

Air Infiltration Review

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An Overview of the AIVC Numerical Data Base

Martin W. Liddament, Air Infiltration and Ventilation Centre

Introduction

The Air Infiltration and Ventilation Centre's Numerical Database has been developed in response to a need to establish a core of numerical data suitable for design purposes and model validation. It has also been developed to provide a focus for data derived from related International Energy Agency projects. Source information is contained within a computerised database from which direct searching for specific material is possible. The purpose of this report is to present an outline of the database.

Data have been derived from as wide a range of sources as possible, with many organisations having contributed to the data presented. By combining information from these sources, it has been possible to consider a far wider range of operating conditions than would be possible by using the results from a single set of measurements.

The database is presented in three sections; these cover:

- 1 - Component Leakage Data
- 2 - Whole Building Leakage Data
- 3 - Wind Pressure Evaluation

Additionally, a summary of the data has been made, with information being presented in the form of median, upper and lower quartile values (Orme et al). Wherever possible, relevant Standards and recommendations for building or component performance are referenced. This summary information is aimed at providing default data to designers and other users who need information on air leakage and ventilation characteristics for use in calculation models and design applications. Users are cautioned that the data presented are based on measurements published in the literature or provided by various institutions for inclusion in this Guide, therefore there is no guarantee that it is suitable for any specific design application. Wherever possible, applicable Standards or airtightness recommendations should be applied to new and retrofit construction.

1 - Component Leakage Data

Cracks and gaps in the fabric of buildings provide the routes for air infiltration. The size and flow characteristics of such gaps depend on the type of joint, material used and the quality of manufacture and fitting. Similar components may therefore be expected to exhibit widely varying leakage characteristics. It is the in-situ performance of components that will define the air leakage of a

In this issue

<i>Energy Efficient Ventilation of Large Enclosures.....</i>	<i>page 5</i>
<i>Natural Ventilation with Heat Recovery</i>	<i>page 9</i>
<i>Conference Report - Roomvent '94 Air Distribution in Rooms.....</i>	<i>page 13</i>
<i>Forthcoming Conferences</i>	<i>page 16</i>

structure and, ultimately, contribute to any energy loss and comfort problems. Data on crack leakage have been derived from measurements published in over 80 technical publications and on measurements provided directly by many research organisations and groups. In total, information is based on an analysis of over 1700 components and fittings used in the construction of buildings. These range from gaps and cracks around door and window openings to gaps around service pipes and other penetrations. The leakage performances of typical construction materials have also been analysed. These data should enable the user to estimate the overall leakiness of a building and to estimate the possible benefit of airtightness improvements. They may also be used as source material for more extensive air flow studies. Guidelines on selecting and using the data are given in the analysis report. Figure 1, for example, illustrates how to identify and assign the correct data to construction components.

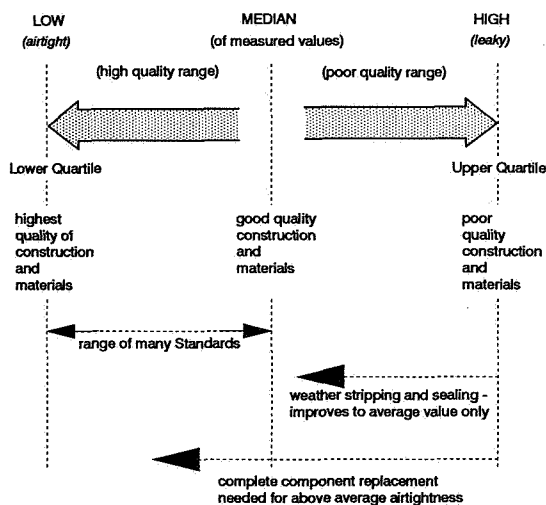


Figure 1 Assessing Air Leakage of Components

Air leakage values are presented as a flow coefficient ('C' value) and a flow exponent ('n' value) for the following component ranges:

- window
- doors,
- component/wall interfaces,
- wall construction, ceilings and floors,

- ceiling/wall/floor interfaces,
- wall/wall interfaces,
- penetrations (service pipes, outlets etc.),
- roofing,
- fireplaces and flues, and
- trickle ventilators and vents.

Examples of the leakage distribution of window data are presented in Figure 2

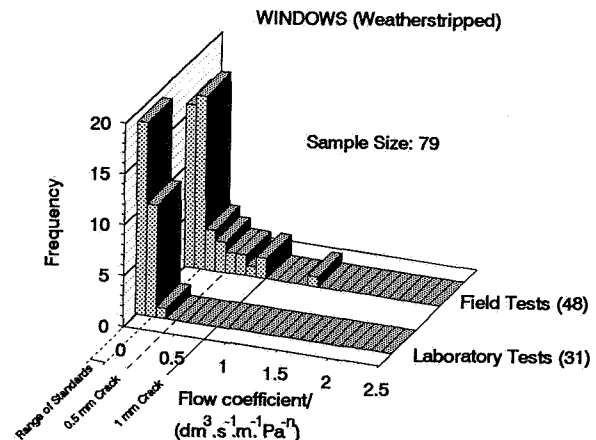


Figure 2 Leakage Distribution of Weather-Stripped Windows

2 - Whole Building Leakage

The infiltration characteristics of a building is ultimately a function of building airtightness. This is the sum of the leakage characteristics of all the cracks and gaps formed during the construction of the building. In theory, building airtightness may be inferred by applying to each leakage path, the leakage data presented in the previous section. An alternative method is to establish the airtightness performance by pressure testing the whole building, in which the air flow rate through the building is measured for incremental changes in artificially induced pressure. Knowledge of airtightness may be used to provide guidance on infiltration performance and on the suitability of various ventilation strategies.

Air Infiltration Review

Editor: Janet Blacknell

Air Infiltration Review has a quarterly circulation of 3,500 copies and is currently distributed to organisations in 40 countries. Short articles or correspondence of a general technical nature related to the subject of air infiltration and ventilation are welcome for possible inclusion in AIR. Articles intended for publication must be written in English and should not exceed 1,500 words in length. If you wish to contribute to AIR, please contact the Air Infiltration and Ventilation Centre. Please note that all submitted papers should use SI units.

Conclusions and opinions expressed in contributions to *Air Infiltration Review* represent the author(s)' own views and not necessarily those of the Air Infiltration and Ventilation Centre.

The relationship between pressure and air flow is normally represented by a Power Law Equation. Typically, air leakage is expressed in air changes per hour (ach) at an artificially induced pressure of 50 Pa. This approach has formed the basis of an increasing number of airtightness Standards. Many countries have undertaken airtightness measurements in representative samples of buildings. Typical examples of results are illustrated in Figure 3. In almost all cases, the range in airtightness values was found to be far too broad to provide simple guidance on average airtightness. It has therefore been important to identify the individual building characteristics that contribute to airtightness performance and to identify the generic types of construction that display a typical airtightness pattern. As a general rule, buildings tend to be constructed to a higher airtightness specification in severe climatic regions. In addition, airtightness is particularly influenced by the type of construction. A cellular concrete apartment block, for example, in which the main path of leakage is through pre-fabricated front and rear facades, tends to be tighter than a single family dwelling of complex floor plan. Building age (year of construction) has some influence on airtightness.

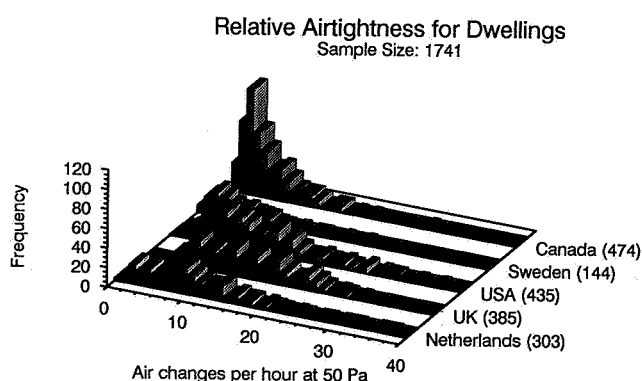


Figure 3 Airtightness Distribution of Dwellings (1 = Netherlands, 2 = United Kingdom, 3 = United States, 4 = Sweden, 5 = Canada)

Building air leakage data contained within the database are based on measurements made in over 2700 buildings, the majority of which are dwellings. Analysis has concentrated on identifying the construction techniques and materials that contribute to airtightness performance and to tabulate these data in a form that may be used for design and evaluation purposes. This has been accomplished by developing a series of data sheets which provide a basic leakage value at 50 Pa for a range of generic forms of building construction and type. Factors which tend to increase or decrease the basic leakage value are then listed with suggested correction values. By working through this list, the user can derive an overall leakage value that provides the closest match to the building under consideration (e.g. Figure 4). All windows, vents, flues and other

purpose provided openings are assumed to be sealed. Allowance for such openings can be made by making reference to the component leakage section. Clearly, these are guideline values only. It is important that the user takes into account any other obvious construction defects or parameters before applying the data. Above all, the data should only be applied in the absence of more accurate information. Furthermore, estimates should be verified on completion of construction or retrofit.

Whole Building Leakage - Data Sheet

Building Type: Timber Frame Insulated Construction, Low Rise

Basic Leakage (at 50 Pa): 3ach

Additions:

No Polyethylene Barrier	(+3 ach)	.....
Basement/Crawl Space/Suspended Floor	(+1 ach)	.....
Complex (Non Rectangular) Floorplan	(+1 ach)	.....
Unweatherstripped Window and Doors	(+1 ach)	.....
Unsealed Service Penetrations	(+1 ach)	.....
Basement Furnace/Open Flue	(+1 ach)	.....
Ducted Air Circulation System	(+2 ach)	.....

Subtractions:

Semi-Detached (Duplex)	(-0.5 ach)	.....
Centre Row/Terrace	(-1 ach)	.....
Gasketed Window/Door Frames	(-1 ach)	.....

Total:

Other Details (User Supplied):

Flow Exponent, n , (0.66)	=
Building Volume	=
Exposed Surface Area	=
Flow Coefficient, C , /Unit Area =	

Figure 4 Example of Building Airtightness Data Sheet

The Generic forms of construction, identified as having a characteristic airtightness performance include:

- timber frame construction (low rise),
- brick and block construction (low rise),
- concrete/curtain wall construction (high rise),
- concrete panel (industrial), or
- metal panel (industrial).

These have been used to form the basis of data sheets. Within each generic form of construction, wide variations in airtightness are possible. Factors contributing to reduced airtightness include:

- absence of air barrier,
- presence of a ventilated basement or crawl space,
- complex floor plan,
- non-weather-stripped windows and doors,
- unsealed service penetrations,
- basement furnace and/or open flue,
- ducted air system passing through unconditioned space,
- poor join/sealing,
- loading bay doors, and
- age of building.

- gasketed windows and doors,
- semi-detached (duplex) or centre terrace location,
- plastered or rendered inner walls, and
- gasketed or caulked joints.

A further aspect of importance is the flow exponent, since this can have a marked effect on flow rate as the pressure across an opening increases. Measurements based on data from several countries are summarised in Figure 5. This shows a distribution about a mean value of approximately 0.66. For this reason a flow exponent of 0.66 has been assumed in all instances.

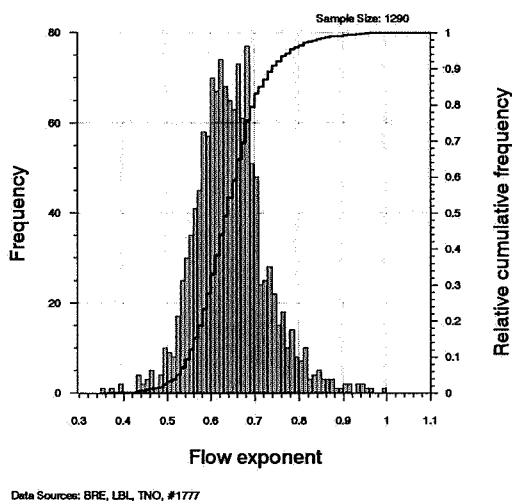


Figure 5 Distribution of Flow Exponent for Whole Buildings

3 - Wind Pressure Evaluation

Knowledge of wind pressure data is essential to estimate the impact of wind driven ventilation. At low wind speed, natural air change tends to be dominated by temperature (stack effect). On the other hand, as the windspeed or the exposure to wind increases, wind provides the main driving force. The evaluation of wind pressure acting on the surface of a building is particularly difficult. Normally the designer must resort to wind tunnel testing (which is expensive and time consuming) or to the use of wind pressure data designed for peak wind loading estimating. This latter approach generally leads to excessive overestimating of wind influence. In the future, it may be possible to use computational fluid mechanics to estimate wind pressure but, at present, this is not a widely available option. As a compromise for basic design analysis, the AIVC has compiled, from published sources, wind pressure data in the form of wind pressure coefficients. These have been selected to be more representative of normal building exposure than is provided by wind loading data.

The compiled data may be used to:

- estimate on-site wind velocity.
- estimate wind pressure for simple building shapes and for varying degrees of surrounding shielding.

Summary pressure coefficient data have been produced for high rise, low rise and courtyard type buildings. An example is illustrated in Figure 6.

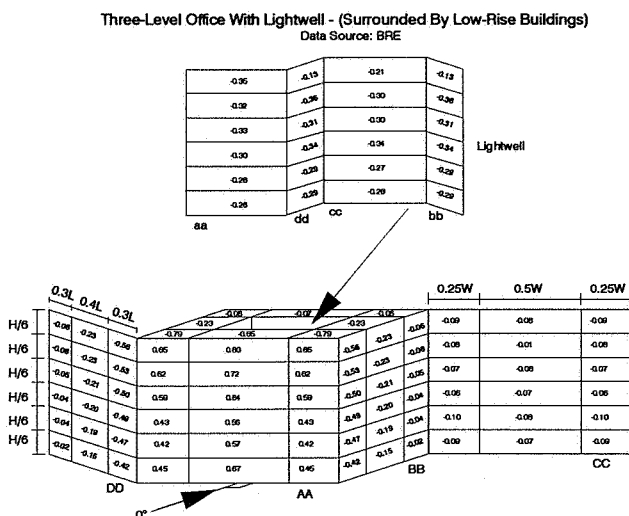


Figure 6 Example of Wind Pressure Coefficient Data

Conclusions

Data are essential for design and model evaluation. An attempt has been made to compile data appropriate to infiltration and ventilation studies. These cover the air leakage characteristics of building components, the characteristics of buildings themselves and data on wind pressure distribution. Component leakage data have been summarised in terms of median values with upper and lower quartiles. Guidance has then been given on the appropriate level to use. Whole building data are presented as a series of data sheets for generic types of building construction.

It is essential that measurement data collected during individual tests should be compiled since, collectively, they may be used to identify trends in the performance of construction techniques. Much more can be accomplished in producing information about the leakage performance of the existing building stock by analysing the key structural components and the corresponding air leakage performance of measured buildings.

Further information on wind pressure coefficients are needed to accommodate a wider range of building shapes. These will enable basic design calculations to be accomplished without the need for excessive modelling or expensive wind tunnel exercises.

Acknowledgements

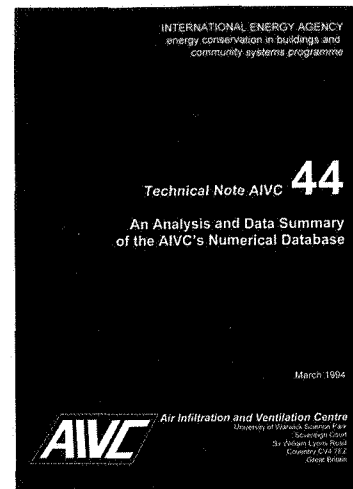
Valuable assistance and data were given to the AIVC by numerous individuals and research organisations during the preparation of this document. Contributors

are listed in the analytical review of the database (AIVC Technical Note 44)

References

Orme, M., Liddament, M.W., and Wilson, A. "An analysis and data summary of the AIVC's Numerical Database" AIVC Tech Note 44, Air Infiltration and Ventilation Centre. March 1994.

The AIVC Numerical Database is now available from the AIVC, for further information please contact Malcolm Orme. An Analysis of the database is published in AIVC Technical Note 44, which is available from the AIVC (see order form at the back of this newsletter).



Annex 26: Energy-Efficient Ventilation of Large Enclosures

What designers really want to know about ventilation of large enclosures

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Abstract

The specialists of IEA BCS Annex 26 have a clear picture of designer needs. The project objectives have not changed, but emphasis will now be placed on the most relevant problems related to air motion, temperature distribution, and energy use. The development of viable solutions by expert teams from twelve countries is primarily based on investigations in existing case-study buildings. Researchers have started to demonstrate advanced experimental and numerical methods at these large enclosures ranging from atria to industrial halls.

We have interviewed design engineers in 12 countries

Annex-26 experts want to work in large spaces, but not in empty space! Therefore they decided in 1993 to interview practising design engineers on their real needs for guidance. At a meeting this Spring in Norway the participants reviewed the answers.

But first, what were the questions we asked:

- (1) What is your design procedure for a large enclosure?
- (2) What sort of information do you need for designing the ventilation and air flows in large enclosures?
- (3) What design tools do you use now?

- (4) What type of guide book would be useful to you?
- (5) Is our proposal attractive?

The answers to these questions are essential for the planning of Annex-26 work in general and for the selection of topics to be covered by the design guidelines in particular. For a summary of Annex objectives, products and organisation, see the project profile on the last page.

Designers agree on main issues

The surveys from Finland, Italy, Japan, Sweden, Switzerland, and the UK have been reported. Although there were some differences, there were many similarities in the answers given by designers from different countries. Examples of the most common comments and requirements are:

- We use the same design procedures for large enclosures as for small enclosures.
- We need to know what the significant differences between normal and large enclosures are.
- We would like guidance on target temperatures and indoor air quality, and on the systems appropriate to particular applications, based not only on research but also on experience in real buildings.
- We need to know that the validity of any recommended design procedures and design tools has been demonstrated on real examples.

Other replies concern scale-model tests, decisions on mechanical or natural ventilation and/or cooling, stratification problems, infiltration, solar and long-wave-length radiation, transient modelling, control strategies, fire prevention and smoke control, cold draft, condensation, and snow melting on inclined glazing.

Conclusions for the Annex-26 design guidelines report

What are the consequences for the Annex-26 design principles guide? The basic concept of the design guidelines has been developed during an earlier workshop. The seven main sections are:

1. Introduction (the purpose and scope of the guide),
2. Design Parameters (specification and targets),
3. Design Consideration (critical design problems),
4. Design Techniques (tools and guidance),
5. Ventilation Strategy (suitability for building type),
6. Energy Implications,
7. Commissioning and Feedback (monitoring).

The result of the survey of designer needs will directly influence the contents of most sections.

A central lesson, that may shift priorities in our project, concerns case studies:

- Our audience wants to see a large number of documented examples of completed large enclosures, hopefully with many successful (or perhaps unsuccessful) combinations of different systems in buildings of various types and uses.

This means that our planned Case-Study report is as important as the Design Principles Guide for providing guidance. It also means that we should document as many buildings as feasible. A focus on a few so-called *Reference Case Studies* would certainly not satisfy designer needs. We should rather try to present in some detail a comprehensive collection of many *Basic Case Studies*.

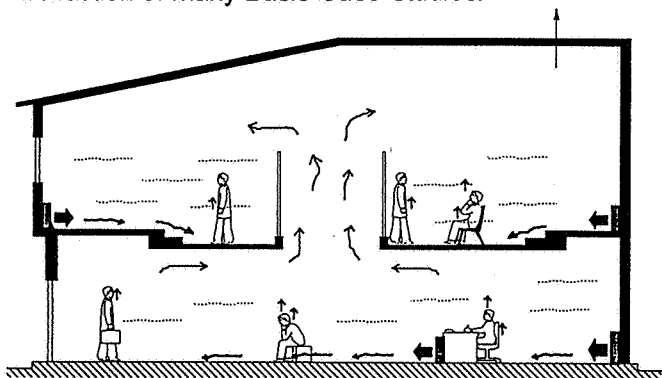


Fig. 1 Displacement ventilation in a room with mezzanine floors [1]. Partitions at the edge of the balconies keep the cold supply air on the upper floor.

A second conclusion may be summarised under the heading "Flow Pattern Control." This involves four procedural steps:

Flow Pattern Control

- (1) Selection of a suitable flow pattern for a particular application.
- (2) Prediction of flow pattern under given boundary conditions by a suitable modelling procedure, such as numerical modelling or scale-model tests. Adjustment of system design to achieve desired flow pattern.
- (3) Strategies to control system to maintain the flow pattern under variable load during all seasons.
- (4) Simple measurements in completed building to establish that the desired flow pattern exists.

Step (1) asks for a close co-operation with the architect designer. It refers to patterns such as fully-mixed ventilation, displacement ventilation, contaminant stratification, or any other type of pattern.

A special flow pattern that could belong to a light well in an office building is illustrated in Fig. 1. The illustration from a textbook by Håkon Skistad shows how a displacement ventilation system works on an open gallery or mezzanine [1]. Figure 2 compares two different prediction methods for temperature stratification in a 28-m-tall atrium. The range of predicted temperatures demonstrates the importance of reliable design methods [2]. One approach to test a flow pattern in a large enclosure, step (4) above, is to observe neutrally buoyant balloons [3]. This was done in an Annex-26 case study building, the NEC Headquarters in Tokyo, Fig. 3.

An IEA Annex cannot address all the problems within a field. The exact scope and specific goals of Annex 26 were defined in the Annex Definition Document [4]. The agreed scope has been reviewed on the basis of the designer survey, and some topics for detailed study will be discussed in the next section.

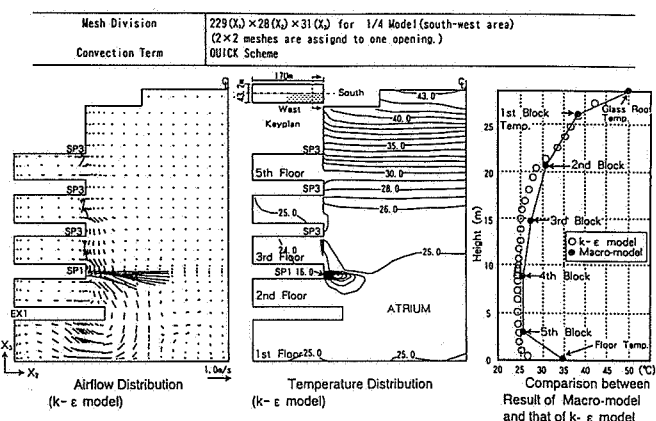


Fig. 2 Comparison of predictions of the temperature profile by an engineering method (macro model) and a numerical field model ($k-\epsilon$) [2]. Also shown are the predicted flow pattern and temperature field in this 28-m-tall atrium. Extremely high temperatures are found in the "heat storage zone" above the 5th floor. Computed glass temperature at the top is 50°C.

Annex-26 develops competence in well-defined areas

The following list of the "10 Problems for Annex 26" is of preliminary character and under discussion by Annex experts. Detailed attention will be paid to these topics, and associated phenomena are studied within the project, and findings reported.

Primary Problems:

- (1) Energy consumption by ventilation, (System)
- (2) Natural Ventilation, (System)
- (3) Displacement Ventilation, (System)
- (4) Mixing Ventilation, (System)
- (5) Contaminant removal, (System)
- (6) Stratification of temperature and contaminant concentrations (Physics)
- (7) Heat transfer by convection and radiation, (Physics)
- (8) Transients of air flow and energy transport, (Physics)
- (9) Flow elements, as plumes, jets, boundary layers, gravity currents, (Physics)
- (10) Draft risk and thermal comfort. (Physics)

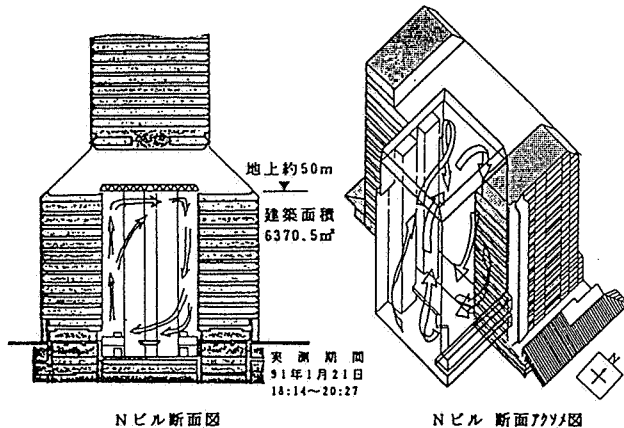


Fig. 3 Examination of air flow pattern by tracking non-lift balloons of 450 mm diameter [3]. Such Helium-filled balloons are used by meteorologists to measure atmospheric currents. The general flow pattern can be determined without much installations as here in the 50-m atrium of the NEC Headquarters in Tokyo, one of the Annex-26 case study buildings.

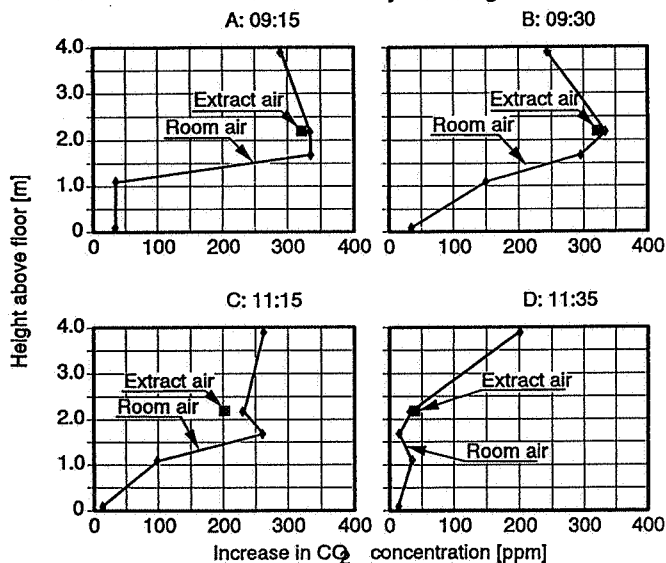


Fig. 4 Measured increase in CO₂ concentrations inside a meeting room at various times [1]. People started entering the room at 09:00 and left between 11:10 and 11:25. Note the position of the air extract: Layered extraction may be of advantage under certain conditions.

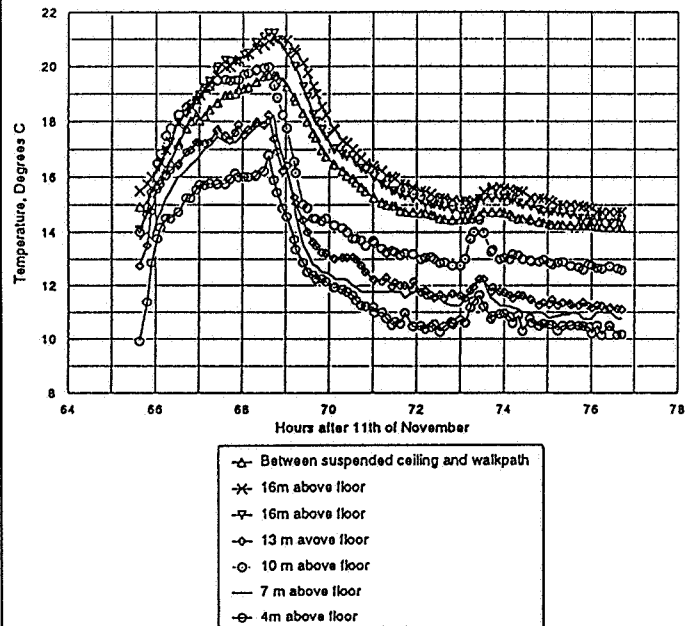


Fig. 5 Full-scale measurements of the temperature profile in the Olympic Mountain Hall during a hockey game [5]. This underground rock cavern in Gjøvik, Norway, is one of the Annex-26 case studies. Correct transient simulation is crucial in a stadium where the air handling system is not dimensioned to remove the heat load of a 4000-people audience continuously. Heat builds up during the performance, hours 66 to 68. Remaining heat is carried away after the game. The transient heat management is assisted by heat storage in the surrounding rock.

An illustration to problems (6) and (8), also taken from Skistad's book [1], is the CO₂ concentration profiles in a meeting room at different times, Fig. 4. Measured time-dependent temperature profiles in the Olympic Mountain Hall at Gjøvik [5] are shown in Fig. 5.

Tightly linked to these primary problems are secondary problems. These include physical phenomena and analysis methods which must be understood and perhaps investigated by Annex-26 participants in order to solve the primary problems. Methods and problems studied by other IEA projects, or for which accepted solutions exist in the technical literature fall into this class. Solutions to secondary problems are only reported by Annex 26 if no accessible references exist and if required by Annex objectives.

Secondary Problems:

Infiltration,
Human response to thermal and IAQ conditions,
health problems,
Building dynamics,

Building energy management systems and control strategies,
 Air handling units and HVAC systems,
 Ice melting on roofs for structural (weight) or lighting (glazing) reasons,
 Condensation on surfaces,
 Smoke control,
 Noise,
 Day-lighting,
 Material properties of glazing and envelope parts.

Identification of specific problems and definition of their scope are important for the selection of the contents of the design principles guide. The section on critical design problems has to concentrate on primary problems and experimentally well supported solutions. The list of recommended design instruments will not touch on tools applicable mainly to secondary problems. The total work load to produce expected Annex results must remain within participants' capacity and time frame.

Conclusions

The effort to contact design engineers is worthwhile. It is of paramount importance to the usefulness of Annex results to account for designer needs. Therefore:

- The designer survey reported here has to be extended to all participating countries and the replies must be carefully analysed.
- The work plan and proposed tables of contents of final reports have to be adjusted where necessary (within Annex objectives). If new work is required, work capacity has to be reassigned accordingly.
- The contact with active design engineers has to be kept up during the course of the project. The appointed Designer-Dialogue Committee has to continue its activity.

To promote further interaction, Annex participants must accept the challenge of making their expert meetings technically attractive to design engineers and design architects. A strong representation of designers at the workshops would assure the best dialogue.

Acknowledgements

The inputs by and discussions with Annex-26 experts at the Gjøvik meeting and the careful review of the article by the subtask leaders J. R. Waters and P. K. Heiselberg are gratefully acknowledged. The work of the Operating Agent is supported by the Swiss Federal Office of Energy (BEW).

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- [5] Mathisen H. M., Kolsaker K., Grande L. B., Lee D.-W., Verification of tool for energy calculation in rock caverns, Proceedings of "Underground Openings for Public Use" Conference, Gjøvik, Norway, June 14-17, 1994.

Project Profile

Title:	"Energy-Efficient Ventilation of Large Enclosures," Annex 26, a task-sharing Annex to the IEA Implementing Agreement on Energy Conservation in Buildings and Community Systems.		
Objective:	To develop methods to minimise energy consumption of large enclosures in the provision of - good indoor air quality and comfort, - the safe removal of airborne contaminants, and - the satisfactory distribution of fresh air.		
Products:	Reports on energy-efficient ventilation of large enclosures: - Measurement and modelling techniques for analysis, - Guidelines for the designer, - Case studies of IEA Annex 26.		
Case studies:	Reference, Advanced, and Basic case-study buildings serve to demonstrate measurement and modelling methods, to study problems, and to develop design guidelines.		
Subtasks:	1. Measurement Techniques and Case Studies, 2. Models.		
Time Schedule:	1-year Preparation Phase: April 1, 1992 - March 31, 1993 3-year Working Phase: April 1, 1993 - July 31, 1996		
Participants:	Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Poland, Sweden, Switzerland, and United Kingdom.		
Operating Agent:	The Swiss Federal Office of Energy (BEW). Contractor: Energy Systems Lab, Swiss Fed. Inst. of Technology, ETH, Zurich.		
Subtask Leaders:	Subtask 1: Dr. Robert J. Waters, Coventry University, UK; Subtask 2: Dr. Per K. Heiselberg, Aalborg University, Denmark.		
Meetings:	Project Definition: Horgen, Switzerland, March 30 - 31, 1992 Kick-Off Meeting: Aalborg, Denmark, Aug. 31 - Sep. 1, 1992 2nd Expert Meeting: Aachen, Germany, March 30 - Apr. 2, 1993 3rd Expert Meeting: Poitiers, France, October 5 - 8, 1993 4th Expert Meeting: Gjøvik, Norway, May 3 - 7, 1994 5th Expert Meeting: Leamington Spa, UK, October 25 - 29, 1994 6th Expert Meeting: Rome, Italy, April 4 - 8, 1995 7th Expert Meeting: (open) Fall, 1995 8th Expert Meeting: Tokyo, Japan, July 15 - 16, 1996		
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Natural Ventilation With Heat Recovery

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Abstract

This paper presents a research project, of which the primary goal was to investigate the possibilities of designing a natural ventilation system with heat recovery solely driven by the indoor-outdoor temperature difference. The theory used for design of a prototype system and the prototype itself is described as well as the measured performance. The project has shown that it is possible to design a natural ventilation system solely driven by the difference between the temperature indoors and outdoors with a heat recovery efficiency of 40-45%.

1. Introduction

Up until the energy crisis in the beginning of the seventies, the necessary air exchange in Danish dwellings was primarily obtained through venting (operable windows) and infiltration of outdoor air through air leaks around window and door openings and in the fabric.

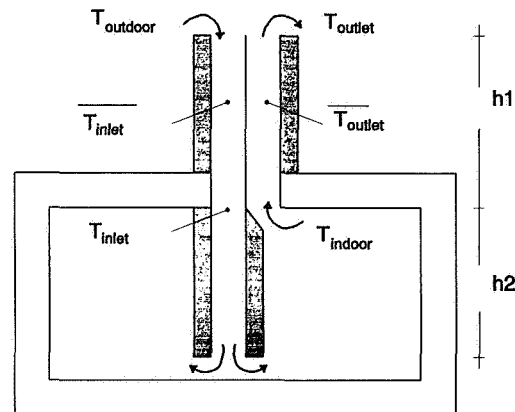
The energy crisis led to air tightening and insulation of the existing buildings and new buildings were built with special care concerning the air tightness. Mechanical ventilation became necessary in most cases simply as exhaust from kitchen and bathroom, but several buildings were equipped with a balanced ventilation system with heat recovery leading to a 50-60% reduction in ventilation heat losses.

However, many architects as well as many of the future inhabitants mistrust these mechanical systems, probably because of the extensive writings about sick buildings and dirty ventilation ducts. But also from an energy point of view, the mechanical ventilation systems are exposed to criticism due to the relatively large energy consumption by the fans.

These facts form the background for the project described in this paper.

2. Theory

The principle of natural ventilation with heat recovery driven by the stack effect is shown in figure 1. It should be noted that the building envelope is considered completely airtight.



$$dp = h_1 g [\rho_{T_{inlet}} - \rho_{T_{outlet}}] + h_2 g [\rho_{T_{inlet}} - \rho_{T_{indoor}}]$$

dp: pressure difference
g: gravitational acceleration
 ρ : density of air
T: air temperature

Figure 1: Principle of natural ventilation with heat recovery.

If $T_{outdoor}$ is lower than T_{indoor} and the air flows according to the arrows (see figure 1), the temperature in the left air column in the "chimney" will be lower than the temperature of the right air column and a pressure difference will be present due to the weight difference between the air columns. The pressure difference will force the air to flow downwards in the left channel and upwards in the right channel of the "chimney".

When the air flows through the channels a reverse force due to the friction between air and channel walls will result in a pressure drop, the value of which is dependent on the velocity of the air flow and the dimensions of the channels. If the outdoor and indoor temperatures are constant a stationary condition will occur, where the pressure drop due to the air flow is equal to the pressure difference caused by the temperature difference.

The heat recovery is obtained by designing the top of the "chimney" as a counter-flow heat exchanger, where the colder outdoor air is separated from the warmer indoor air by a thin wall. Heat is transferred across the partition wall heating up the fresh air. However this leads to a decreasing temperature difference between the 2 air columns and thereby a decrease in air velocity.

The design of the heat exchanger part of the system is a complex interaction of many parameters such as: channel dimensions, channel material, height of heat exchanger, temperature indoors and outdoors,

pressure drop due to system components and influence from the wind.

A computer simulation program has been developed during the project to perform several parameter analyses forming the basis for the prototype design. The results of the analyses can be found in [1]. One of the analyses is shown in figure 2, which illustrates the complex function of the heat exchanger.

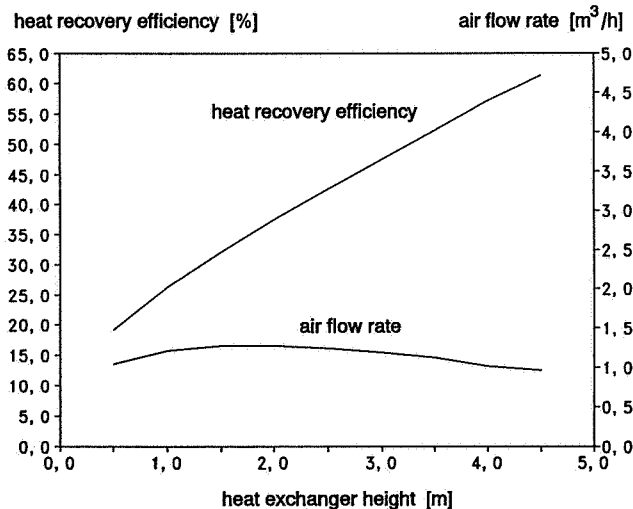


Figure 2: Heat recovery efficiency [%] and air flow [m^3/h] for one pair of channels as function of heat exchanger height. Channel cross section = $0.035 \times 0.035 \text{ m}^2$, channel material = steel, $T_{\text{out}} = 0^\circ\text{C}$, $T_{\text{in}} = 20^\circ\text{C}$.

Figure 2 shows that the heat recovery efficiency, η defined as:

$$\eta = \frac{T_{\text{inlet}} - T_{\text{outdoor}}}{T_{\text{indoor}} - T_{\text{outdoor}}}$$

increases with heat exchanger height which is caused by the increase of the heat transfer area. The air flow rate is increasing when increasing the heat exchanger height from 0.5 m to 1.5 m where the maximum is reached. Further increase of the height leads to lower air flow rates.

When the heat exchanger height is increased also the height of the air columns increases. In the region where the heat recovery efficiency is rather small the increased height of the air columns leads to an increase in the driving pressure. Further increase of the heat exchanger height leads to the observed increase in heat recovery efficiency meaning that the temperature difference between the cold and the warm air column decreases and thereby also the air flow rate. Furthermore, also the pressure drop due to friction increases proportionally to the channel height.

Prototype design

The parameter analyses were used to design a prototype system intended for ventilation of a test room of approx. 150 m^3 with an air exchange rate of

0.5 h^{-1} and a heat recovery rate of 50% calculated for an outdoor air temperature of 10°C and an indoor air temperature of 20°C .

The total air flow rate to ventilate the test room is achieved by use of several pairs of channels in parallel.

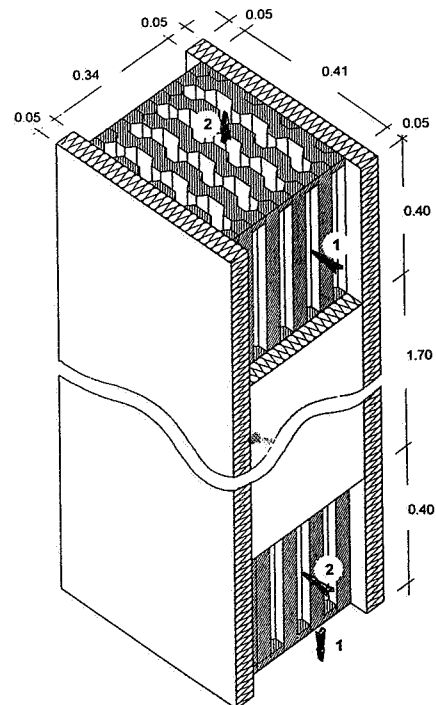
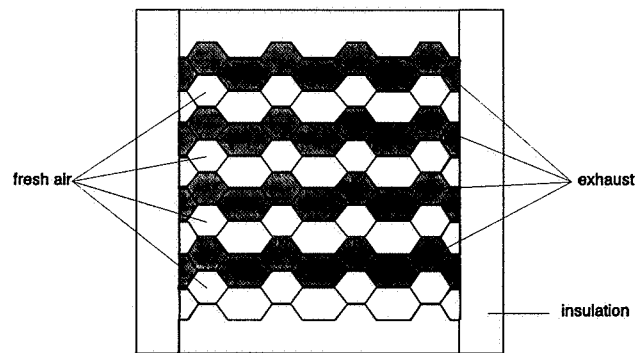


Figure 3: Cross section of the prototype heat recovery unit (top) and total heat recovery unit with indication of the separated air streams (bottom). All measures in [m].

For the prototype system, no options to control the maximum air flow rate were planned meaning that outdoor temperatures below 10°C should lead to an air change rate larger than 0.5 h^{-1} .

The principle of the system is identical to figure 1 except for the heat exchanger part. The fresh pre-heated air is passing through an insulated duct to a level 0.4 m above the floor. The warm room air is entering the heat exchanger part just beneath the ceiling. Due to the natural temperature stratification indoors this arrangement forces the air to move in the right direction.

The heat exchanger is made of trapezoid-profiled galvanized steel plates arranged as shown in figure 3. The special arrangement separates the fresh air from the exhaust air in 2 x 28 separated channels. The dimension of the channels is approx. $0.065 \times 0.035 \text{ m}^2$.

3. Prototype performance

The prototype was installed in an extremely airtight low-energy experimental building on campus, [2]. The top of the heat exchanger ends in an unheated attic that prevents the heat exchanger from exposure to eg rain and snow, and lowers the influence of the wind. However, measurements had to be made before sunrise or on cloudy days - otherwise the attic was heated by the sun.

The measurements were taken as single values at stationary conditions. Each observation included the air temperature in the attic, 2 air temperatures in the test room and 5 air temperatures as well as 3 air velocities measured across the opening of the fresh air inlet in the test room.

The air flow rate is calculated from the measured air velocities, while the heat recovery efficiency is calculated from the measured temperatures in the attic, in the test room, and the mean value of the 5 measured temperatures at the fresh air inlet.

The results are shown in figure 4.

Looking at figure 4 it can be seen that the calculated and the measured air flow rate are within reasonable agreement. But a comparison of the calculated and measured heat recovery efficiency shows that the used simulation program does not describe the heat transfer in a correct way.

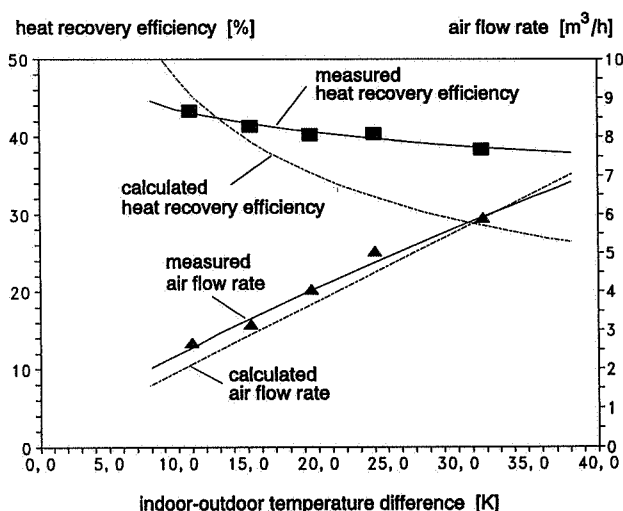


Figure 4: Measured and calculated values of heat recovery efficiency [%] and air flow rate [m^3/h] as function of the indoor-outdoor temperature difference.

The reason could be that the simulation program uses the ordinary formulas for heat transfer of air flow in ducts, while the air flow in this case is very complex. In the heat exchanger cold air is forced downwards while it is heated near the channel walls, which will create a reverse force in that region. A detailed study of the air flow pattern near the channel walls is required to clarify and describe the actual heat exchange coefficient. It has not been possible to find any information on this specific topic, but different articles dealing with mixed free and forced convection [3] support that an increase in heat transfer coefficient compared to the results calculated from the ordinary formulas should be expected.

4. Energy savings

The energy consumption due to ventilation losses and electric power for fans in case of mechanical ventilation has been estimated for 4 different systems. The results are given in table 1.

Table 1: Total energy consumption (ventilation heat load plus fan electricity) for 4 different ventilation systems calculated for the typical Danish heating season (October - April incl.).

System	Heat recovery efficiency	Electric consumption		Total energy consumption
		W	kWh	
	%			kWh
Mechanical, heat recovery	65	70	330	1050
Natural, heat recovery	43	0	0	1170
Mechanical, exhaust	0	50	235	2290
Natural, no heat recovery	0	0	0	2055

In all 4 cases a very airtight building envelope has been assumed. One of the systems is equipped with a cross-flow plate type heat exchanger. The calculations cover the typical heating season in Denmark (October - April incl.). In this period the outdoor temperature will be below 10°C in 92% of the time meaning that the natural ventilation system with heat recovery will be running nearly all the time. A self controlling damper is assumed to keep the air exchange rate at 0.5 h^{-1} ($75 \text{ m}^3/\text{h}$).

Table 1 shows that the natural ventilation system with heat recovery is nearly as energy efficient as the traditional mechanical system with a well functioning heat exchanger. The natural system with heat recovery can be designed to give an even better heat recovery rate, by use of smaller channels, and by increase of the number of channels in the heat exchanger part to compensate for the reduced air flow.

Discussion

The prototype described is difficult to handle due to the dimensions and the weight. The latter can be significantly reduced by choosing another type of material for the heat exchanger construction, e.g. a thinner metal or a kind of plastic material. In the second case, a decrease in heat transfer coefficient could be expected, but as long as the wall thickness is low the convective heat transfer coefficients are dominant to the conductive heat transfer in the exchanger walls.

Many practical problems have to be considered before the principle can be used in real buildings, e.g. design of the top end with respect to rain and wind protection (using experience from chimney top design), condensation inside the heat exchanger, interaction with bathroom and kitchen exhaust, influence of the air tightness of the building, opening and closing of windows, etc.

Other designs have to be considered for easy cleaning and special attention should be paid to the risk of thermal discomfort due to draught caused by the relatively cold air inlet during winter.

Finally measures should be taken to ensure the necessary air exchange when the outdoor temperature is above 10°C.

Conclusions

The project carried out shows that it is possible to design a natural ventilation system with heat recovery solely driven by the stack effect during the heating season in Denmark.

A prototype has been made and installed in a test building. The heat recovery rate is measured to 38 - 43% with corresponding temperature differences of 30 - 10 K between indoors and outdoors. Theoretically calculated heat recovery rates show much more variation (27 - 50 %).

However, the calculated and measured air flow rates are almost equal.

The natural ventilation system with heat recovery is almost as energy efficient as a traditional balanced mechanical system with a cross-flow plate type heat exchanger, when the electric energy consumption for the fan(s) is included.

Several problems with respect to design and installation have to be solved before the natural ventilation system is ready for use in real buildings.

References

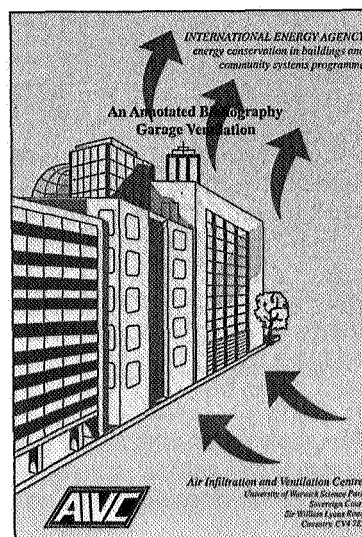
- [1] Schultz J.M. (1993). Natural ventilation with heat recovery. Report No. 249, ISSN 0905-1511. Thermal Insulation Laboratory, Technical University of Denmark. (In Danish with a summary in English).
- [2] Rasmussen N.H., Saxhof B. (1984). Experimental Low-Energy House at the Technical University of Denmark, description of a system for simultaneous testing of heating systems for conservation houses under actual climate conditions. Report No. 128, ISSN 0905-1511. Thermal Insulation Laboratory, Technical University of Denmark.
- [3] Noto K., Matsumoto R. (1978). Mixed-convection Heat Transfer around an Isothermal flat Surface of Finite Length. pp 7-12, Vol. 1, Proceedings of the Sixth International Heat Transfer Conference, Toronto, Canada.

An Annotated Bibliography: Garage Ventilation

Introducing a new series of detailed bibliographies on a variety of subjects from the AIVC

This bibliography summarises research into the health, energy and design aspects of the various systems used in garage ventilation. It is aimed at researchers, designers and engineers who would benefit from an introductory overview of research into this area. References quoted in the report are available to enquirers from AIVC participating countries (see back of this newsletter), and are recorded in the AIVC's bibliographical database, "Airbase".

The document is divided into chapters as follows: introduction including pollutants and ventilation rates; the main problems associated with car parks; research into naturally ventilated garages; research into large scale bus and hangar type garages; small scale car park problems and solutions and conclusions, with a detailed list of references.



Roomvent '94 - Air Distribution in Rooms

held in Cracow, Poland, on 15th - 17th June 1994

Report by Prof S Mierzwinski, Silesian Technical University, Poland

Introduction

Roomvent conferences are dedicated to problems of aero- and thermodynamics of ventilated rooms. The conferences bring together scientists and engineers interested in the air distribution field predicting and provide a forum for discussing the current state and future development of the art. The experience shows that the conferences bring in a perceptible contribution to the world achievements in the scientific and technological approach to ventilation efficiency, predicting and development. It is of great importance both with regard to indoor air quality control and energy management in buildings.

Roomvent conferences were initiated by SCANVAC, Scandinavian Federation of Heating, Ventilating and Sanitary Engineering Associations. The first conference Roomvent '87, was held in Stockholm, the second one, Roomvent '90, in Oslo and the third, Roomvent '92, in Aalborg, Denmark.

Roomvent '94 was organized for the first time out of Scandinavia, in Poland.

The Organising Committee was pleased to acknowledge the valuable help received from the co-sponsoring organisations and the assistance of the International Advisory Committee, and also the financial support for the conference received from the Polish Government and several companies.

Organisation and Schedule of the Conference

Roomvent '94 was organised in Cracow by Silesian Technical University in Gliwice and the Polish Association of Sanitary Engineers and Technicians (PZITS).

The conference was attended by 118 delegates from 17 countries. Eighty two papers were presented, and the proceedings are available from:

Conference Secretariat, Roomvent 94
Department of Heating, Ventilation and Dust
Removal Technology
Silesian Technical University
ul. Akademicka 5, 44-100 Gliwice, Poland

Tel: +48 32 37 12 80
Fax: +48 32 37 25 59

Agenda of the Conference

The opening ceremony was followed by a presentation of landscapes and architecture of Poland, accompanied with music by F Chopin.

The opening lectures given by invited speakers were focussed on highly important subjects influencing the development in room air distribution research. Lectures were on: air distribution in rooms - research and design methods by Prof P V Nielsen; micro/macrosopic analysis of air mass, heat and energy transport within an enclosure, by Prof S Murakami; measurement techniques in room air flow, by Prof M Sandberg; energy efficient ventilation of large enclosures, IEA research programme, by Dr A Moser.

- Session 1: models I, case study contained fourteen papers.
- Session 2: Flow element models, contained ten papers.
- Session 3: Models II, contained 14 papers.
- Session 4: Validation of models, ventilation efficiency, contained seventeen papers.
- Session 5: Scale models, measurement techniques, engineering methods, contained fourteen papers.
- Session 6: Measurement "in situ", contained nine papers.

The closing session included a summary and general discussion, conclusions, and preview and welcome to Roomvent '96 in Yokohama, Japan, and closing speeches, followed by music by Chopin.

Besides the scientific programme of the conference, there was a wide selection of accompanying events. On the first day, the Mayor of the Royal City of Cracow invited the conference participants to the welcome reception which was held a Collegium Novum of the Jagiellonian University, one of the oldest universities in Europe. The reception followed a visit to the Collegium Maius museum, housing a collection started in the fifteenth century.

The conference organisers invited the participants to a banquet in the ancient salt mine Wieliczka, 130m below ground level. The banquet followed a visit to the salt mine.

The participants also had a chance to take part in some sightseeing tours and to visit the Royal Castle Wawel and the Museum of the Extermination Camps Auschwitz in Oswiecim.

Ideas and Trends: Summary of the Sessions

Sessions 1, 2 and 3 were mostly devoted to modelling: CFD, global models, multizone models, flow element models.

After Dominique Blay from the University of Poitiers, France, all those interesting papers illustrate the increasing importance of modelling in the field of indoor ventilation. Due to the complexity of real buildings, models still have to be improved but it is apparent that there is an obvious lack of consistent and accurate experimental data which could be used as a reference for testing the models.

CFD is nowadays widely used to model airflow patterns in real cases. Particular attention was paid to some problems such as thermal boundary conditions, geometry complexity and mesh refinement which are of great importance when dealing with real and large enclosures.

Some papers presented CFD modelling coupled with thermal modelling in order to take into account radiative and conductive heat transfer at the walls. This allows us to determine the airflow pattern with realistic wall temperature distributions resulting from the heat balance.

In global models the airflow pattern is not determined. Airflow effects are taken into account through a heat transfer coefficient or using Bernoulli's formula. Though methods which are used are classical, these models still have to be improved in order to better take into account physical phenomena such as natural ventilation or radiation in the presence of shadowing.

The multizone models presented were devoted to dispersion of contaminant in a multizone building.

After P K Heiselberg from Aalborg University, Denmark, air distribution in ventilated rooms consists of several flow elements such as supply air jets, plumes, exhaust flows, boundary layer flows etc. Now a man is introduced as a new flow element. It was shown that the presence and movement of persons has a great impact on the air distribution in rooms in many cases and that it could be important to take the presence of persons and their influence on the room air movement into account in the evaluation of air distribution systems.

Different flow elements occurring at the same time in a room might influence one another and the air flow pattern will depend on the individual strength of each element and on the way they act together.

Session 4 was the largest of the conference and covered most aspects of room ventilation. Some innovative and promising ideas were presented. After H B Awbi the subjects can be summarised as follows:

Measurement and prediction of the age of air, coefficient of air change performance, ventilation effectiveness and other parameters for assessing the indoor air quality

- The interaction of the clean air zone and the polluted zone in displacement ventilation.
- Diffusion of air jets and thermal plumes in confined spaces.
- Convective currents around people and their effects in displacement ventilation.
- Effect of people's movement on the ventilation process.
- The movement of large particulates in a room.
- Zonal heat transfer models for predicting the thermal environment.
- Developments in computational fluid dynamics and turbulence models for room air movement prediction.

Sessions 5 and 6 were mostly devoted to scale-model tests, advanced measurement methods and case studies "in situ". Presented scale model tests had in view physical identification of complicated flow phenomena occurring in ventilation processes, such as flow between two enclosures at different temperatures and effects of internal configuration on ventilation conditions in a naturally ventilated building.

Thanks to the presented advanced equipment and methods of air velocity and thermal comfort conditions measurement it is much easier to achieve the required accuracy in measurements of field parameters. However, good sensors are needed to measure the overall air quality.

Papers and poster discussion on case studies show a great progress in organisation and finalisation of measurements "in situ". Measurement strategy is applied to obtain much information on air flow pattern and comfort conditions from very few measurements. Experimental identification of parameters of sensitivity interacting ventilation flow elements becomes possible.

After Ir. E Vranken from Belgium, real-scale measuring in the field will always be very important to build and validate computer models for air distribution in rooms or within different regions.

Although several new modelling techniques for air flow distribution are developed, there still remain a lot of ventilation problems in the field. An important reason is that up till now these models have not been applied in the design process and control system. Only very simple models are used to evaluate the field data.

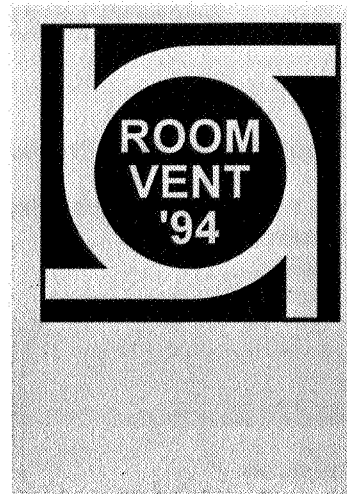
To introduce new ventilation techniques in the field there is a need for collaboration between researchers, manufacturers, designers, contractors and managers.

Conclusions

When summarising the conference, Dr Alfred Moser (Switzerland) said that thanks to CFD and experiment methods it becomes possible to take into account more and more sensitive flow elements and to obtain more and more detailed pictures of air flow patterns in rooms in the system of mutual aerodynamical and thermodynamical relations:

- The very sensitive flow around humans
- The very sensitive flow of natural ventilation, including "solar pump"
- The very sensitive heat balance coupling radiation + flow + building
- The study and modelling of properties of such sensitive flows and critical components should be subordinated to the logic of "intelligent validation" (e.g. a careful look at intermittence when interpreting turbulence measurements).

As it was proved by Roomvent '94, the present state of knowledge allows us to take into account both "intelligent validation" in research works and needs of engineers: to understand results and to formulate them in design friendly models.



According to Dr Hazim Awbi's conclusion, Roomvent '94 covered most aspects of room ventilation and some innovative and promising ideas were presented. We look forward to Roomvent '96 in Yokohama, Japan to see how far these ideas have matured.

Indoor Air '93

Summary Report

- An annotated bibliography of the 690 papers presented in the 29 sessions of the Indoor Air '93 Conference.
- Includes a 32 page executive summary by the President of the Conference, Prof. Olli Seppanen.
- Summaries of the 29 sessions have been written by the Finnish organisers of the Conference.
- Complete with a listing of all papers presented at the Conference, a keyword index, and an author index.
- Published by the Finnish Society of Indoor Air Quality and Climate - FiSIAAQ.
- This complete reference to the state-of-the-art of indoor air research is now available for the price of FIM 300 including postage by air mail.
- Orders can be sent to: FiSIAQ, PO Box 87, Fin-02151 Espoo, Finland, or by fax on +358 0 451 3611

AIVC Glossary of terms now available in French

Adaptation française de la Note Technique AIVC no 36

Glossaire sur la ventilation et la perméabilité à l'air

by Mark Limb

To order copies, please contact the Air Infiltration and Ventilation Centre at the address shown on the back page of this newsletter.

Forthcoming Conferences

Ventilation '94

From Research to Practice, from Practice to Research

4th International Symposium on Ventilation for Contaminant Control

5-9 September 1994

Stockholm, Sweden

Contact: Ventilation '94, National Institute of Occupational Health, Inger Wahlbeck, S-171 84 Solna, Sweden

Fax: +46 8 27 53 07

ASTM Symposium on

Methods for Characterising Indoor Sources and Sinks

25-28 September 1994

Washington DC, USA

Contact: Environmental Protection Agency, Air and Energy Engineering Research Laboratory, Indoor Air Branch, MD-54, Research Triangle Park, NC 27711, USA

Tel: 919 541 2991

CIBSE National Conference 1994

2-4 October 1994

Brighton, UK

Contact: CIBSE National Conference, Member Services Dept, Delta House, 222 Balham High Road, London, SW12 9BS, Fax: 081 675 6554

Healthy Indoor Air '94

6-8 October 1994

Anacapri, Italy

Contact: Guastalla Lucchini S.r.l., Piazza del Castello, 26, 20121 Milano, Italy

Tel: +39 2 72 00 45 36

Fax: +39 2 80 52 151

IAQ '94: Engineering Indoor Environments

30 October - 2 November 1994

St Louis, Missouri, USA

Contact: IAQ '94, Manager of Technical Services, ASHRAE, 1791 Tullie Circle NE, Atlanta, GA 30329, 2305, USA

European Conference on Energy Performance and Indoor Climate in Buildings

24-26 November 1994

Eurexpo Congress Centre, Lyon, France

Contact: LASH/ENTPE, rue M. Audin, 69518 Vaulx en Velin Cedex, France

Indoor Air - An Integrated Approach

27 November - 1 December 1994

Gold Coast, Australia

Contact: Indoor Air - An Integrated Approach, PO Box 1280, Milton Qld, 4064 Australia

International Building Performance Simulation Association

Fourth International Conference

14-16 August 1995

Madison, Wisconsin, USA

Contact: John Mitchell, Professor, Mechanical Engineering, 1500 Johnson Drive, Madison, WI 53706, 1687, USA

Tel: 608 262 5972

Fax: 608 262 8464

Email: mitchell@engr.wisc.edu

ISES 1995 Solar World Congress In Search of the Sun

9-16 September 1995

International Conference Centre, Harare, Zimbabwe

Contact: In Search of the Sun, PO Box 2851, Harare, Zimbabwe

Tel: 263 4 730707

Fax: 263 4 730700

Email: XCARELSE@ZIMBIX.UZ.ZW

Tsinghua - HVAC '95

2nd International Symposium on Heating, Ventilation and Air Conditioning

23-25 September 1995

Beijing, China

Contact: Prof Yi jiang, Secretariat of the Symposium, Department of Thermal Engineering, Tsinghua University, 100084, Beijing, P R China

Tel: +86 1 2561144 ext 2746

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AIVC Staff News

Congratulations to AIVC Scientist Mark Limb and his wife Judith on the birth of their daughter Rebecca Laura Ann.

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Air Infiltration Review. Quarterly newsletter containing topical and informative articles on air infiltration research and application.

Recent Additions to AIRBASE. Quarterly bulletin of abstracts added to AIRBASE, AIVC's bibliographic database.

AIRBASE DATABASE

AIRBASE the AIVC's bibliographical database, containing over 7,000 records on air infiltration, ventilation and related areas, is available as a diskette package for your personal computer.

CURRENT TECHNICAL NOTES

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TN35 (1992) Knoll B 'Advanced ventilation systems - state of the art and trends.'

TN 36 (1992) Limb M J 'Airgloss Air Infiltration Glossary.'

TN 37 (1992) Liddament M W, 'A Strategy for Future Ventilation Research and Applications'.

TN 38 (1992) Limb M J 'AIRGUIDE: Guide to the AIVC's Bibliographic Database'.

TN 39 (1993) Liddament M W 'A Review of Ventilation Efficiency'.

TN 40 (1993) Kendrick J F, 'An Overview of Combined Modelling of Heat Transport and Air Movement'.

TN 41 (1993) Wilson D and Walker I, 'Infiltration Data from the Alberta Home Heating Research Facility'.

TN 42 (1994) Limb M J, 'Current Ventilation and Air Conditioning Systems and Strategies'.

TN 43 (1994) Limb M J 'Ventilation and Building Airtightness: an International Comparison of Standards, Codes of Practice and Regulations'.

TN 44 (1994) Orme M S, 'An Analysis and Data Summary of the AIVC's Numerical Database'.

TECHNICAL NOTES (Back Issues)

Participants - photocopy £15, microfiche £5

Non participants - photocopy £30, microfiche £10

Applications Guide (1986) Air Infiltration Calculation Techniques **Handbook** (1983) Air infiltration control in housing

TN 11 (1983) Validation and comparison of mathematical models

TN 13 (1984) Wind pressure data requirements

TN 13.1 (1984) 1984 Wind Pressure Workshop Proceedings

TN 16 (1985) Leakage Distribution in Buildings

TN 17 (1985) Ventilation Strategy - A Selected Bibliography

TN 20 (1987) 'Airborne moisture transfer: workshop proceedings

TN 21 (1987) Review and bibliography of ventilation effectiveness

TN 23 (1988) Inhabitants' behaviour with regard to ventilation

TN 24 (1988) AIVC Measurement Techniques Workshop

TN 25 (1989) Subject analysis of AIRBASE

TN 26 (1989) IEA Annex IX 'Minimum ventilation rates

TN 27 (1990) Infiltration and leakage paths in single family houses

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TN31 (1990) AIVC's fifth worldwide survey of current research

TN32 (1991) Reporting guidelines for airflows in buildings

TN33 (1991) A review of building air flow simulation

TN34 (1991) Air flow patterns: measurement techniques.'

(Unlisted technical notes have been superseded)

ANNOTATED BIBLIOGRAPHIES

(Participants only - price see order form)

BIB1 (1993) Ventilation and infiltration characteristics of lift shafts and stair wells

BIB2 (1994) Garage Ventilation: Summarises research into the health, energy and design aspects of the various systems used in garage ventilation.

BIB3 (1994) (Available soon) Natural ventilation: Covers the main elements of natural ventilation research, the fundamental equations, driving forces and associated factors, as well as useful reports which focus on modelling and calculating natural ventilation air flows.

AIVC CONFERENCE PROCEEDINGS

AIVC Conference Proceedings nos 1-9 are available as individual papers, or in microfiche form. Details of contents can be forwarded on request.

10th 'Progress and trends in air infiltration and ventilation research' Espoo, Finland, 1989;

11th 'Ventilation System Performance' Belgirate, Italy, 1990;

12th 'Air Movement and Ventilation Control within Buildings', Ottawa, Canada, 1991, 3 volumes.;

13th 'Ventilation for Energy Efficiency and Optimum Indoor Air Quality', France, 1992;

14th 'Energy Impact of Air Infiltration and Ventilation', Denmark, 1993

15th 'The role of ventilation', Buxton, UK, 1994

LITERATURE LISTS

(Available to participants only - free of charge)

1) Pressurisation - infiltration correlation: 1. Models.

2) Pressurisation - infiltration correlation: 2. Measurements.

3) Weatherstripping windows and doors.

4) Caulks and sealants.

5) Domestic air-to-air heat exchangers.

6) Air infiltration in industrial buildings.

7) Air flow through building entrances.

8) Air infiltration in commercial buildings.

9) Air infiltration in public buildings.

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15) Identification of air leakage paths.

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17) Flow through large openings.

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