

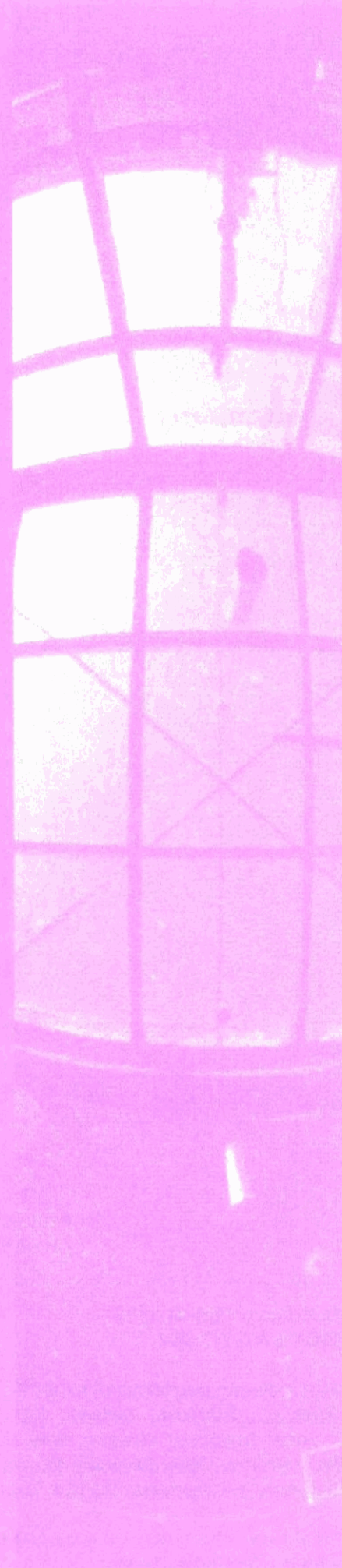
International Energy Agency

Energy Efficient Ventilation of Large Enclosures

**Technical Synthesis Report
- IEA ECBCS Annex 26**



*Energy Conservation in Buildings
and Community Systems Programme*



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Energy-Efficient Ventilation of Large Enclosures

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IEA Annex 26: Energy Efficient Ventilation of Large Enclosures - Synthesis Report

1.0 Background

1.1 Introduction

Large enclosures have become a major feature of modern building design. Spaces such as atria and covered areas are used in all varieties of buildings including office complexes, shopping malls, airports and public buildings. Essentially they create an environment protected from the outdoor climate in which a wide range of activities is possible. However such spaces demand very careful design to ensure good indoor air quality and thermal comfort and to protect occupants from the risk of fire and smoke spread.

The purpose of this report is to provide a technical summary of the work of Annex 26 in relation to airflow in large enclosures. Its aim is to provide details of what was accomplished and summarise information about proven technology for the design of ventilation in such spaces.

This report covers Sections on:

- Analysis and prediction techniques;
- Measurement techniques;
- Case studies;
- Lessons learnt.

For a brief summary of the work and results, it is recommended that Section 1 (Introduction) and Section 5 (Lessons Learnt) should be read. The remaining Sections provide more details about the work undertaken and the structure of the case studies.

1.2 What is a Large Enclosure?

A large enclosure is space within a building, enclosed by walls, glazing, or roof structures. It is considered to be "large" if one or several of these statements apply:

- The thermal buoyancy has a dominant effect on air motion;
- The occupied zone is small compared to the total volume;
- The Rayleigh Number, Ra , is large (i.e. airflow is dominated by temperature effects).

1.3 Ventilation Design Needs

Ventilation of large enclosures deserves careful attention by design engineers for the following reasons:

- Usually, only a small portion of the entire volume is occupied, therefore energy efficiency may be achieved by special strategies aimed at directing ventilation air and thermal conditioning to the occupied zone;
- Vertical air streams driven by temperature differences gather large momentum in tall spaces. Resultant cold down-drafts from vertical surfaces may have severe comfort implications;
- Large enclosures are often found in unique buildings where no previous experience exists;
- Architects are keen to apply novel ideas in these advanced buildings. Again, the necessary experience does not always exist and therefore careful analysis of the ventilation design is advisable.

1.4 Goals and Products of Annex 26

The objectives of Annex 26 were 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. The final Annex 26 report is entitled: "Ventilation of Large Spaces in Buildings, analysis and prediction techniques", edited by Per Heiselberg, Shuzo Murakami, Claude-Alain Roulet.

1.5 Approach

The approach of the project was to identify case study buildings and to review their operation and performance in relation to energy efficiency performance, ventilation strategies and any problems. Based on this case study survey, methods for analysis and design were evaluated and, in some cases developed or adapted.

Airflow patterns were analysed through field measurements, laboratory experiments, and computer simulation. Methods of flow analysis, appropriate to designers, were identified, based on both simple computer models and specialist computational fluid dynamics methods. In each case the roles of these methods in the design and evaluation process were identified.

1.6 Participants

Twelve countries participated in this task-sharing project:

Denmark, Finland, France, Germany, Italy, Japan, the Netherlands, Norway, Poland Sweden, Switzerland, and the United Kingdom. The Operating Agent was the Swiss Federal Office of Energy (BEW). The executive Operating Agent was Dr. Alfred Moser of the Swiss Federal Institute of Technology, Research in Building Technology, ETH, Zurich, Switzerland .

2.0 Analysis and Prediction Techniques

2.1 Background

Various prediction tools are available for use in the design and evaluation of ventilation in large enclosures. They are needed to ensure that the airflow pattern is well optimised for good indoor air quality and energy efficiency. Common problems in poorly designed buildings can include oversizing of equipment, excessive energy requirements and a poor indoor environment. These problems are usually caused by a lack of knowledge and guidance at the design stage. This Section illustrates methods suitable for designing and analysing ventilation in large enclosures. It reviews the application of various mathematical models for the simulation of temperature distribution, air motion and contaminant spread. Essentially, tools are needed for design, construction, commissioning and trouble shooting. During the first stages of the design process, information tends to be limited. Approximate HVAC solutions are generally developed based on engineering experience and the use of simple (macroscopic) analytical tools. At the later stages of design, more information is usually available and hence detailed analytical tools (microscopic models) can be applied.

Annex 26 work has developed a simple strategic procedure for designers and HVAC engineers to identify the most appropriate model for each step of the design stage. A summary of appropriate tools and applications is given in Table 2.1

2.2 Design and Analysis Methods

Techniques for design and ventilation analysis can be categorised into the following two main groups:

- **macroscopic models:** these are 'simplified' models which are used for a first estimate and for basic design development. They provide general information about the building such as overall heat losses and heat gains and air change rates.
- **microscopic models:** these are detailed models for design evaluation and troubleshooting. They can provide comprehensive information about time dependent and spatially varying thermal, pollutant and airflow behaviour;

Additionally, various complementary models are used to complete the design and evaluation process. These include:

Table 2.1 Outline of analysis and prediction techniques for airflow in large enclosures.

	Macroscopic Model	Microscopic Model	Ventilation Efficiency Model
Design Stage	Initial and ventilation design phase	Ventilation design evaluation and troubleshooting	Ventilation design evaluation and troubleshooting
Purpose	Macroscopic analysis of airflow and temperature distribution at a few typical points	Microscopic analysis of airflow and temperature distribution in detail	Evaluation of efficiency of HVAC system
Available models	Flow Element model Engineering model Zonal model	CFD based on turbulence model Scale model experiment	Analysis by experiment Analysis based on results of CFD
Output	Mean temperature Vertical temperature distribution Heat load Airflow Pattern Boundary conditions for CFD	Detailed distribution of airflow and temperature Study of problems to be solved in design phase	Distribution of ventilation efficiency index Mechanism of heat transfer and airflow in actual situation
Necessary equipment	Personal computer etc.	Super computer or EWS for CFD Scale model with devices for model experiment	Super computer or WS for CFD Scale model with devices for model experiment
CPU time	Few minutes	10-30 hours a case for CFD	1-10 hours a case for CFD
Required time for application	About half a day for each case to prepare input data	About 1 week for each case to make input data for CFD 1-3 weeks for each case for model experiment	About 1 day for each case to make input data for CFD 1-3 weeks for each case for model experiment

Abbreviations: *CFD-Computational Fluid Dynamics, CPU-Central Processing Unit, WS-Workstation, HVAC-Heating, Ventilating & Air Conditioning*

- **Scale Models:** These are useful for flow visualisation and for quantitative analysis;
- **Ventilation Efficiency Models:** these are used to evaluate ventilation performance in relation to the distribution of air and pollutants based on the results of the macro- or microscopic models or measurements in the actual building.

2.3 Macroscopic Models

At the start of the design process, analysis is largely based on engineering experience (such as data on existing similar buildings) and the use of simple analytical tools. Such tools are defined as ‘macroscopic’ models and their purpose is to give a general picture of conditions (e.g. energy needs, airflow rates and thermal conditions) in a space rather than a detailed spatial distribution. For conventionally sized enclosures, such analysis may be all that is necessary but for specialised and more complex buildings there is an increasing need for greater complexity of evaluation. For all building types, however, macroscopic tools form an essential part of the initial design process. Typical types of macroscopic models are summarised below.

2.3.1 Flow Element Methods

This approach relies on dividing the flow process into different elements such as supply air jets, exhaust flows, thermal plumes, boundary layer flows, infiltration and gravity currents (Figure 2.1). Such models are applicable when the airflow pattern in a region of the enclosed space is dominated by a single flow element or by flow elements which are not interacting with each other.

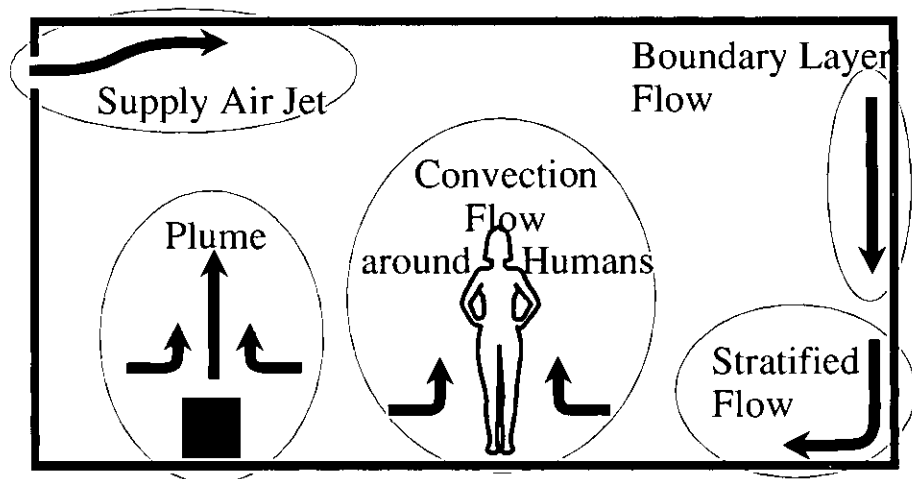


Figure 2.1 Structure of Flow Element Model

Reliability often depends on a database of comprehensive measurement results combined with engineering experience. Appropriate data includes manufacturer's data for the characteristics of air supply jets etc. and published information on performance for simplified geometrical and physical conditions. More details are presented in the analysis and prediction section of the Annex 26 Final Report. Simplified examples can give very good results in cases where real conditions are close to the experimental conditions, but difficulty occurs when the real layout of the building differs from example data.

Flow element models are relatively easy to use, and require little input data (i.e. geometrical and physical conditions). Analysis is often possible using a pocket calculator or a spreadsheet program. However applicability is restricted to simple situations in which there is only weak interaction between the individual elements. In spaces where there is strong interaction or coupling this method cannot be reliably used. Since large enclosures often have complicated geometrical shapes and physical conditions, and the airflow is influenced by interacting flow elements, the locations in which such modelling is appropriate will often be limited to very small parts of the enclosure.

2.3.2 Engineering Models

Engineering models form a more advanced form of 'macroscopic' approach. They range from fairly elementary calculation methods to elaborate models describing very complex problems. Examples include models for natural ventilation into a space, 'zonal' models and building thermal dynamic models.

Multi Zone Airflow Models: In its simplest form, a ventilation model approximates a space as a single, perfectly mixed environment bounded by the building envelope (i.e. the external walls, floor and ceiling). Air passes into and out of the building through cracks, gaps and purpose provided openings, and is driven by wind, temperature difference and mechanical ventilation systems. Physical equations are used to represent the flow rate through each opening. More detailed methods involve dividing the space into individual rooms. Public domain computer codes include AIDA (Liddament 1996) and COMIS (Feustel 1997). This method is also known as "Multi-zone Air Flow model", (Dorer, V., Weber A., 1996).

Zonal Models: Zonal models are similar in concept to ventilation models, except that they apply to a single open space which is divided into 'macro-volumes' (Figure 2.2).

In other words, unlike ventilation models, there is no solid boundary between each zone (except at the surfaces of the enclosure itself). The flow of air between each volume or zone is calculated on the basis of energy and mass balances. In comparison to other flow analysis techniques, zonal models are relatively straightforward to apply.

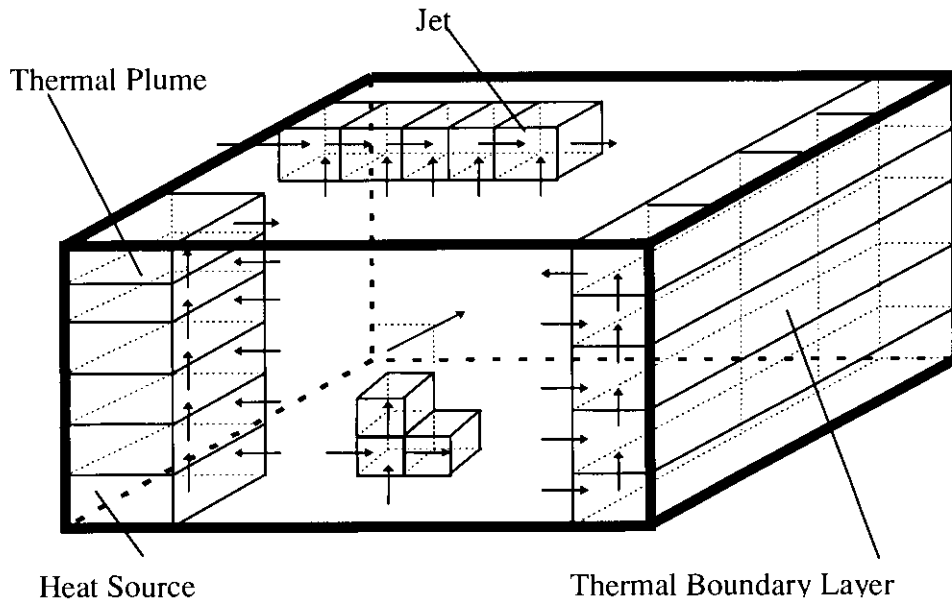


Figure 2.2 Schematic of the model used by Togari (1993) to predict vertical temperature stratification. The space is subdivided into five stacked zones.

In addition, both steady state and time varying (transient) conditions (e.g. varying airflow rates, pollutant flow, driving forces and temperature etc.) can be analysed. The main difficulty is evaluating the airflows (and to a less extent the heat fluxes) between each of the macro-volumes. Zonal models were successfully applied in several of the case studies (Section 4). In practice, each zone necessarily represents a relatively large segment of the indoor space and, therefore, a detailed analysis of the spatial distribution of parameters is not possible. Also prediction accuracy becomes lower when the flow field is complicated.

Thermal Dynamic Models: The pattern of airflow in large enclosures is strongly influenced by 'boundary' conditions at the surfaces. Temperature and heat flux is particularly important since these either impart energy to or take energy from the interior air mass.

Often such thermal loading is time dependent (e.g. through diurnal variations of outdoor temperature, solar radiation etc.). Evaluation of such conditions must increasingly involve the use of thermal dynamic models.

These have been reviewed and evaluated extensively as part of IEA Annex 21 (Månsson, 1998). Unfortunately, many existing thermal models do not incorporate sufficient detail on enclosure geometry, solar radiation and coupled internal convection and radiation exchange to make the results directly usable in detailed flow field analysis. Methods to overcome this were developed within Annex 26 and included in the Case Study programme.

2.4 Microscopic 'Field' Models - Computational Fluid Dynamics

Microscopic or 'Field' Models describe the entire spatial distribution of conditions throughout a space. They are used, for example, to evaluate whether the proposed airflow design will work as intended, or to identify potential problems with local thermal discomfort, poor IAQ and condensation etc. Such models are fundamentally based on computational fluid dynamics (CFD) methods. These may be used to predict velocity, temperature and other flow properties throughout a whole space with a high degree of resolution. Essentially the space is divided into many thousands of 'control' volumes (typically $10^4 - 10^5$) (Figure 2.3).

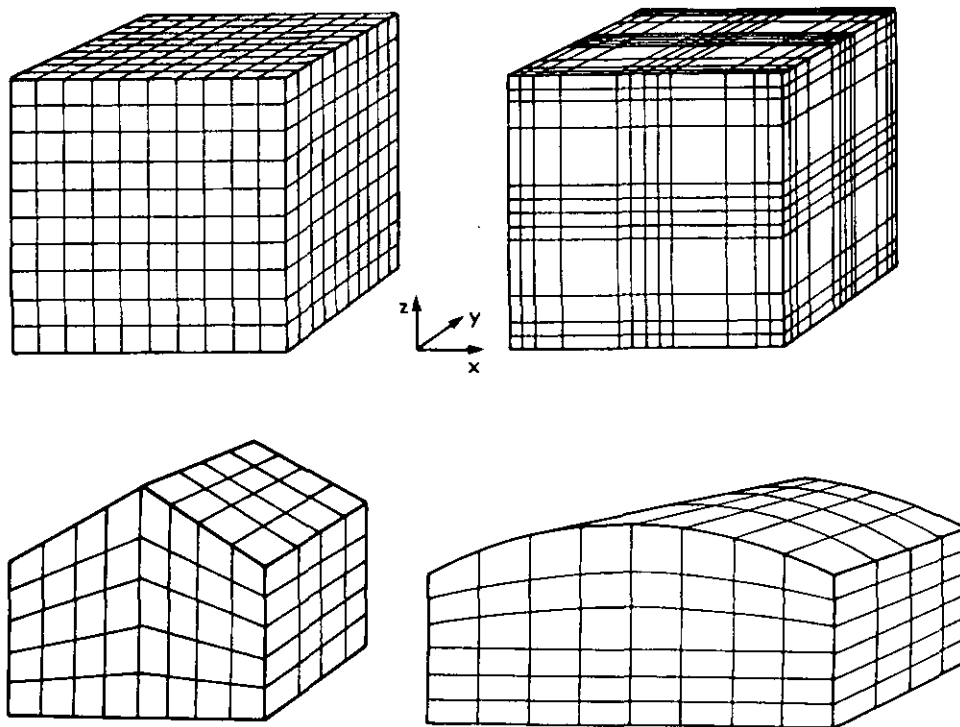


Figure 2.3 Examples of CFD Volume 'Control' Grids (See also Figure 4.3)

The transport of flow, heat, pollutants etc. is described by a set of equations based on the conservation laws of mass, energy and momentum. Many commercial CFD tools are available and have become routinely applied to building airflow analysis.

CFD simulation of the flow field in large enclosures presents many difficulties due to the large size of the enclosure and the complicated flow field. Furthermore a high number of control volumes or flow cells is needed to represent the flow. This adds to the complexity of simulating phenomena such as turbulence and increases the risk of numerical errors. In large spaces, airflow tends to be dominated by buoyancy forces. These are stimulated by a high degree of coupling with the external

environment through radiation and thermal exchange through extensive areas of glazing. It is therefore especially important to represent accurately surface heat transfer processes such as natural/mixed convection, solar radiation, long wave thermal radiation, heat transfer through external walls and structural heat storage. Accurate prediction of such a flow field is very difficult and, the popular k- ϵ turbulence model sometimes fails to achieve reasonable results.

Part of the Annex study investigated alternative approaches of dealing with this problem in order to produce general guidance to overcome such difficulties (see Lessons Learnt, Section 5). Despite many difficulties in applying CFD to large enclosure flow field analysis it is the only method that makes a detailed analysis possible. Although basic research into applying CFD to room airflow evaluation began 20-25 years ago, it is only within the last decade of growth in PC computing power that CFD has become a practical proposition for real design applications. Other examples of CFD developments include Capellman et al (1994), Hiramatsu et al (1996) Ozeki et al (1995,1996), and Inard C., (1995).

2.5 'Scale' Models

Scale models are primarily used to determine airflow patterns in an enclosed space subjected to various boundary conditions (geometry, location of openings and thermal conditions etc.). Airflow patterns are usually 'visualised' while temperatures and mean velocities are measured. Accuracy relies on achieving a similarity of conditions between the real building and the model.

In addition to matching the geometrical shape and processes, it is necessary to match the Reynolds Number (scale of turbulence), Prandtl Number (mixing characteristics) and Archimedes Number (strength of buoyancy forces in relation to momentum). In many cases it is impossible to maintain similarity of all these Numbers for the whole ventilation process range and therefore it is usually important to concentrate on the desired operating range of most significance. In this way, model construction and experiment is much simplified. It is assumed that similarity of the air mean velocity fields can be fulfilled when the airflows in the real space and in scale models are fully turbulent. Thermal sources and stratification are often represented by using fluids of different density (e.g. salt bath methods Figure 2.4).

In constructing the model it is crucial to achieve the following:

- a model length scale to ensure Reynolds Number independent flow.
- accurate representation of boundary conditions;
- scaling of temperature difference for accurate representation of thermal boundaries
- have sufficient size to enable ease of air velocity measurements, other field measurements and airflow visualisation.



Figure 2.4 'Salt Bath' Scale Model [Courtesy, University of Cambridge Dept Mathematics and Theoretical Physics]

The closer the model size and flow parameter values are related to those of the full scale object, the more reliable the test results will become. In practice, it is recommended to divide the design to be investigated into those aspects which require precise quantitative analysis (for example flow field in the occupied zone) and those requiring qualitative observations. Generally, small models will provide good qualitative guidance (e.g. on the general pattern of airflow).

2.2.4 Ventilation Efficiency Models

Ventilation models are used to evaluate the 'age' of air throughout a space. Generally any physical or computational model that provides information about the pattern of airflow can be used to determine ventilation efficiency parameters. An example illustrating the application of CFD to evaluate these parameters is described by Liddament 1993. The reliability of the assessment of the ventilation efficiency is therefore dependent on the quality of airflow modelling. Optimising of ventilation efficiency may result in the need for a smaller HVAC plant than would otherwise be necessary. This can result in further energy efficiencies as well as reduced capital and life cycle costs.

Energy efficient ventilation in large enclosures concentrates on ensuring good air quality in the occupied zones. Since these zones only represent a small proportion of the total volume, conditions in the remaining parts can be relaxed. This results in a considerable saving over providing a uniform environment throughout the entire

volume. Separation of the zones can be accomplished by using the properties of stratified flow.

3.0 Measurement Techniques for Large Enclosures

3.1 Background

Measurements in large enclosures are needed for commissioning, diagnostic and evaluation purposes. Unfortunately, the extensive volume and envelope area associated with large enclosures adds to the complexity of making measurements. Techniques applied and adapted as part of the study included:

- Building Airtightness;
- Ventilation Performance (Effectiveness);
- Air Movement;
- Temperature Field.

A review of existing methods was made to assess their applicability to large enclosures. Various techniques were applied to the case studies (Section 4) to gain experience in practical use. These adaptations are outlined below.

3.2 The Special Needs of Large Buildings

Several problems must be addressed before measurements can be adapted for large buildings, such as:

- Many measurement or sampling points are needed for air quality, airflow rate and ventilation rate measurements;
- Pressurisation (air leakage) equipment requires a high flow capacity (at least $30\text{m}^3/\text{s}$);
- Large volumes of tracer gas may be needed for air change rate measurement. This may be overcome by adapting metabolic CO_2 or by using perfluorocarbons tracers (PFT's) which can be detected in minute concentrations.
- Non-homogeneity of conditions (temperature, velocity and pollutant concentration varies significantly throughout the space). As a result measurement techniques based on uniform conditions cannot be easily applied.

Typical techniques and applications are summarised in Table 3.1 below.

Table 3.1 Summary of Measurement Techniques and Applications

Problem	Measurable Variables	Measurement Methods
Draughts	Velocity, Turbulence, Temperature	Anemometry (uni or omni-directional) Thermometry
Thermal Radiation	Radiant Temperature	Radiometer, Comfort Meter
Over Heating	Temperature Comfort	Thermometry Comfort Meter
Contaminants	Contaminant Concentration	Analysers, Samplers (Passive and Active)
Simulation of Contaminants	Concentration Removal Efficiency	Tracer Gas, Smoke
Air Infiltration	Leakage Parameters Leak Detection	DC Pressurisation Stack Pressurisation Thermography, Smoke Detection Tracer Gas Measurements
Correct Ventilation	Specific Airflow Rate Age of Air Airflow Visualisation	Tracer Gas, Constant Concentration Tracer Gas Homogeneous Emission Smoke Tests, Balloons

3.3 Summary of Measurement Techniques

A detailed analysis of measurement methods is presented by *Roulet et al 1992*. Those techniques developed or adapted by the Annex for large buildings include:

3.3.1 Evaluation of Air Leakage Distribution by Stack Pressurisation

A simplified method to estimate the air leakage distribution in tall buildings was developed by the Annex. It is based on the pressure distribution induced in buildings by the stack effect. To apply this method, the building should be tall and the temperature difference between indoors and outdoors should be large enough to ensure that stack pressure is the dominant driving force. To achieve this, the product of the height of the building multiplied by the temperature difference should exceed 240 [K.m]. The technique is illustrated in Figure 3.1.

To the right of the Figure, the pressure distributions for three experimental cases are given; these are:

- (i) Closed building envelope.
- (ii) Ground floor door open.
- (iii) Top level window(s) open.

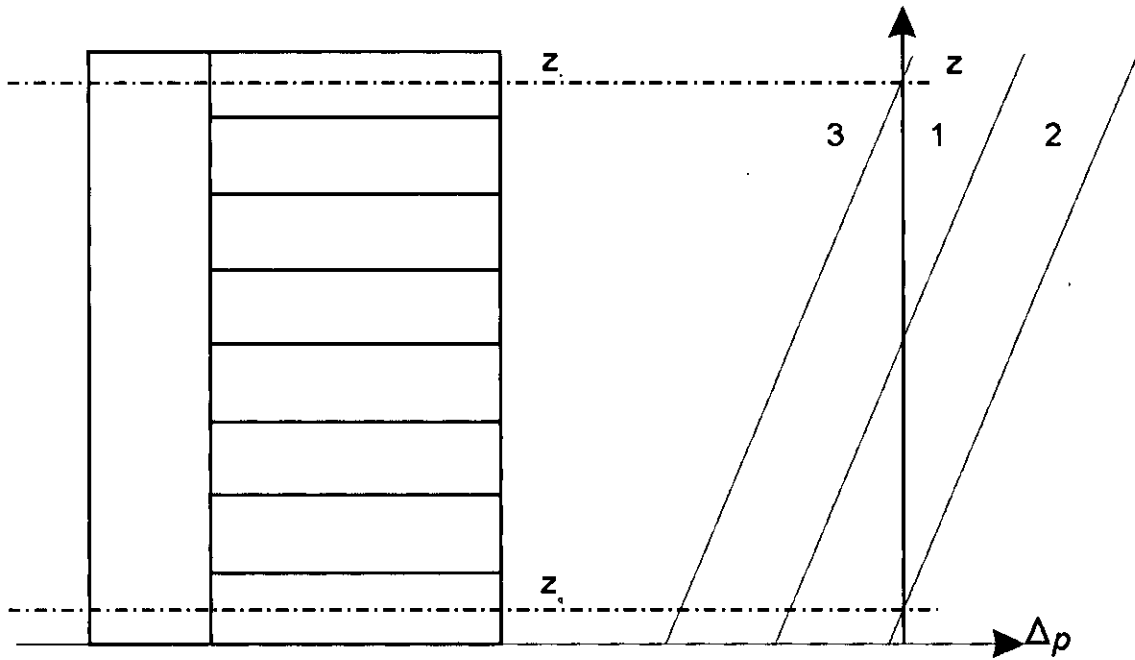


Figure 3.1 Evaluation of Leakage Distribution by Stack Pressurisation

If the building has all its internal doors open as well as the staircase and/or the lift shaft and if the temperature does not vary too significantly throughout the building, there is, a priori, only one neutral plane at the height z_0 (Case 1 above). The Air leakage characteristics of the building can be evaluated by measuring, for each of the above cases, the temperature and the pressure difference at selected heights and the airflow rate through the open windows and doors. This procedure was proposed by *Hajakawa and Togari, (1989)*. A further simplification enables the airflow characteristics to be measured based on determining the level of the neutral pressure plane (*Van der Maas et al, 1992 and 1994*). This method was used with success on an atrium (*Schaelin et al, 1996*), where unexpected openings were found this way.

3.3.2 Ventilation Performance (Efficiency and Effectiveness)

The parameters that are of greatest interest in assessing the ventilation performance of a large enclosure include:

- The fresh air exchange rate (or specific flow rate)
- The air change efficiency parameters (especially the local mean age of air and the local air change index.
- The contaminant removal effectiveness (especially the local air quality index, the dosage index, the transfer index.

Definitions of these parameters may be found in *Sutcliffe [1992]*, *Brouns and Waters [1991]*, and *Liddament [1993]*.

Measurement of these parameters is most easily accomplished by tracer gas methods. There are no new techniques for large enclosures, and so it is necessary to consider the effect that the size and function of such enclosures may have on the application of existing techniques. Experience suggests that measurement difficulties become progressively more important as the size of the space increases, especially when the internal volume of an enclosure is greater than approximately 5000m³. The problems of large enclosures may be summarised as follows:

- **Difficulty in injecting enough tracer gas:** The amount of tracer gas needed may become prohibitively expensive. One solution is to use a combination of tracer gas and a detection system which can operate at very low concentrations. The most commonly used tracers are Sulphur Hexafluoride and the Perfreons combined with electron capture detection (*Liddament 1996*).
- **Difficulty in distributing the tracer:** When the tracer gas is used to mark a given mass of air, it should be homogeneously mixed to that mass of air. This is not a major problem when the tracer gas can be injected into the supply duct. Consequently it should always be possible in mechanically ventilated spaces. However, when measuring contaminant removal effectiveness parameters, it is necessary to imitate contaminant release in the space, and it is often difficult to achieve a realistic distribution in the zone of release.
- **Time span of the measurements:** Measurements to assess the ventilation performance during normal operating conditions are particularly difficult at highly intermittent operation with high occupancy levels, as for example in sports halls and auditoria.
- **Number and positioning of injection and sampling points:** Some sampling positions are determined by the requirement to obtain ventilation parameters at specific locations (e.g. close to occupants). Others need to be chosen to give a satisfactory image of the variation of ventilation parameters throughout the enclosure. The positioning of sampling points can be assisted by the use of prior knowledge, either from velocity measurements or from modelling studies (*Brouns et al 1994*).
- **Identification of ventilation and air distribution paths:** The method of ventilation and air distribution is often very complex. Although the majority of large enclosures are ventilated either partly or wholly by mechanical means, there is often a high proportion of uncontrolled air movement through doors, roof vents and other leakage paths. Also, there may be several local systems within one enclosure. This makes it difficult to identify inlet and extract paths for the ventilating air, which in turn limits the choice of tracer gas technique and the parameters which can be measured. Furthermore, modern control systems often adjust supply and re-circulation rates in response to several parameters, including air quality and energy consumption rate, creating continuously variable ventilation regimes.

- **Temperature gradients:** In many large spaces there may be significant temperature gradients. This may affect the analysis of tracer gas measurement methods. (*Roulet and Compagnon (1989)*) have published equations which avoid the assumption of isothermal conditions. However, the errors due to this assumption must be weighed against the many other errors and uncertainties in large enclosures, and, except where temperature gradients are particularly severe (i.e. larger than 30 K), it may be reasonable to ignore the effect of temperature on tracer measurements.

The most satisfactory adaptations of tracer gas for large spaces include constant emission methods and 'transient' techniques in which tracer gas is released as a pulse. The transient approach is particularly versatile and is based on monitoring the response to tracer gas injection (e.g. at the ventilation supply grille or at a location of potential pollution) at the places of interest.

Ventilation performance can be judged from the time in which it takes the gas to be detected at any location and then the characteristics of its decay (e.g. rapid or slow) and the peak concentration measured.

3.3.3 Visualisation of Air Movement

Several methods are applicable to visualise room airflows in large enclosures. These involve the release of small particles or neutrally buoyant bubbles into a space and capturing their movement through a variety of monitoring methods.

Three dimensional methods include:

- Stereophotogrammetry using two or more cameras (*Scholzen 1994*);
- Illumination with a gradually coloured light sheet ;
- Tracking of particles or balloons over time (*Alexander, 1994, Maas 1993*) (Lagrangian approach);
- Streak photography (Eulerian approach);
- Correlation techniques on one double exposed frame or two consecutive frames, (standard particle-image velocimetry or PIV techniques, commercially available for 2D).

Small particles or bubbles provide dense velocity information, but are restricted to small fields of about $2 \times 2 \times 0.1 \text{ m}^3$. Balloons allow coverage of large rooms but provide only a few tracks.

3.3.4 Thermography

Temperature measurement in rooms can be divided into two fields of application, i.e:

- wall temperature distribution:
- three-dimensional air temperature field.

Temperature measuring techniques in large enclosures are limited, since both a high spatial resolution is required and a short monitoring time. Furthermore, a number of methods are not suitable for application in large enclosures, because they entail extensive technical effort and high cost. For this reason, only the application of thermography for the wall (surface) temperature measurement is addressed.

When properly interpreted, thermography gives a two-dimensional temperature distribution of surfaces. The initial camera image (Figure 3.2a) records the intensity of infra-red emission from the surfaces. This is dependent on the temperature of the surface and on its 'emissivity' or reflective characteristics. To determine the actual temperature, the effect of emissivity must be filtered out.

Emissivity correction involves identifying the surface components and incorporating their emissivity factor. This varies from zero for a totally reflective surface and 1.0 for a totally absorbant surface (black body). The result of emissivity correction is illustrated in Figure 3.2b.

4.0 Case Studies

An important task within Annex 26 was to evaluate a number of case studies. The emphasis of these case studies varied but the main objectives were to:

- Evaluate measurement techniques;
- Evaluate the performance of calculation methods;
- Evaluate the robustness of the various case study buildings and ventilation design.

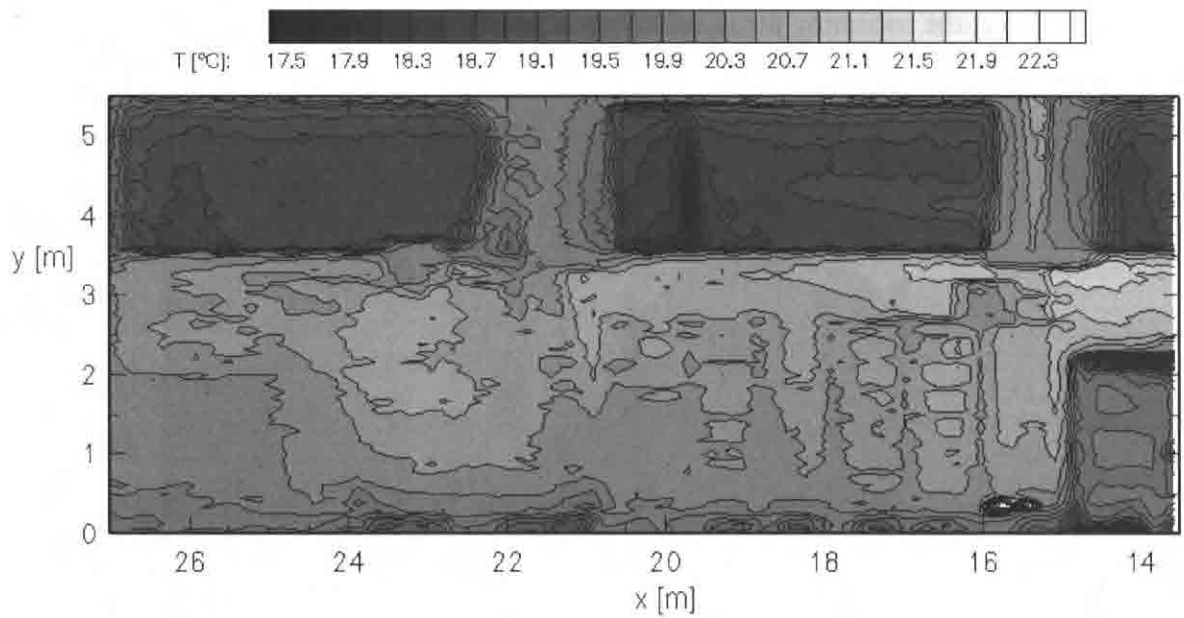
A summary of these case studies and their results is presented below:

4.1 De Montfort University Auditorium (United Kingdom)

The main purpose of this particular case study was to evaluate the performance of the building and compare measured results with the original design calculations.



(a) Original infrared picture with corner points A, B, C and D for rectification.



(b) Obtained picture with isolines after emissivity correction.

Figure 3.2 Thermographic Surface Temperature Evaluation

[Courtesy EPFL, Switzerland]

4.1.1 Building and Ventilation System

This is a modern purpose designed, naturally ventilated structure in the Queen's Building at De Montfort University, Leicester. Ventilation rates, air velocities and temperatures were monitored during "winter", "mid-season" and "summer" conditions over periods of average occupancy. A prime feature of the building as a whole is the use of tall ventilation stacks (Figure 4.1) to promote natural buoyancy driven ventilation, as a means of avoiding the need for air conditioning. Cooler outside air enters through openings in the facades of the building, displacing warmer, "stale" air which is discharged via the chimney exits. Extensive use is made of daylighting using skylights. Night-time ventilation is an integral part of the strategy to cool the exposed, thermally heavyweight structure in Summer. Reliance on natural ventilation contributes to significantly reduced energy use and maintenance costs in comparison to more conventional buildings. Outside air is drawn from a zone which is adjacent to a lightly used road. It enters into three plenums via modulated control dampers. From these it disperses through under floor voids and enters the room by way of vertical grilles positioned at ankle height beneath the seats. Air leaves the space via two large openings at the base of two stacks and is exhausted through eight 'windows' at the top, at a height of 18.5m above the ground. Intake and outlet positions can be varied by the operation of motors controlled by the building management system. A "punka" or "ceiling" fan is installed in one of the stacks to stimulate ventilation in the event of flow stagnation. In winter, the incoming air is heated as it passes over finned, hot water filled tubes situated directly behind the underseat grilles.



Figure 4.1 DeMontfort University Lecture Hall [Photograph Courtesy of BRE, UK]

During an occupied period, the inlets and outlets open if the average internal temperature exceeds a set point (e.g. 19°C) and the air temperature is greater inside than outside. At all other times the openings close to minimum positions which are determined by a carbon dioxide sensor located in one of the stacks; i.e. 10 % open with a CO₂ concentration of 350 ppm and 100 % open when the CO₂ concentration equals or exceeds 1,000 ppm.

The start-up fan in the stack operates if the average internal temperature is 3°C above the room set point and more than 2°C above the external air temperature (provided the inlets and outlets are open and it is not raining). Night-time ventilation occurs to pre-cool the building to a set temperature in Summer conditions, when the 24-hour average minimum outside temperature is greater than 13°C. When the space is unoccupied in Winter the inlets and outlets are closed. The temperature of the heating tubes is controlled according to the average room temperature. In the event of a fire, the ventilation inlets and outlets fully open and the extract fan is switched on.

4.1.2 Measurement and Calculation Programme

The following measurements were undertaken:

- Overall ventilation rate for a range of different conditions using tracer gas techniques;
- Identify and measure the bulk airflow paths, local air movements and local ventilation rates;
- Establish the pressure/flow characteristics of key ventilation components.
- Comparison of the measured thermal and ventilation performance with design calculations;
- Scale, salt bath model;

Parameters measured included the local mean age of air, indoor air and surface temperatures, external conditions (wind speed, wind direction and air temperature). Outdoor conditions were measured from a nearby meteorological site and, in later tests, at the roof level of a nearby tall building.

4.1.3 Results

Results indicated the following:

- Ventilation rates were driven by both 'stack' and wind, and were higher than design calculations based on computer and physical (salt-bath) models;
- Air movement was confirmed to generally occur along a path leading from the inlet grilles beneath the seats, rising vertically upwards and leaving via the openings at the base of the stacks. Occasionally, as openings at the top of the stacks began to close, air entered one stack and left via another;

- Air speeds in the occupied zone, away from the inlets under the seats were low;
- Thermal mass had a dominant effect, with internal temperatures remaining stable and invariably cooler than outside in summer;
- Ventilation distribution was uneven in the occupied space (due to the uneven layout of inlets in the underfloor supply plenum);
- CO₂ control of intakes and exhausts in winter did not function. However, high CO₂ concentrations were avoided in practice since occupancy was intermittent and rarely high;
- When intakes were opened during cool conditions (as designed), a combination of relatively high air speeds and low temperatures indicated that the pre-heat network was ineffective. This problem could be reduced by finer control of intake and exhaust dampers.

4.2 Experimental Atrium, Japan

This atrium provided a carefully controlled and well monitored environment in which measured data could be used to evaluate the performance of airflow models.

4.2.1 The Building and Ventilation System

This south facing experimental atrium was built in Yokohama, Japan (Figure 4.2). It has three glass walls (south, west, and east), a glass roof and two insulated surfaces (north wall and floor). Long term observations over two years were made of the indoor climate.

Since the atrium was built for experimental purposes, no one was permitted to enter it. Uncertainties in the boundary conditions, such as unexpected air exchanges resulting from people going in and out, were therefore greatly reduced in comparison to observations of atriums in general use. The impact that boundary conditions, such as envelope material properties, had on the indoor thermal environment and heat budget were analysed in detail.

Various sets of boundary conditions and air and temperature distribution data were used in validating mathematical analysis methods, including CFD (Computational Fluid Dynamics) and macroscopic models. The accuracy and reliability of predicted convective heat transfer coefficients (or convective heat transfer rate) in CFD models were examined in detail.

Predicted vertical air temperature distributions using both CFD models and zonal models were also investigated by comparing their results with those of the measurement. Various configurations of ventilation strategies and cooling were applied by both natural and mechanical means.

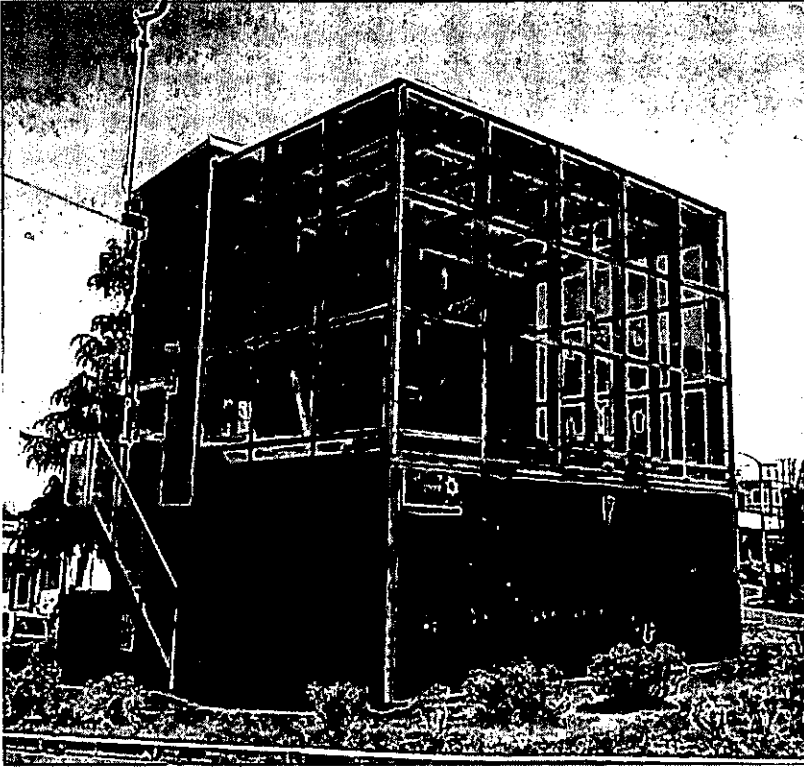


Figure 4.2 Experimental Atrium [Photograph courtesy of Asahi Glass Co., Ltd., Japan]

4.2.2 Measurement and Calculation programme

Measurements included outdoor environment (solar radiation, temperature; wind velocity), absorption, solar radiation transmitted through each glass wall, glass temperature, inner surface temperature distribution of each wall, surface temperature of steel frames, indoor air temperature and indoor airflow.

The resultant datasets were used to evaluate a wide range of calculation methods including CFD and Zonal Model simulations airflow and temperature distribution.

The primary aims were to evaluate:

- How simplification of the boundary conditions affect CFD prediction results;
- How accurately the convective heat transfer from the walls to the air is predicted;
- How zonal models function in the prediction of the vertical temperature distribution of the large enclosure.

Numerical simulations were carried out independently by several groups using various models. Most of the simulations were carried out based upon the given measured temperature boundary conditions, assuming a steady state. A time dependent CFD simulation was also carried out which included the effect of solar radiation and the surface to surface radiation. CFD simulations, including the effect of air infiltration, were also conducted. Other factors investigated included the use of different grid systems, comparisons between conventional k- ϵ model turbulence models and Low Reynolds Number k- ϵ simulation, radiation simulation and conductive heat transfer.

The heat gain from the obstacles inside the computational domain (steel frames) was also considered in most of the simulations. The surface temperature of the obstacles (the steel frames) and the prescribed convective heat transfer coefficient were used for calculating the resultant convective heat gain. The heat gain from the obstacles was often assumed to be a uniform heat source throughout the whole computational domain. However, in some simulations, they are distributed in the source term of the temperature transport equation according to their positions.

4.2.3 Results

Measurement results indicated the following:

- With no cooling, the vertical temperature difference is relatively small, because indoor air is well mixed by the natural convection of the solar heated floor and cooled glass wall.
- With cooling and supply air emitted from an opening close to the floor, highly stable temperature stratification was achieved.
- With no sun shading on the roof, natural stack driven ventilation occurred.
- Convective heat transfer from the steel frames was a major factor in indoor air heating.

Calculation results included:

- The structural steel frames and glass sashes considerably affect the thermal environment.
- CFD methods incorporating turbulence models, such as the k- ϵ model, in general gave reliable prediction results.
- Simplification of the boundary conditions sometimes gave a divergence in predicted and measured properties, however, small-scale change of the boundary conditions did not significantly influence the whole scale flow and temperature distributions.
- Convective heat transfer simulation from the walls to the air by CFD was not so reliable when the usual log-law type wall function and coarse mesh system near

the wall was used. It is recommended that in CFD simulation, when a course mesh system is used, prescribed convective heat transfer coefficients should be used, rather than the more usually applied log-law type wall function. It is easy to give the appropriate value of the convective heat transfer coefficient. Low Reynolds number k- ϵ model, without any wall function, improve results but this procedure would require too much computational time and would be difficult to use in a practical situation.

- The temperature gradient obtained by the low Reynolds Number k- ϵ model in the near-wall region was rather steep when compared with the standard k- ϵ model. The velocity gradient obtained by the low Reynolds Number k- ϵ model is also evaluated to be thin.
- The space averaged temperature is affected by the simulated convective heat transfer rate at the walls and by the degree of the given infiltration and the heat gain from the steel frames. The latter factors (heat loss/gain by the infiltration and by the heat gain from the steel frames) have significant influence on the simulations.
- Solar radiation analysis gave a satisfactory reproduction of the solar absorption properties of the glass covered large enclosure.
- The simplification of the shading effects of the steel structure, affected the simulation results significantly. The room air obtains considerable heat from the structure frames and sashes. Hence solar radiation analysis and simulation of shading effect is important. As a consequence, coupled simulation of radiation analysis with CFD is beneficial in analysing the heat transfer properties in the space. However, such a model required considerable computational time and space. Nevertheless, detailed simulations were performed incorporating solar and long wave radiation based on an hourly time-step. In all cases the predicted room air temperature was found to be lower than the measured value. The reason for this discrepancy was not certain although there was a possibility that the measured room temperature was affected by radiation from the steel structure. However, the degree of correspondence between simulation and the measurement for most parameters was fairly good. Discrepancies between calculated space-averaged between the different groups undertaking these simulations were thought to be due to the different assumptions being applied about air infiltration and heat gain from the steel frames. Results were found to be sensitive to these parameters. It should also be noted, however, that measured values themselves also had a degree of scatter.
- Because the steel structure of the test atrium was of considerable surface area, it absorbed significant amounts of solar energy. This could not be ignored in the temperature simulation.
- The zonal model gave a satisfactory reproduction of the vertical temperature distribution in the large enclosure, even if the air is thermally stratified. In the zonal model simulation, it is also important to apply an appropriate convective heat transfer coefficient;

4.3 Gjøvik Mountain Hall, Norway

Gjøvik Mountain Hall is a purpose built sports stadium cut into a mountainside. It was used for ice hockey in the 1994 Winter Olympic Games. Its inclusion in this study was for the purpose of comparing thermal measurement data (steady state and transient) with the performance of CFD simulation.

4.3.1 The Building and Ventilation System

The stadium is cut deep into the mountain side and is accessed by a 100m long entrance tunnel. Displacement ventilation is used in which fresh air is supplied from low velocity outlets, at floor level, at slightly below the main stadium temperature. Air is extracted at ceiling level. Ventilation flow rate varies from between 25000 m³/s and 140000m³/s. Thermal conditioning is through the ventilation supply and internal heat gains.

4.3.2 Measurement and Calculation Programme

Both long term and transient measurements were made of airflow rates (supply and exhaust ducts), air temperature distribution and energy consumption. Calculations were based on CFD analysis undertaken at the Polytechnique Federale de Lausanne (EPFL) in Switzerland. Using the advantage of symmetry, a finite volume grid was generated for one quarter of the hall using a grid generator (Figure 4.3). The calculation domain dimensions were 30.5 m (half width), 45.5 m (half length) and 23.8 m (height). Radiant (heating and cooling) panels are modelled as several elements, at two levels. Air enters at 5 locations in the modelled quarter of the hall. Boundary data included the ventilation rate, lighting heat power and occupancy.

4.3.3 Results

The calculated Vs measured temperature and velocity fields compared favourably. A detailed look at the transient behaviour however pointed out some problems in the simulation of the transient evolution of the temperature profile in the hall. Although the increase rate of the simulated temperature agrees well with the experimentally observed behaviour, the comparison with the experimental values shows first that the temperature level is generally too high (by about 2 degrees).

It is thought that this result could be improved by imposing improved surface temperature conditions, but this is yet to be undertaken. It was also observed that the predicted mixing of the air is generally higher than observation. There is also much less stratification in this simulation than observed.

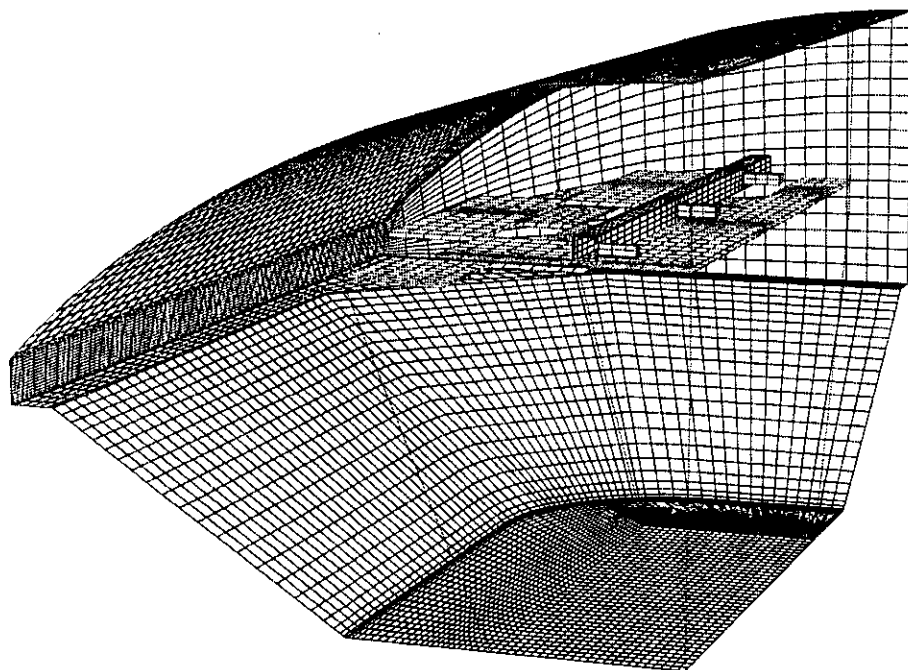


Figure 4.3 CFD Grid system for Gjøvik Mountain Hall

The calculation values are within 2°C between 4 and 13 m, whereas the measurements show a temperature difference of 2.5°C at 18.00 and 4°C at 19:30. A possible reason could be the use of the standard k- ϵ turbulence model without damping terms due to temperature stratification.

In general, the results are satisfying but deserve a more careful treatment of the transient thermal boundary conditions such as applied in the case of the Japanese experimental atrium. It seems necessary to adjust dynamically the thermal boundary conditions. Another remaining problem is the temperature gradient of the calculated results which is smaller than in the measurements.

4.4 Fibre-Glass Reinforced Polyester Factory (France)

This is a light industrial building located in Normandy France and is used for the production of polyester components. The process is performed manually by spreading styrene resins over moulds, thus workers are potentially exposed to styrene vapour emissions. This case study provided a good opportunity to develop a database of measurements in an operating industrial environment which could be used to evaluate the performance of CFD simulations.

4.4.1 The Building and Ventilation System

Its overall dimensions are 35m x 6m x 42m with an internal volume of 8820m³. It is a new workshop which communicates with an older one through two large openings (size 4m by 4m). There are no major outside doors. A mixing ventilation system is used in which dilution calculations were based on a safety ratio of 4.0 for the threshold limit value for styrene fumes. The theoretical fresh air supply is 70000m³/h and the extract rate is 42000m³/h. This supply rate corresponds to a renewal rate of about 8 volumes per hour.

The building is overpressured with the residual flow rate supplying the adjacent workshop through the two large openings. Twenty identical spherical inlet units located at a 4m height over the floor supply fresh air. Twenty four exhaust grilles are located at the floor level. The air is supplied by two independent fans and is heated by two make-up systems.

Pollution sources are located on moulding tables. Their number can be estimated to be 40 in the whole space. The actual styrene emission rate is difficult to estimate since it depends more on the mould area than on the total amount of styrene used. Since fabrication requires moulds of various shapes and sizes actual conditions at any one time are uncertain. Total styrene emission was estimated as 3.75 kg/h for the whole workshop.

4.4.2 Measurement and Calculation programme

Measurements included styrene concentration, air temperature, omnidirectional and vectorial velocities in the bulk of the workshop. Sections of the building were investigated by moving a mast equipped with all sensors on the same profile.

The first set of measurements focused on establishing the actual operating conditions of the ventilation system. This showed the total fresh airflow rate to be approximately 46600m³/h while the extract rate was 36100m³/h. The air renewal rate was estimated to be 5 volumes per hour

Simulations included:

- Zonal model (1 attempt);
- CFD model based on k-ε closure (4 examples);
- CFD model based on constant turbulent viscosity (1 example).

An example output is illustrated in Figure 4.4

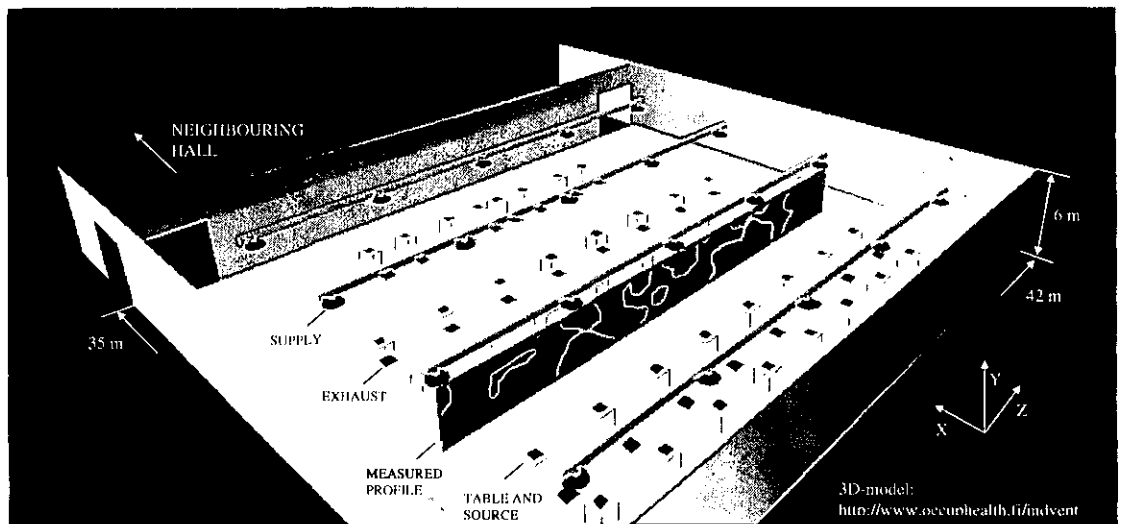


Figure 4.4 Example Numerical Output Fibre-Glass Reinforced Polyester Factory (France)

Because of geometrical complexity, simulation tools had to be applied with some extra assumptions; these included:

- Velocity profile at supply devices are supposed to be isotropic around anemosthats (45° angle with vertical axis) and zero in the middle of them. Measured flow rates are available for each inlet. A symmetry plane $z=21$ m can be imposed, since flow rates through the large openings are low compared with the total fresh air volumes.
- The styrene pollutant source is assumed to be emitted at the 40 working places at the total flux of 3.75 kg/h. Two configurations were considered:
 - (i) uniform flux over the 40 sources;
 - (ii) fluxes weighted upon estimated mould sizes (coefficients 1, 1, 4, 4 and 1/2 respectively for pollutant source).
- No obstacles apart from ventilation ducts were included in the occupational region of the building.

The outputs of the zonal model were limited to styrene concentration, whereas the CFD codes provided both velocity and pollutant concentration fields.

In addition the age of air was determined for the 1.5m high horizontal Section of the workshop located at breathing level.

4.4.3 Results

Measurement results indicated the following:

Measurements indicated that the ventilation system complied with the two main objectives given by the building designer. In particular, temperature gradients stayed within a 1 or 2 degree range while styrene concentrations remained mostly in the range between 20-30 ppm. In some locations, where very large moulds were used, higher styrene concentrations were measured. No clear airflow pattern within the space could be determined from the measurement results. There was interaction between air inlets and velocity profiles. Omnidirectional velocities are generally over 0.2-0.3m/s, which means that ventilation is acting as designed.

Calculation results included:

The main results from the simulations were that:

- Mixing ventilation induces very complex flows;
- The upward air motions in between jets lead to pollutant dispersion in the upper part of the workshop;
- Actual flow rates create a sufficient dilution to remain below the styrene TWA;
- The flow rate difference between the 2 openings has a locally limited effect. - velocities in the bulk of the workshop are very low (often <0.1m/s);
- No clear influence of the grid size can be detected from the CFD calculations.

Comparisons between calculations and measurements:

- The orders of magnitude of styrene concentration levels were found to be in good agreement in the bulk of the workshop;
- The concentration peaks were well predicted by CFD models;
- Calculated upward motion velocity vectors were observed by measurement despite a coarse grid of measurement points. These vectors were also detected by ultrasonic anemometry.
- CFD simulations indicated that the of age of air was characteristic of a good mixing at the breathing level. Most of the workshop normalised ages of air ranged from 0.8 to 1.4. Over-ventilated regions were limited to terminal devices, whereas under-ventilation was detected in the opposite corner of the large opening wall.
- In the factory case, ventilation seems to perform better than perfect mixing. This may be due to over-pressure which creates a horizontal displacement of part of the flow in the direction of the two openings. More precisely, the weighted source assumption leads to higher efficiencies than the uniform source

hypothesis. As a matter of fact, this comes from the fact that, in the weighted case, sources are concentrated in the middle of the workshop in a well ventilated area. On the contrary, homogeneous styrene sources create larger contaminated regions.

- Attempts to compare CFD concentration results and styrene exposure estimated by passive sensors were not very successful. In fact, concentration gradients are high near sources and a slight misplacement of a source leads to significant differences between both approaches. Moreover, because of the operator movements, exposure measurements do not match local concentration values. since they are averaged not only in time but also in space.
- Comparisons showed that CFD simulation is technically feasible, even if a large amount of information is needed to implement it accurately.

4.5 Case Study Turnhalle München

Turnhalle München is a gymnasium building attached to a school. (See Figure 4.5) The main intention of this study was to compare the performance of CFD models with measurements of airflow and temperature profiles.

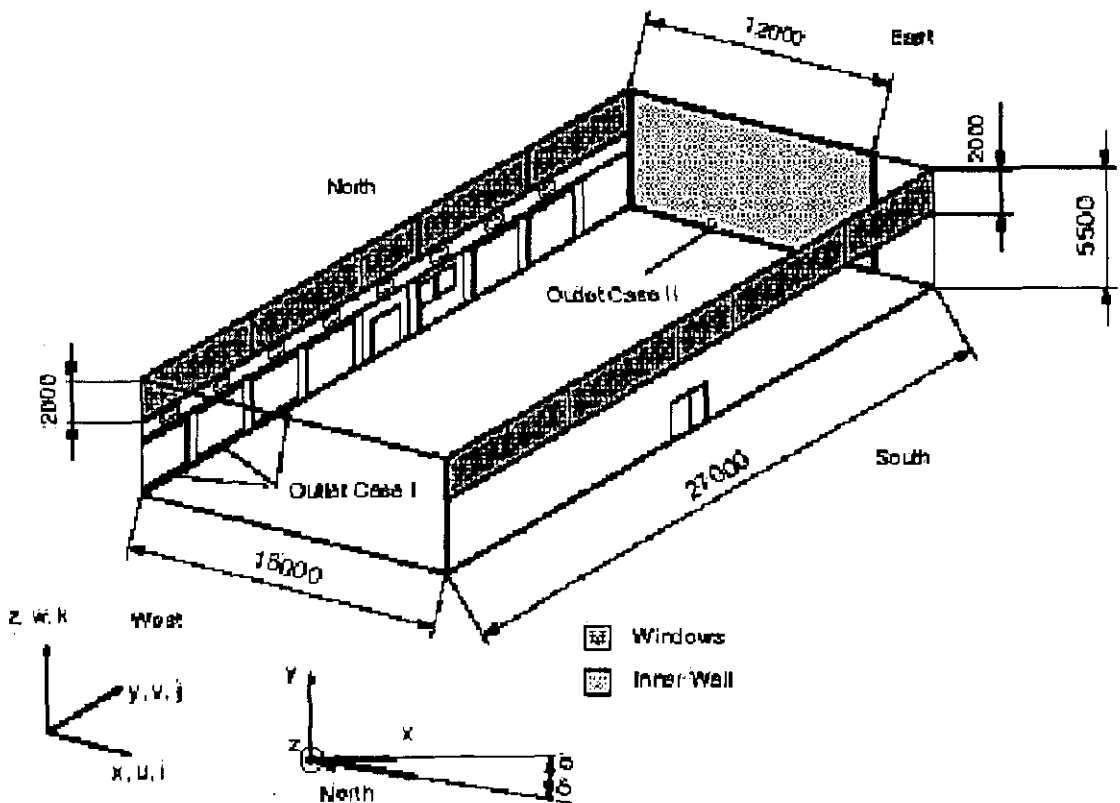


Figure 4.5 Details of Turnhalle München

4.5.1 The Building and Ventilation System

This single enclosed space is ventilated by a series of eight mechanical air inlets combined with various outlet configurations. As part of the design and numerical exercise various configurations were attempted, these included:

- (i) All inlets have the same flow velocity and magnitude. Inlets and outlets are located on the same (north) wall, with the inlets positioned at a low level and the outlets at a higher level.
- (ii) Conditions as for (1) above, but the incoming supply air heated to 30°C.
- (iii) Each inlet had a different velocity. The inlets are located on the north wall and the outlets on the south wall.

4.5.2 Measurements and Calculation Programme

Measurements included air velocity profiles and temperature distribution. Calculations were based on the use of CFD. A total of eight organisations used various CFD codes including both commercial and research algorithms. Much of the analysis was involved in comparing the output from each of the simulation codes.

4.5.3 Results

Instabilities (time varying results) could be seen in both the measurements and the simulations for examples (1) and (3) above. Hence although the ventilation conditions themselves were constant throughout each of the monitoring periods, the flow patterns and temperature profiles did not remain constant. This made comparison between measurement and modelling very difficult.

Problems associated with measurement were thought to be due to the ventilation system itself and the impact of air infiltration. It could not be determined if instabilities in calculations were related to physical phenomenon or to numerical instabilities of the solvers. Some solutions, however, demonstrated strong grid dependency on the numerical results.

In the first example, flow behaviour is dominated by the inlet jets. In the second, buoyancy, created by temperature difference resulted in a more stable flow field.

The values of the heat fluxes predicted by the wall functions depended very much on the distance of the first grid points near the walls. In particular, when buoyancy effects are present in the boundary layer (as in test case 2) a more sophisticated treatment of the boundary layer was found to be necessary. It is uncertain whether the boundary conditions of the simulations and the measurements are identical. The successful application of CFD codes to the simulation of large enclosures depends

mainly on the choice of proper boundary conditions. In all examples, it was difficult to compare calculated parameters with measurement.

5.0 Lessons Learnt

Technical lessons may be grouped in five classes: Design guidance, measurement techniques, prediction techniques, computational fluid dynamics, and future trends.

- **Design guidance:** In large enclosures, ventilation is not an add-on that can be attached to a finished design; ventilation must be integrated at the outset of the building and system design. The occupied zone only must be ventilated. Stratification layers in a temperature gradient often achieve zoning. Local conditioning is sometimes necessary. With large glazed surfaces, controlled solar shading is essential.
- **Measurement techniques:** Because of large distances, measurements are costly and good planning is compulsory. Techniques without the need for sensors and long cables include infrared temperature imaging and leakage measurements by the new neutral-pressure-level method (see Section 3)
- **Prediction techniques:** Design tools of different levels are now available to the engineers. Some 'simple' tools require practical experience and good judgement on the part of the user. (see Section 2). The flow element is a clever combination of highly accurate experimental correlation in a simple-to-use procedure. The only condition for applicability is that elements, such as plumes or boundary layers, must not interact. If strong interaction exists, computational fluid dynamics should be applied.
- **Computational fluid dynamics:** The eddy-viscosity concept combined with two-equation turbulence models still provides economical and reliable predictions of temperature, air velocity, and pollutant fields (k- ϵ model). Small changes to boundary conditions may significantly affect the main pattern of airflow and temperature distribution. It is therefore essential that boundary conditions are accurately represented. The extra effort expended to obtain realistic data is of proven value. Radiative heat transfer is important in large spaces with glazing and if the inside envelope has non-uniform surface temperatures (e.g., in atria). Convective heat transfer from boundaries to the air is not correctly predicted using coarse grid and log-law wall functions. The use of prescribed convective heat transfer coefficients is one alternative. Another approach employs new wall functions for free-convection heat transfer. Slow or non-existent convergence was sometimes encountered for flows dominated by thermal buoyancy. Using a coupled rather than a segregated or sequential (SIMPLE) solver can overcome this problem.
- **Future trends:** Large enclosures are built to accommodate large audiences, pedestrian traffic, exhibitions, or industrial processes. Architects design large

spaces to be attractive. The visitor should feel comfortable in a thermal, olfactory (odours), visual, and acoustic sense. Indoor climate and air quality, lighting, sound, and colours have to be right. A person entering the space will then feel at mental ease and has a positive social experience. It is a new trend that the visitors also expect an environmental message from a large enclosure. Buildings should not block off nature. On the contrary, they should become an integral part of the natural environment. People like to see green plants in air terminal buildings and daylighting in offices. They prefer natural ventilation to high-powered mechanical systems, they vote for low-energy cooling, and solar or underground air preheating.

Other important conclusions are:

- ***Ecological consciousness:*** Many building operators want to signal ecological consciousness; it improves the image of a business and attracts environmentally aware customers.
- ***Consequences for ventilation design:*** Energy consumption by the system must be reduced to a minimum. Natural ventilation (perhaps combined with some mechanical ventilation) with clever control strategies must be considered. Since buoyancy and wind drive natural ventilation, simulation methods for natural convection and thermal buoyancy and for flow around buildings become important. Simulation will have a stochastic component because of wind and meteorological data. The engineer has to get used to statistical results. For the prediction of flow around buildings, large-eddy simulation, LES, is superior to time-averaged turbulence models. But LES requires more computer resources. A general trend is the graphical rendering of computed flow fields:
- ***Design visualisation:*** The designer likes to see 3-dimensional maps of temperature or comfort parameters and animated flow patterns. Calculated vector fields must be translated into moving video clips. Concentration fields are perceived as three-dimensional if the display on the computer screen can be rotated and zoomed by the user. Scalar fields need to be displayed by travelling Sections.

6.0 Conclusions

This Annex has made a successful evaluation of large enclosures and of the measurement and calculation techniques needed for design and evaluation. The success of the project and the relevance and quality of the results are due to two principles:

- The use of real case studies to support any design guidance or development of prediction tools.

- The intimate interaction between research teams of different countries and the open exchange of specialised knowledge.

7.0 References

Alexander, D.K., Jones, P.J., Jenkins, H., Harries, N., Tracking Air Movement in Rooms, *15th AIVC Conference, Buxton, 1994.*

Brouns, C. E., A Guide to Contaminant Removal Effectiveness, *1991 AIVC Technical Note 28.2, 1991*

Brouns, C.E., and Waters, J.R., The Positioning of Tracer Gas Sampling Points in Large Enclosures, *IEA Annex 26, Forum Presentation, 4th Expert Meeting, Gjøvik, May 1994.*

Capellman, C. Schild, P., Tjelflaat, P O ., Measurements of the ELA-ATRIUM under Summer Conditions *Report of SINTEF (STF15 A94024) 1994*

Dorer, V., Weber, A., Multi-zone air flow model COMVENT-TRNSYS Type 57, *IEA BCS, Annex 23 report, May, 1996.*

Feustel, H., *COMIS 3.0 User's Guide*, Berkeley, USA, 1997

Hajakawa, S., and Togari, S., *Simple Test Method of Evaluating Exterior Tightness of Tall Office Buildings*. Air Change Rate and Air Tightness in Buildings (MH Sherman, Editor) STP 1067, pp231-248 (ASTM, Atlanta, 1990)

Hiramatsu, T. et al, "Studies of the Thermal Environment in an Experimental, Actual scale atrium" *Roomvent 1996.*

Inard, C., *Technical report of Annex 26, 1995*

Liddament, M., A Review of Ventilation Efficiency, *AIVC Technical Note 39, 1993.*

Liddament, M., *Guide to Energy Efficient Ventilation*, AIVC, UK, 1996. ISBN 0 946075 85-9.

Månsson, L-G, Calculation of Energy and Environmental Performance of Buildings, *IEA-ECBCS Annex 21 summary report*, AIVC, UK, 1998

Ozeki, Y., et al, "Analysis on Indoor Climate and convective Heat Transport without Air-Conditioning", *Annual Meeting of SHASE (the Society of Heating Air-Conditioning and Sanitary Engineers of Japan) 1995.*

Ozeki, Y., et al, "Numerical Analysis on Flow and Temperature Fields in Experimental Real Scale Atrium" *Roomvent, 1996.*

Ozeki, Y., et al, "Effect of Sash Modelling on Solar Gain Simulation in the following Heat Transfer Simulation Room" *Annual Meeting of SHASE, 1996*.

Maas, H.G. Grun, A., Papantoniou, D., Particle Tracking Velocimetry in Three-dimensional Flows, *Experiments in Fluids, 15, 1993*.

Roulet, C-A., and Vandaele, L., Air Flow Patterns within Buildings - Measurement Techniques, 1992, *AIVC Technical Note 34*.

Roulet, C-A., Compagnon, R., Multizone Tracer Gas Infiltration Measurements - Interpretation Algorithms for Non Isothermal Cases. *Building and Environment 24* pp221-227, 1989.

Schaelin, A., Moser, A., Van Der Maas, J. And Aiulfi, D., Application of Air Flow Models as Design Tools for Atria. *Roomvent 1996*.

Scholzen, F., Moser, A., Suter, P., Particle-Streak-Velocimetry for Room Air Flows, *15th AIVC Conference, Buxton, 1994, UK*.

Sutcliffe, H., A Guide to Air Change Efficiency, *AIVC Technical Note 28, 1990*

Van der Maas (editor) Air Flow Through Large Openings in Buildings., *IEA-ECB&CS Annex 20 report, LESO,EPFL,CH 1015 Lausanne, 1992*

Van der Maas, J., Hensen, J.L.M. and Roos, A., Ventilation and Energy Flow Through Large Vertical Openings in Buildings. *Proceedings of the 15th AIVC Conference, Buxton, 1994*.

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The International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems Programme (ECBCS)

The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Co-operation and Development (OECD) in 1974, with the purpose of strengthening co-operation in the vital area of energy policy. As one element of this programme, member countries take part in various energy research, development and demonstration activities. The Energy Conservation in Buildings and Community Systems Programme has sponsored various research annexes associated with energy prediction, monitoring and energy efficiency measures in both new and existing buildings. The results have provided much valuable information about the state of the art of building analysis and have led to further IEA sponsored research.

