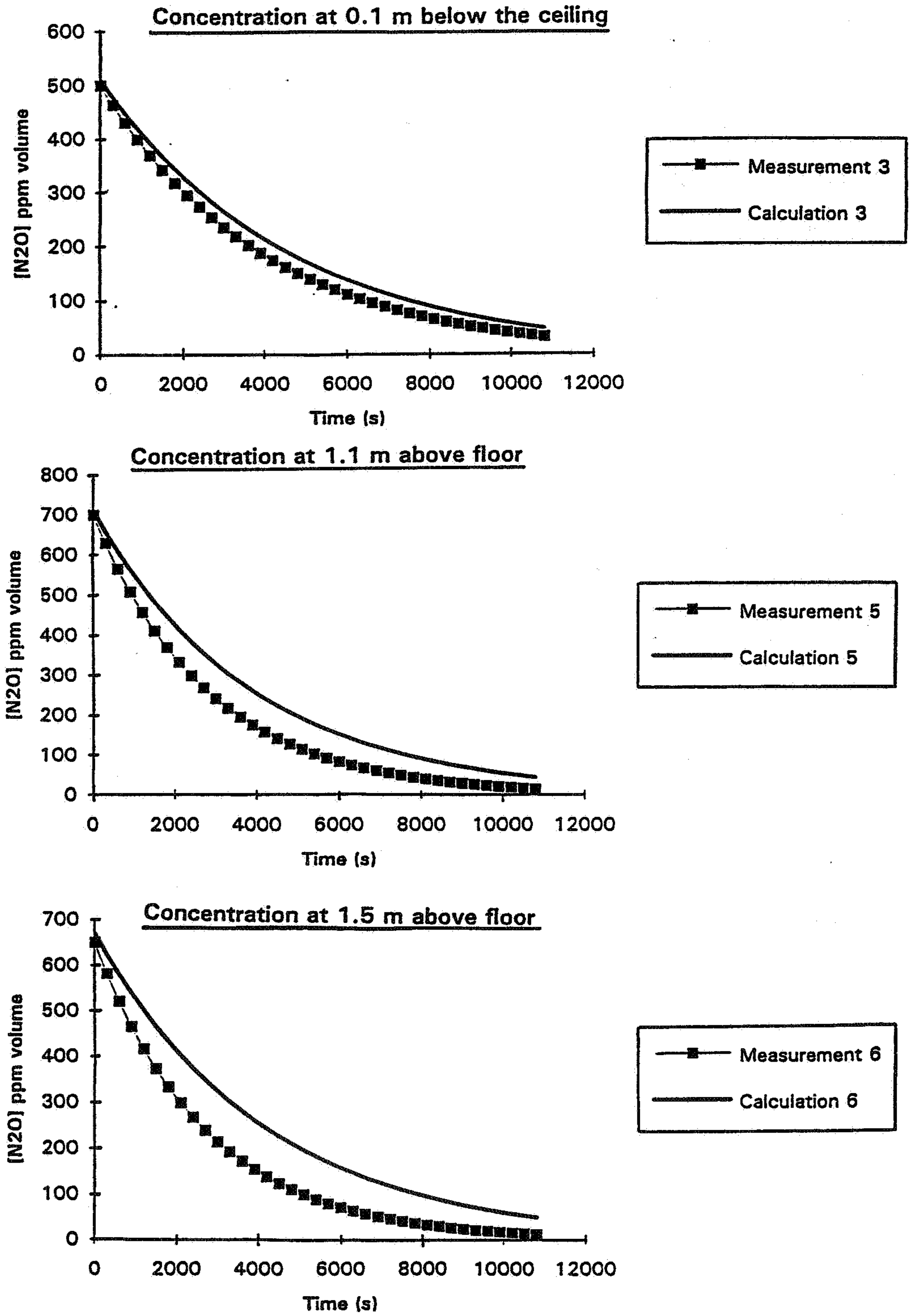

Figure 3 : Evolutions of concentrations at different points comparison between measurements and calculation

Measurements and calculations are congruent ; so, the simulation can be used for a practical study.

4. Exploitation of numerical results

In this part of the study, different configurations are compared, according to their efficiencies, which are established using the criteria coming from the simulation results : results in steady state conditions with continuous pollutant generation, and results in dynamic conditions when the concentration decreases after a pollution phase.

4.1. The studied configurations

On the geometrical base defined in paragraph 2 (Figure 1), four configurations were considered. They differ in the relative positions of supply and exhaust devices. The configurations are described in Table 1.There are all mixing ventilation.

Table 1

Configuration n°	Name	Supply	Exhaust
1	"straight up-up"	up	up
2	"cross up-down"	up	down
3	"cross down-up"	down	up
4	"straight down-down"	down	down

In all the cases, the air change rate is two volumes per hour (so an air flow of 108 Nm^3/h).

The pollutant used here is the CO2 ; it is introduced in the same way as with the measurements.

The calculation gives, among the results, the pollutant concentrations in two particular points situated in the middle of the room at 0.1 m and at 1.1 m above the floor. These results, in the steady state and dynamic conditions are used to qualify each of the ventilation systems.

4.2. Ventilation efficiency in steady state conditions

It is characterised with a criterion called "pollutant removal effectiveness" [2, 4, 5], which represents the capability of the system to evacuate a continuous production of pollutant. In the simple case where the supply air is free of pollutant, it is defined by the ratio between the pollutant concentration at the exhaust $\overline{[CO_2]}$ and the pollutant concentration at the considered point $[CO_2]_\infty$ in the ventilated room :

$$\eta_e = \frac{\overline{[CO_2]}}{[CO_2]_\infty}$$

where $\overline{[CO_2]}$ is the concentration in steady state conditions at the exhaust, which is simply calculated with the ratio between the pollutant generation flow on the ventilation air flow.

The better the local ventilation effect is, the bigger the pollutant removal effectiveness is.

4.3. Ventilation efficiency in dynamic conditions

As the figure 4 gives an example, the results show that during the period following the pollution phase, the decrease of the concentration in one point is always very close to a linear system response :

$$[CO_2]=[CO_2]_{\infty}\bullet\left[1-EXP\left(\frac{-t}{T}\right)\right]$$

where t represents the time. This fact allows to characterise the dynamic behaviour of the ventilation system at a constant time.

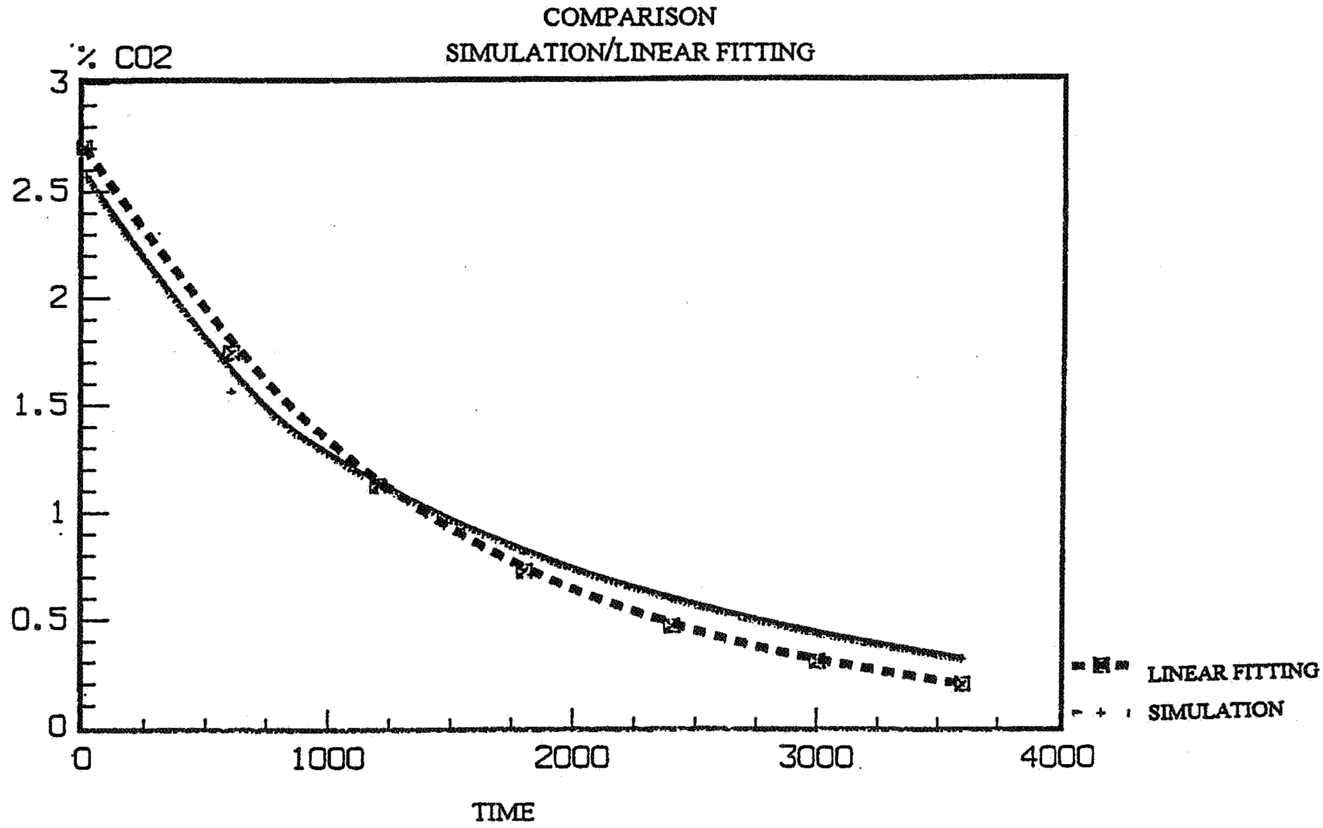

Figure 4 : Decrease of concentration in one point, during the time - Approximation with simple model

Then, this constant time can be used to determine the "air change efficiency". This criterion characterises the efficiency of the ventilation system in quickly replacing the polluted indoor air [3] with new (or fresh) air. This criterion is expressed by the ratio between the average duration for changing air and the previously defined constant time :

$$\rho_r=\frac{\bar{\tau}}{T}$$

The quicker the ventilation is able to evacuate a temporary pollution from indoor air, the bigger the air change efficiency is.

4.4. Application to the studied configurations

The previous defined criteria are calculated for the four studied configurations, and for the two observation points. The results are summed up in Table 2.

Table 2

Configuration	Position (observation point)	Pollutant removal effectiveness	Air change efficiency
1	1	0.704	1.044
	2	0.799	0.847
2	1	0.897	1.318
	2	1.070	1.082
3	1	1.241	1.115
	2	1.006	0.915
4	1	1.192	1.009
	2	0.957	0.834

These values allow to classify the four studied ventilation systems, according to their efficiencies.

If we consider the observation point n°2, the more closest to the occupied zone, then we get the following decreasing classification related to both criteria (Table 3).

Table 3

Classification	Pollutant removal effectiveness	Air change efficiency
1	"cross up-down"	"cross up-down"
2	"cross down up"	"cross down up"
3	"straight down-down"	"straight up up"
4	"straight up up"	"straight down-down"

Then, if we are interested by the pollution at the floor level, we can choose the observation point n°1. The classification is then given in Table 4.

Table 4

Classification	Pollutant removal effectiveness	Air change efficiency
1	"cross down-up"	"cross up-down"
2	"straight down-down"	"cross down up"
3	"cross up-down"	"straight down-down"
4	"straight up-up"	"straight up-up"

As the ventilation system in configuration "cross up-down" seems to be the more efficient in the majority of the cases (all configurations are mixing ventilation), the results show that the relative interest of one system compared to another differs according to the criteria and to the position into the room.

5. Conclusion

This work, made on four ventilation systems, showed the interest in using the numerical simulation which allows to study in an accurate and detailed manner, complex and dynamic phenomena.

We also showed how the detailed results in the concentrations evolution in time given by the calculation, can be reduced, by a simple model identification, to some specific parameters. These parameters can be used, at the end, to apply the evaluation criteria of the systems performances.

These criteria allow to compare the different ventilation systems, but we can see that the performance classification depends on the chosen criterium, and on the region of the space in the considered ventilation room.

Today, comparisons and calculations are made with non-isothermal conditions.

Acknowledgements

The ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie), the French Agency for the Environment and the Energy Saving, is taking part in this study.

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OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS
17th AIVC Conference, Gothenburg, Sweden
17-20 September, 1996

Comparison of Indoor Levels of Radon Between Workplaces and Homes Located Nearby in Different Parts of Finland.

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SYNOPSIS

The aim of this study was to compare the radon levels at workplaces and in homes located nearby. Homes (number of 57) and partly or fully underground workrooms (number of 55) have been studied at the four workplaces in southern Finland and one workplace in northern Finland. Radon concentrations both at workplaces and in homes seemed to be at the same level in the same district. The mean radon concentration in all workrooms was 357 $Bq.m^{-3}$, and in homes concentration was 423 $Bq.m^{-3}$. At the workplaces having mere exhaust ventilation the mean radon concentration was higher (arithmetic mean of 839 $Bq.m^{-3}$, n=14), than the places having mechanical exhaust and supply ventilation (arithmetic mean of 209 $Bq.m^{-3}$, n=33). In an average the naturally ventilated workplaces (n=8) had the lowest level of indoor radon (arithmetic mean of 124 $Bq.m^{-3}$). The highest radon level, both in the workrooms (2937 $Bq.m^{-3}$) and in the homes (3080 $Bq.m^{-3}$), was found in the northern Finland. The high values of indoor radon might be partly explained by the hill-construction of buildings without sealed constructions against soil, and partly by depressurisation caused by mechanical exhaust ventilation.

INTRODUCTION

Radon is a radioactive noble gas, which is the decay product of radium. Radon enters a building mainly from soil below the building. Radon could also be exhaled from tap water or building materials. In addition, indoor radon concentration depends on meteorological factors, subgrade structures, air exchange rates and pressure conditions. Effective mechanical ventilation reduces indoor radon concentration, if the constructions of the buildings have been properly sealed and the underpressure is not increased /1, 2/. Houses having crawlspace usually have lower radon levels than slab-on-grade constructed houses. Variation in both outdoor temperature and wind induce the subterranean air-flows in the esker, which was observed to result in winter/summer radon concentration ratios of 3-30, in esker top areas, whereas in slope areas with amplified summer concentrations, the ratio is typically 0.1-0.5. Typical values in flat areas are 1.5-2. /2/. In the Chinese study at underground workplaces the radon concentrations increased from 13.6 $Bq.m^{-3}$ to 119.0 $Bq.m^{-3}$, with the underground depth of 5 meters to 35 meters, respectively /3/. In Finland the radon levels in homes have been studied by the Finnish Centre for Radiation and

Nuclear Safety (STUK). The overall radon level in flats and in single-family houses was 82 $Bq.m^{-3}$ and 145 $Bq.m^{-3}$, respectively /4/. Radon levels at workplaces have been studied by STUK and the radon levels at partly or fully underground workplaces have been studied by our group. The concentrations have been found to vary a lot in different parts of Finland. The mean concentrations during working hours have been 90 $Bq.m^{-3}$ in central Finland and 300 $Bq.m^{-3}$ in southern Finland /5/.

MATERIAL AND METHODS

The workplaces in this study were located in southern Finland in four different districts (places A-D) and one place in northern Finland (place E). The total number of measured workplaces was 55 and number of the homes was 57 (table 1.). Most of the workrooms had mechanical supply and exhaust (n=33) and the rest had either mere mechanical exhaust (n=14) or natural ventilation (n=8) (table 1.). All the homes had natural ventilation and a ground level foundation.

Table 1. The number of workrooms with different types of ventilation, different types of foundations and number of the homes in each place .

	Workplaces							Homes
	Types of ventilation			Types of foundation				
	MSE	ME	NV	U	G	H	N	N
Place A	7	-	1	7	1	-	8	4
Place B	9	1		3	6	1	10	11
Place C	6	5	7	3	15	-	18	1
Place D	6	1	-	5	2	-	7	1
Place E	5	7	-	-	1	11	12	40
Number of places	33	14	8	18	25	12	55	57

MSE	mechanical supply and exhaust	U	underground workroom
ME	mechanical exhaust	G	ground level workroom
NV	natural ventilation	H	hill-constructed workroom
		N	number of workrooms or homes

Radon levels were analysed continuously near the workers' breathing zone by using the Lucas cell method /6/ with a Pylon AB-5 assembly, which includes a detector, a photomultiplier and a system of data collection based on a microprocessor. The output data of the Pylon detector were processed with SP-55 software run on a PC. The flow rate of air was 0.4 l/min. The interval of continuous measurements was 30 minutes (averaged to one hour). Concentrations were measured during periods ranging from few hours to several days. The integrated long-term radon levels at workplaces and homes were determined by alpha track etch films and analysed by STUK /7/. At workplaces alpha films revealed the average radon level during one month. This integrated radon concentration also included the radon levels at nights and weekends, when the ventilation was not usually operating at full capacity. In homes alpha films revealed the average radon level during two months. The pressure differences across the wall, either separating or external, were monitored by an electronic manometer together with a datataker. The pressure differences were measured continuously averaging every 30 minute to one hour. During daytime working hours, air exchange rates were measured by the tracer gas technique and by the dilution method using nitrous oxide as the tracer gas and an infrared spectrophotometer, Miran 1A, as the analyser.

RESULTS

The continuously measured and integrated radon levels varied from 27 to 2937 Bq.m^{-3} (arithmetic mean of 415 Bq.m^{-3}, n=40) and from 20 to 405 Bq.m^{-3} (arithmetic mean of 182 Bq.m^{-3}, n=20) at the workplaces, respectively. The integrated radon levels varied from 20 to 3080 Bq.m^{-3} (arithmetic mean of 426 Bq.m^{-3}, n=57) in homes (figure 1. and table 2.). The arithmetic mean of the air exchange rates in the underground workrooms or workrooms on the ground level were 3.1 h^{-1} (n=35) and the arithmetic mean of pressure difference was -5.6 Pa (n=11) (table 2). The highest average value, 658 Bq.m^{-3}, when comparing the different types of ventilation, was found from the places having mere mechanical exhaust (table 3.). The mechanical exhaust causing underpressure (tables 2. and 3, place E) elevated the radon level. The underground location of the workroom did not seem to increase the radon concentration (fig. 2. and table 4.).

The radon concentrations in the place A were quite low (table 2.), although 7 of those places were underground (table 1.). This may be due to effective ventilation in the underground workrooms (7 h^{-1}) (table 2.). The highest radon concentration, measured both with continuous and integrated methods, existed in the workroom located ground level. This workroom had only natural ventilation (tables 3. and 4.). Also the integrated radon level in the home was at the same level than the level in ground level workroom, but higher than the levels in the underground workrooms (figure 1. and table 4.).

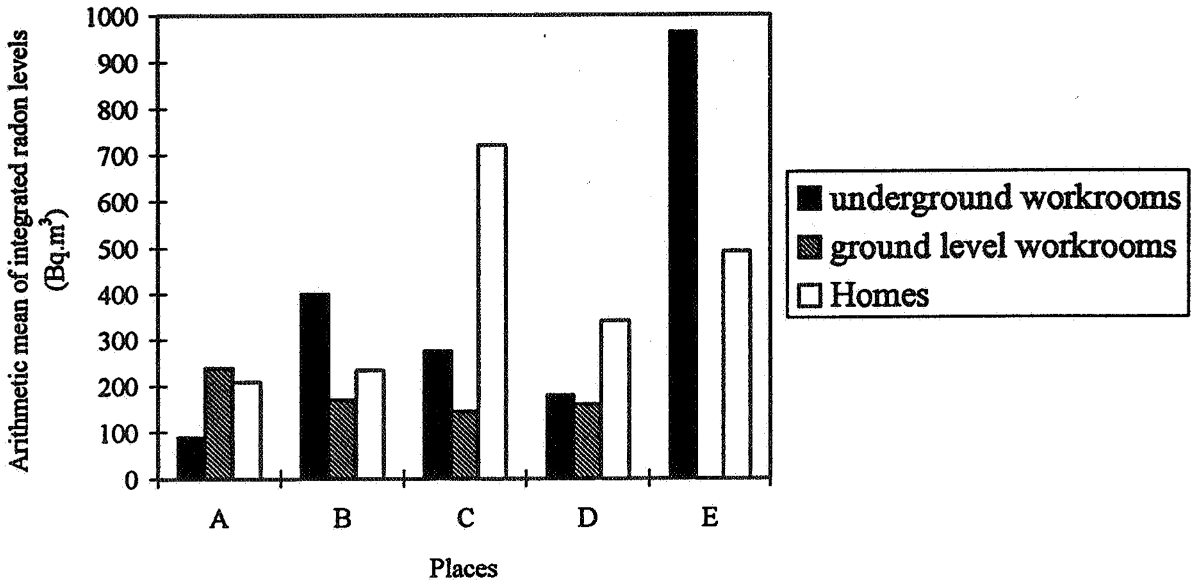

Figure1. The arithmetic means of integrated radon concentrations (Bq.m^{-3}) on the ground level and underground workrooms and homes in each place .

Table 2. The arithmetic mean, the range and the number (#) of the continuous and integrated radon concentrations (C_{Rn}, Bq.m^{-3}), air exchange rates (h^{-1}) and pressure differences (Pa) in the workrooms and integrated radon concentrations in the homes.

Places	Workplaces				Homes
	Continuous C_{Rn} (Bq.m^{-3})	Integrated C_{Rn} (Bq.m^{-3})	Air exchange rates (h^{-1})	Pressure differences (Pa)	Integrated C_{Rn} (Bq.m^{-3})
Place A	68 (27-174, 8)	120 (70-240, 5)	7.0 (0.4-12.0, 7)	-1.3 (-3.7-1.2, 4)	208 (20-400, 4)
Place B	288 (48-653, 6)	285 (160-450, 4)	2.6 (2.0-4.0, 5)	-	233 (60-460, 11)
Place C	134 (36-349, 9)	172 (20-370, 9)	1.3 (0.1-3.2, 6)	-5.1 (1)	720 (1)
Place D	306 (41-1163, 5)	243 (160-200, 2)	2.8 (1.3-4.7, 5)	0.6 (0.3-0.8, 2)	340 (1)
Place E	965 (56-2937, 12)	-	1.6 (0.4-2.7, 12)	-10.4 (-19.3--2.8, 5)	491 (20-3080, 40)(*
Average	415 (27-2937, 40)	182 (20-450, 20)	3.1 (0.1-12.0, 35)	-5.6 (-19.3-0.8, 11)	423 (20-3080, 57)

(* the measurements have been done by STUK

In the place B the integrated radon levels were at the same level both at workrooms and at homes (table 2.). The highest radon concentration was at the workroom having mere mechanical exhaust (table 3.). In this district the continuously measured radon levels were higher on the ground level rooms than underground, and integrated levels were lower (table 4.). In the place C the integrated radon concentration in the home was 720 $Bq.m^{-3}$, which is the highest radon concentration in this district (tables 2. and 3.). With the same type of ventilation, natural ventilation, radon levels in workrooms were lower than the level in the home (table 3.). The ventilation in these workrooms was not so effective, which might cause elevated indoor radon levels. In this place integrated and continuously measured radon concentrations were at the same level on the ground level rooms (table 4.). In the place D the highest continuously measured radon concentration was 1163 $Bq.m^{-3}$. This workroom located underground and had mechanical exhaust and supply ventilation (tables 2., 3. and 4.). The circulation of the exhaust and supply air were used which may have increased the radon level. The home that located little further from the ground level workrooms had higher radon concentration than the workrooms (tables 3. and 4.). The highest radon concentrations were observed in place E, both in the workrooms (arithmetic mean of 965 $Bq.m^{-3}$) and in the homes (arithmetic mean of 491 $Bq.m^{-3}$). Also these workrooms were depressurized (down to -20 Pa) and the air exchange rates were quite low (0.4-2.8 h^{-1}, n=12) (table 2.). The workrooms, except one, and homes were located on the slope of the esker. All these buildings, where former workrooms locate, had one wall against the ground (table 4.) and most of them had mere mechanical exhaust (table 3.).

Table 3. Continuous and integrated radon levels (C_{Rn}, $Bq.m^{-3}$) and numbers (N) of workplaces and homes with the different types of ventilation.

	Arithmetic mean of radon concentration ($Bq.m^{-3}$) (N)			
	MSE	ME	NV	Homes, NV
Place A, continuous / integrated	53 (7) / 90 (4)	- / -	174 (1) / 240 (1)	208 (4)
Place B, continuous / integrated	260 (5) / 285 (4)	426 (1) /	- /-	233 (11)
Place C, continuous / integrated	184 (5) / 175 (2)	75 (2) / 230 (3)	71 (2) / 136 (5)	720 (1)
Place D, continuous / integrated	306 (6) / 200 (1)	- /160 (1)	- / -	340 (1)
Place E, continuous / integrated	252 (5) / -	1474 (7) / -	- / -	491 (40)
Total average	199 (28) / 188 (11)	1089 (10) / 195 (4)	105 (2) / 153 (6)	423 (57)

MSE mechanical supply and exhaust ME mechanical exhaust NV natural ventilation

Table 4. The continuous and integrated radon levels (Bq.m^{-3}) and numbers (N) of different types of foundation in workrooms in each place ..

	Arithmetic mean of radon concentration (Bq.m^{-3}) (N)		
	underground	hillside	ground level
Place A, continuous / integrated	53 (7) / 90 (4)	- / -	174 (1) / 240 (1)
Place B, continuous / integrated	59 (1) / 400 (1)	48 (1) / -	405 (4) / 170 (2)
Place C, continuous / integrated	68 (1) / 275 (2)	- / -	142 (7) / 146 (8)
Place D, continuous / integrated	372 (4) / 180 (1)	- / -	41 (1) / 160 (1)
Place E, continuous / integrated	- / -	1041 (11) /-	126 (1) / -

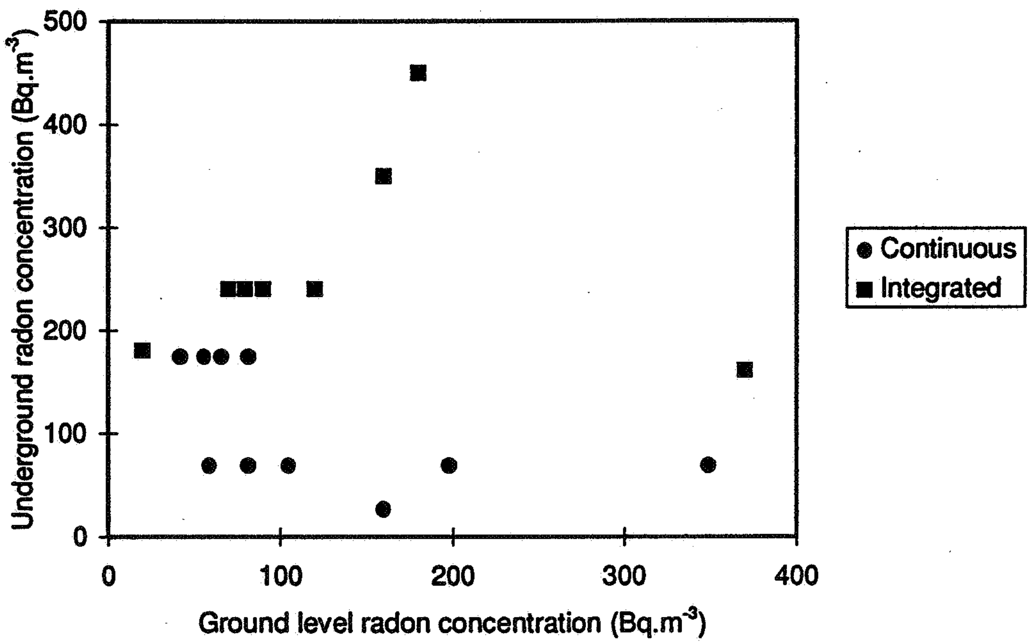

Figure 2. The radon levels (Bq.m^{-3}) measured by continuous and integrated methods in underground and ground level workrooms.

In the place A continuous and integrated measurements have been done at the same time in 5 of the workrooms. The radon concentrations seemed to be at the same level with both used methods (figure 3.).

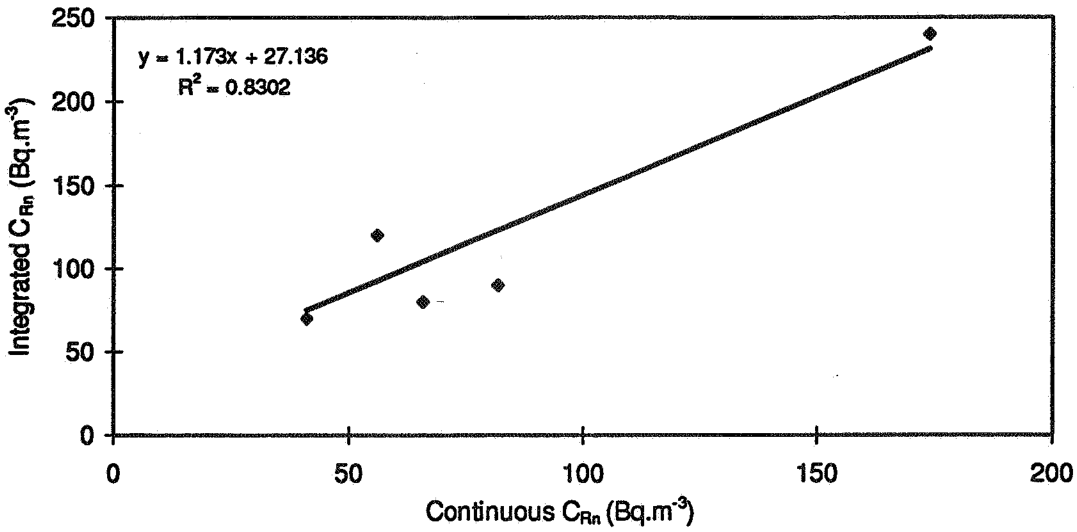

Figure 3. Comparison of the continuous and integrated methods of radon measurements.

CONCLUSIONS

The radon levels were highest on the hillside area in northern Finland where the hill-constructed workrooms had mere mechanical exhaust. The possible explanation to the high radon concentration could be that the parts of the walls of these buildings were constructed against the soil, which made radon entry possible. Also the high underpressure due to mechanical exhaust increased radon entry from soil. Also the homes on the hillside area had highest radon levels, when compared to other homes. Generally, the radon levels at workplaces and in homes were observed to be at the same level in the same district. The underground location of workrooms did not rise the indoor radon levels at all the places. Some places had even lower radon level in underground workrooms than the ground level workrooms. This was possibly caused by effective dilution by mechanical supply and exhaust ventilation at underground workrooms.

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