AIVC Guide **5**

Ventilation Modelling Data Guide

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems (ECBCS) Programme

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the Programme is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date, the following projects have been initiated by the Executive Committee (completed projects are identified by *):

1. Load Energy Determination of Buildings *
2. Ekistics and Advanced Community Energy Systems *
3. Energy Conservation in Residential Buildings *
4. Glasgow Commercial Building Monitoring *
5. Air Infiltration and Ventilation Centre
6. Energy Systems and Design of Communities *
7. Local Government Energy Planning *
8. Inhabitant Behaviour with Regard to Ventilation *
9. Minimum Ventilation Rates *
10. Building HVAC Systems Simulation *
11. Energy Auditing *
12. Windows and Fenestration *
13. Energy Management in Hospitals *
14. Condensation *
15. Energy Efficiency in Schools *
16. BEMS - 1: Energy Management Procedures
17. BEMS - 2: Evaluation and Emulation Techniques *
18. Demand Controlled Ventilating Systems *
19. Low Slope Roof Systems *
20. Air Flow Patterns within Buildings *
21. Calculation of Energy and Environmental Performance of Buildings*
22. Energy Efficient Communities *
23. Multizone Air Flow Modelling (COMIS) *

24. Heat Air and Moisture Transfer in Envelopes *
25. Real Time HEVAC Simulation *
26. Energy Efficient Ventilation of Large Enclosures *
27. Evaluation and Demonstration of Domestic Ventilation Systems
28. Low Energy Cooling Systems *
29. Daylight in Buildings *
30. Bringing Simulation to Application *
31. Energy Related Environmental Impact of Buildings
32. Integral Building Envelope Performance Assessment*
33. Advanced Local Energy Planning *
34. Computer-aided Evaluation of HVAC System Performance *
35. Design of Energy Efficient Hybrid Ventilation (HYBVENT)
36. Retrofitting in Educational Buildings - Energy Concept Adviser for Technical Retrofit Measures
37. Low Energy Systems for Heating and Cooling of Buildings
38. Solar Sustainable Housing.
39. High Performance Thermal Insulation (HiPTI)
40. Commissioning of Building HVAC Systems for Improved Energy Performance

Annex 5 - Air Infiltration and Ventilation Centre

The Air Infiltration and Ventilation Centre (AIVC) was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

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

Disclaimer

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Contents

- Background information about the Ventilation Modelling Data Guide with an example application
- Frequently asked questions about air infiltration and ventilation in buildings

1 Introduction to Ventilation Modelling

Numerical ventilation and air infiltration models are used to calculate air flow rates into and out of buildings and between individual rooms or 'zones' within a building. This report discusses the input data that must be provided in order to use them and highlights areas of application. It is intended to give an introduction to these models for building services practitioners and designers and assumes a basic knowledge of ventilation-related building physics.

The primary purpose of ventilation (and air infiltration) models is to evaluate the rate and direction of air flows. The principle behind this type of model is that for given boundary conditions, they predict the steady state mass flow rate of air through a building's envelope (i.e. it's exterior surface), and sometimes between different zones inside a building. It is a basic assumption in these models that the incoming and outgoing flow rates must balance each other, due to conservation of mass.

Sections 2 includes general observations that must be considered when attempting to formulate suitable input data. The features and capabilities of the following models are then summarised in Section 3, for which contact information is provided in Appendix A:

- AIDA
- AIM-2
- AIOLOS
- BREEZE
- CEN simplified calculation procedures
- CIBSE 'inverse sizing' model
- COMIS
- CONTAMW

- LBL
- LESOCOOL
- NatVent®
- NatVent® NaVIAQ
- NiteCool
- PASSPORT Plus
- SUMMER
- VENT

Furthermore, Section 4 contains example applications of several of these models.

Network Models

Most of the models considered here are 'network models'. In a network model, a building is represented by a collection of 'zones', interconnected by air flow paths. This representation is known as an air flow path network. Each zone typically represents an individual room, while flow paths represent air infiltration routes, purpose provided openings or ducts. Flow equations are applied that relate the pressure difference across each flow path to the resultant flow through it. Additional equations represent pressure differences generated by ventilation fans. The essential steps for configuring network models are:
- identifying the relevant flow equations for air leakage paths, ventilation openings or ducts,
- developing an air flow path network,
- specifying the wind pressure distribution on the building, and
- specifying the natural (wind and temperature difference) or mechanical (ventilation fans) driving forces.

Applicability of ventilation models

Table 1 provides an overview of the areas of applicability of the models discussed. There are a number of general reasons why ventilation modelling is desirable. Principally these are:

- pre-construction or retrofit evaluation of design,
- prediction of indoor climate,
- energy efficient conditioning and ventilation design, or
- validation of design.

These may depend on supplementary calculations, based on air flow and ventilation predictions, which include:

- determining the energy impact of ventilation,
- predicting pollutant concentration (indoor air quality analysis and pollutant removal effectiveness),
- estimating the transfer of pollutants between zones or between the outside and inside of a building,

Table 1 Overview of the areas of applicability of the ventilation models

	Ventilation rates	Indoor air quality	Indoor air temperature	Sizing of natural ventilation openings
Simplified single zone	AIM-2 CEN-explicit LBL VENT			CIBSE 'Inverse Sizing' Model
Simplified thermal + ventilation	LESOCOOL NatVent® NiteCool SUMMER- Build.		LESOCOOL NatVent® NiteCool	LESOCOOL NiteCool
Single zone ventilation	AIDA CEN-implicit			
Multi-zone ventilation	AIOLOS BREEZE COMIS CONTAMW	BREEZE COMIS CONTAMW NatVent® - NaVIAQ		
Thermal + ventilation	Passport Plus SUMMER-Tech.		Passport Plus	

- calculating room and building pressures for back-draughting or cross contamination assessment,
- sizing of ventilation openings (to optimise ventilation performance),
- cost and energy performance analysis (e.g. to compare alternative ventilation strategies), and
- thermal comfort analysis (temperature and draft risk).

Several design tools are discussed in this report. These differ from simulation tools in that they are intended to be used in the initial stages of the design process of buildings. Design tools are intended to be quick and easy to use, so that the effects of changes in the design can be quickly assessed. The two types of tool complement each other, with simulation generally being used later in the design process. In general, the simpler the model, the less input data that will be required. Moreover, the quality of the results will also reflect the quality of the input data, as well as the results being influenced by assumptions made in the model itself.

Evaluation and measurements

It is important to have confidence that ventilation models reproduce measured results ("the real world") with reasonable accuracy. So, evaluation exercises have been undertaken to compare the results predicted by the models with experiments. (This is sometimes known as 'validation'.) Short accounts are given in Section 2.6 of these exercises, conducted for COMIS and also the LBL model. Moreover, Harrje and Piggins (1991) provide reporting guidelines for the results of measurements of air flows and related factors in buildings. If this format is followed, then adequate measurement results should be available to provide valuable input data for modelling studies based on those measurements.

Related work

The International Energy Agency's Energy Conservation in Buildings and Community Systems Programme Annex 23 has carried out extensive work of direct relevance to this subject. This Annex was concerned with "Multizone Airflow Modelling (COMIS)". The product of this Annex, the COMIS model, is included among the applicable models described in Section 5.

1.1   Single and multi-zone models

In some of the simpler ventilation models, buildings are treated as single zones. The internal air is assumed to be at a single uniform temperature. These types of model can be configured quickly and the numerical solution procedures are also able to operate quickly. However, this speed of use and operation is at the expense of the detail provided in the results, which are fairly crude. A schematic representation of a building treated as a single zone is given in Figure 1(a). But, no allowance can then be made for internal walls or floors and the consequent air leakage paths and other openings that are found in them in practice.

Multi-zone models allow the division of a building into separate zones, which may be at internal pressures and temperatures distinct from one another. Their solution can provide detailed results about the mass flow rates through all air flow paths, but solution usually takes longer than for single zone models. Figure 1(b) is a schematic representation of a multi-zone building. Both single and multi-zone models depend on 'mass balance' of the air flows through the building. (Another possible approach, which may be desirable when designing to obtain prescribed flow rates, is outlined in CIBSE, 1997, the 'inverse sizing' model and is also expanded by Axley, 1998. The appropriate sizes of natural ventilation openings to achieve these flow rates may then be found with this technique.)
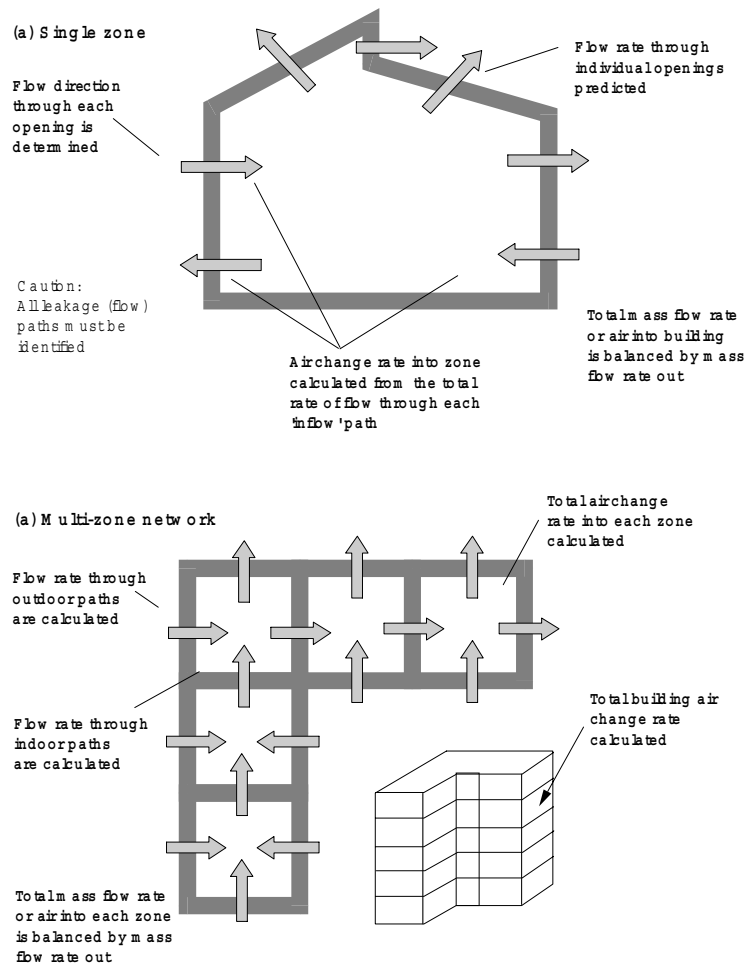
Figure 1 Single and multi-zone flow path networks (from Liddament, 1996)

1.2   Ventilation models and building thermal simulation tools

Air change itself is partially driven by thermal conditions, so it is not always possible to consider ventilation models, based on mass balances, in isolation from thermal models, which are based on energy balances. So, it may be required that the two types of model are 'coupled together'. A brief account of different approaches to coupled thermal and air flow modelling is presented in Section 8.1, together with an overview of the required input data.

Thermal models, related to ventilation models, consider heat transport into and out of buildings. They are able to take account of heat storage in and transfer through the building fabric, solar gains, and other heat gains or losses. Therefore, in isolation, they will not provide solutions to questions concerning indoor air quality, or completely address thermal comfort issues. As part of the input data for thermal models, it is sometimes assumed that all air flow rates are constant, i.e. they do not change over time. In reality, air flow rates in naturally ventilated or leaky buildings may change considerably over time. So, assuming constant air flow rates may then conceal the actual thermal behaviour of such a building.

Examples of thermal simulation tools are PASSPORT Plus and SUMMER, but there are many others. These are included here as examples of this class of simulation tool, which include some elements of ventilation modelling. A full discussion of this type of model is outside the scope of this report. However, these models have been examined in detail by IEA

ECBCS Annex 21, "Calculation of Energy and Environmental Performance of Buildings" (Månsson, 1998).

Ventilation models and night cooling

Night cooling is a ventilation strategy sometimes adopted in sufficiently dry climates to avoid (or at least reduce) the need for active cooling, by using night-time air to cool the building fabric. Sensible cooling of incoming air is then achieved during the day-time, as the building reaches thermal equilibrium with its environment. Certain ventilation models, for example the simplified tool NiteCool, are particularly well-suited to the calculation of the effect of night cooling on daytime indoor temperatures. This is because the models themselves allow heat storage in the building fabric and solar gains to be taken into account.

1.3   Availability of ventilation models

Certain ventilation models have been placed in the public domain (e.g. CONTAMW, COMIS, and AIDA) while others are available commercially (e.g. BREEZE). Only these two categories of model are considered - models developed only for 'in-house' use are not dealt with here. The emphasis is firmly on models that are generally available. Previously, Feustel and Dieris (1991) have undertaken an extensive survey of 50 multi-zone air flow models, of which about two fifths were available either commercially or in the public domain.

1.4   The influence of model users

It is a challenge for model users to configure models correctly, and their influence on the results obtained is potentially very significant. Input data must be correctly applied and results properly interpreted. Therefore, careful guidance is required on set-up procedures in the documentation for any model. Furthermore, users may make different interpretations of what is required to describe the same input configuration. Fürbringer et al (1996a), for example, describe user tests performed with COMIS and other ventilation models, concluding that different users may sometimes produce a wide range of results when modelling the same case.

2   Ventilation Modelling Data

2.1   Building-Related Input Data

In order to configure ventilation models, it is essential to formulate some kind of 'air flow path network'. This comprises both air leakage paths between construction elements and ventilation components linking different parts of a building with the outside air (and to each other in the case of multi-zone flow models). Typically air leakage paths are assigned according to the construction elements of a building. Before one may proceed with devising an airflow path network, a number of characteristics of the building must first be established. These are:

- the whole building airtightness, or
- individual building component airtightness, and,
- the size and locations of designed ventilation provisions, and
- characteristics of installed ventilation fans (if any),
- wind pressure coefficient (c_p) data.

Subsequent sections will examine these in more detail. *However, it is important to stress that airtightness characteristics alone are not sufficient to determine the ventilation rate. Such information must be combined with knowledge about the driving forces of air change, i.e. wind, temperature difference, and mechanical ventilation, to evaluate actual ventilation rates. This is the role of ventilation modelling.*

It is essential to carefully formulate the air flow path network of the modelled building, even before using a graphically-based input procedure. By using a clear description of the network, the process of configuring the model becomes more straightforward. The possibilities for omissions and other errors are also reduced, by systematically identifying zones and their inter-connections with leakage paths.

In practice, judgements are needed on the specification of items such as the number and location of flow paths, leakage coefficients and exponents and wind pressure distribution. Default input data provide a useful way for programmes to become more widely accessible. However, it is still critical that users understand the meaning of the data and their implications. The ability of the user is vital in securing reliable predictions.

Whole dwelling airtightness data are available from:

- USA,
- France (plus a description of another survey of airtightness and ventilation performance),
- Netherlands.

2.1.1   Air leakage paths

- *Component data has been summarised from a variety of sources.*

Air leakage data are essential for the formulation of air flow networks, and therefore for ventilation modelling. Leakage paths can occur either within building construction elements or between them. Orme et al (1998) have summarised available data concerning air leakage paths and their characteristics, and tables of building component airtightness data can be found in Appendix E.

Only the minority of air leakage paths are isolated, easily identifiable openings, which can sometimes be appropriately modelled as 'orifice' openings. Most leakage paths are more diffusely located. In fact, flow of opposing direction may occur through different parts of the same element. It may therefore prove necessary to devise approximations to such leakages to keep the flow network simple, while still allowing a representation of the actual flow. One possibility, for example, to model extended vertical leakages would be by using two flow paths as a first approximation, one positioned at one quarter the length of the true leakage above its base level and the other at three quarters. (Note that the total leakage of the two paths combined should still equal the leakage of the original element.) This technique is sometimes used to model closed doors or windows. Certain ventilation models allow more sophisticated modelling of air flow through large vertical openings, so that two way flow through a single opening can occur.

Characteristic air flow equations

For a given applied pressure difference across an opening, the rate of air flow through it is a function of its size and geometry. Appendix E provides an overview of characteristic air flow equations commonly used to relate these quantities:

- The power law equation is an empirical expression applicable to general gaps or cracks in the building fabric. Appendix E also contains tabulated airtightness values for many building components based on this approach.
- For relatively large openings (for example, purpose-provided vents, visible gaps around service penetrations, and very ill-fitting components) the air flow can sometimes be best represented by an equivalent flow through a flat plate orifice, expressed by the orifice equation.
- Another air flow to pressure difference relationship, known as the quadratic formulation, is used in VENT, discussed in Section 5.15.

Current availability of component airtightness data

Available airtightness data for different construction elements are as follows, and measurement data exists in varying extent for each:

- windows,
- doors,
- interface of window or door frames with walls,
- wall constructions, ceilings, and floors,
- ceiling or floor to wall interfaces,
- wall to wall interfaces,
- service penetrations,
- roofing,
- fireplaces and flues, and
- trickle ventilators and vents.

Appendix E contains tables of airtightness values for different building components, collated from both published and unpublished sources.

2.1.2   Treatment of whole building airtightness data

- *Whole building data from numerous references have been summarised.*

If only an overall airtightness value is available for a building, then, in order to use that data, it would be necessary to make judgements about the distribution of the air leakage paths around the building envelope. Numerous approaches are possible, but the simplest would be

to assign a high-positioned and low-positioned leakage path to each facade, together with a roof level leakage path. The combined airtightness of these paths should be equal to the desired overall value. If more knowledge is available about any construction characteristics, then it may be possible to refine the distribution by taking into account the positions of, for example, doors and windows, and also the construction type of the walls and roof. If sufficient information is at hand concerning both the construction type and quality, then using individual component airtightness data is an option, as introduced in Section 2.1.

A technique for the prediction of building airtightness

Perera et al (1997) have devised an airtightness prediction design tool, specifically for application to large commercial buildings before construction. This was based on data contained in Orme et al (1998). The tool, currently in spreadsheet format, can be used to assess total building airtightness by specifying a minimum amount of information. Key data required to be entered by users are:

- building volume,
- surface permeable envelope area (usually walls and the roof),
- number of storeys,
- percentage of glazed wall area, and
- number of single and double external doors.

Then further information needed to identify the construction type is obtained from the user through a series of 'yes/no' check boxes, including:

- composition of walls,
- whether windows and doors are weather-stripped or not, and
- whether joints are caulked.

2.1.3   Wind pressure coefficients

- A summary of wind pressure coefficient measurements from 50 references has been made.
- Detailed measurements from the 'Tånga School' are also presented.

The shape of a building and the degree of wind shielding by other structures (or vegetation) together determine the surface pressures due to wind forces for any given wind direction. These surface pressures will vary with the wind direction. Wind pressure coefficients are dimensionless coefficients that allow the pressure distribution due to the wind pressure acting on a building to be reconstructed for all wind speeds. They are specific to a particular building, with given wind shielding, and for a specified wind direction. Furthermore, it is important to realise that they are always relative to wind velocity at a stated reference height in the undisturbed air stream.

This is an important area in which model users may experience difficulties in identifying suitable input data for unusual building shapes. Previously Allen (1984) and AIVC (1984) have considered wind pressure data requirements for air infiltration and ventilation calculations. In fact, Orme et al (1998) present default values of wind pressure coefficients for simple building shapes (i.e. low rise with pitched roof, high rise with flat roof, and high rise with flat roof and central lightwell.) Examples of these are presented within Appendix F. Furthermore, Knoll et al (1995) have developed a prediction technique for wind pressure coefficients which takes into account the effects of building form and surrounding shielding (see Section 2.6.1), whilst Walker and Wilson (1994) have produced a method for correcting

known wind pressure coefficients for a building at an open site to a site shielded by other buildings. For unusual building geometries, it is usually necessary to use either wind tunnel experiments or computational fluid dynamics (CFD) to determine the pressure coefficients.

Wind pressure coefficient generation tools

The determination of wind pressure coefficients for use in ventilation models may sometimes be problematic, except for very simple building shapes in isolated terrain. (Coefficients for simple shapes can often be found from tables e.g. Orme et al, 1998.) In order to try to provide more assistance in determining suitable values, Knoll et al (1995) have produced a computer-based tool to generate them. Straightforward input of the co-ordinates and orientations of buildings and surrounding obstacles allows the automatic calculation of wind pressure coefficients on facades and roofs of block shaped buildings. This may avoid the need for wind tunnel measurements to determine these coefficients for use in ventilation models.

Additionally, Grosso (1991) has produced a parametrical model of wind pressure distribution around buildings. This work was extended (Grosso et al, 1994) to formulate a parametrical model of wind pressure distribution on flat and tilted roofs. The latest version of the model, CPCALC+, is included in Allard (1998). It predicts wind pressure coefficients for simple building geometries with either flat or sloped roofs. A number of input parameters may be varied, including wind direction, terrain roughness, density of surrounding buildings, height relative to the surrounding buildings, and the building geometry itself, including dimensions of the walls and roof.

2.2   Meteorological Data

Meteorological data summarised here are:

- London, UK - coincidence of wind speed, direction and air temperature,
- EC Test Reference Years (principally for thermal calculations),
- a compression technique for meteorological data,
- driving forces in several European locations from the EU NatVent project,
- a condensed ventilation weather year for the Netherlands, and
- data collated through the IEA ECBCS Annex 27 project.

2.2.1   ISWO and other datasets

The most comprehensive low cost meteorological database available at present is the International Surface Weather Observations (ISWO) dataset (from NCDC), supplied on 5 CD's. The dataset includes hourly and/or synoptic (every three hours) climatic data for approximately 1500 stations world-wide for 1982-1997 (ISWO station list). It provides worldwide coverage of city locations, including U.S. stations. The elements included are:

- total sky cover,
- cloud types by layer,
- lowest cloud height,
- ceiling height,
- temperature and dew point,
- sea level pressure,
- altimeter setting,
- wind direction, speed, and gust,
- visibility,
- three-hour pressure change,
- present weather,

- past weather.

However, it does not include solar radiation data. The data and inventory files are organized with directories by state for the U.S.A. and by WMO (World Meteorological Organisation) block for the rest of the world. Each data file contains data for one station-year. The data format is shown here.

A description of a less extensive but summarised data, with monthly and annual summaries for 800 stations world-wide is contained on the Engineering Weather Data CD-ROM (data sample). The Meteonorm package covers a similar, but not identical range of data for Europe. A summary of weather data across the USA, including infiltration degree day data was produced during the Minnesota High Radon Project by LBNL. Also, the following links may be of interest:

- a study of solar radiation across Europe,
- a wind data generator for various terrains, and
- a weather data format converter for the COMIS programme (see Section 3.7).

2.2.2   Meteorological data for ventilation modelling

The minimum requirements for ventilation modelling are site wind velocity (speed and direction) and external temperature. Thermal modelling (see Section 5.1) also requires solar radiation data to allow solar heat gains to be calculated. Often they are in the form of 'hourly' weather data files (i.e. measured data is taken to be representative of the whole hour, mostly achieved by averaging values over the hour). However, see Section 2.2.2, concerning conversion of wind velocities and urban temperature data.

There are two principal natural driving forces which affect air infiltration rates and ventilation rates through purpose-provided openings. These are wind pressure on buildings and temperature differences between the indoor and outdoor environments.

Many models are able to take into account not only steady state conditions, but also varying meteorological conditions (for instance using 'hourly' weather data files as inputs) and other occupant-related time dependent 'schedules'. It is under these circumstances that the time needed for solution sometimes becomes appreciable, especially for large numbers of runs, such as would be needed to simulate an entire heating season. Additionally, meteorological data should be obtained from a measurement site as close as possible to the building location.

2.2.3   Wind and temperature in urban environments

Measurements of air temperature are often made at meteorological stations, which can be located at considerable distance from the building location. Furthermore, these stations are often also positioned in rural (or semi-rural) terrain, and consequently may record lower temperatures than may be found in an urban environment. This 'urban heat island' effect is most pronounced at lower wind speeds and with cloudless skies. In fact, wind limits development of the heat island, due to its cooling capability. Above a certain speed, the effect is cancelled (Allard, 1998). (For urban populations of one million, this value is approximately 9 m/s, and for one hundred thousand, it is about 5 m/s.)

As part of the POLIS Project (within European Commission DGXII Joule Programme), the Group of Building Environmental Studies at the University of Athens are making extensive measurements, in Athens, Greece, to monitor this effect. (In fact, twenty temperature and humidity stations have been installed in and around the city, which have been recording

hourly data since June, 1996.) Preliminary results from these measurements indicate that daytime temperature differences between urban and suburban stations range from 5 °C to 17 °C.

The urban canopy is the atmospheric layer that extends from ground level to above roof level in the urban area. (See for example, Allard, 1998.) A reduction of 20% to 30% is often observed in the average wind speed within this layer, from suburban to urban areas, and with the turbulence intensity increased by 50% to 100%. Moreover, in lighter wind conditions there is an increase in urban wind speeds due to pressure gradients created by the urban heat island effect. Warm air rising in the heated centre causes reduced pressure and so is replaced by accelerated air from the surrounding region. The presence of water bodies and elevated terrain may also have significant impact on urban wind flow. The 'urban boundary layer' is situated above the canopy layer, increasing from the upwind direction and over the city.

Santamouris et al (1998) report on measurements made in ten 'urban street canyons', located in Athens, Greece, together with ventilation rate modelling results based on those measurements. They conclude that the flow reduction may be up to ten times that corresponding to undisturbed ambient wind conditions. This is an example of the necessity of selecting appropriate meteorological input data, especially wind velocity. Also, their account of the experiments describes stable flow structures most usually found within such canyons: when the prevailing wind direction is approximately normal to the long axis of the street canyon, the observed wind behaviour is strongly influenced by the ratio of the height of the surrounding buildings, H, to their separation (the canyon width), W. (This assumes that the building heights are about equal.) When W is greater than about 20H, there is virtually no interaction between the building wakes. If W is less than this, then at an intermediate building separation, there are strong secondary downward flows in the canyon. At a critical separation distance lower still, a stable circulatory vortex system forms in the canyon. This is caused by a 'skimming' shear layer at roof height, in which the bulk of the flow does not enter the canyon. This skimming regime is the most common one in urban areas.

2.2.4   *Conversion of rural to urban meteorological data*

Wind velocity data

There are two areas about which users of ventilation models must be careful concerning wind-related input data. The first is the wind velocity itself, as discussed in this section, and the second is the effect that building geometry and nearby shielding have on the pressure distribution that wind causes on building surfaces, which has been discussed previously in Section 2.3.

The treatment of wind-related data is an important consideration in ventilation modelling. Meteorological data concerning wind velocities are sometimes only available in the form of measurements made at a significant distance from the site of interest, typically at airports or other open sites. A conversion must then be made from these velocities measured at a given reference height (10 m above ground level is common) to velocities at the building location at another reference height, taking into account the effect of the intervening terrain. The reference height at the building location is customarily taken to be the eaves (or roof) height of the building. The usual conversions rely on assuming that a stable atmospheric boundary layer is present between the measurement site and the building location. The wind pressure acting on a building is proportional to the square of the wind speed, so it is especially important that the correct value is used.

Since the value of wind speed is squared in the wind pressure equation, the use of raw data from a meteorological station can result in a significant calculation error. This is a common fault in the application of network methods. Ideally wind data should be obtained from a local site which shares similar topography (e.g. not separated by isolating hills). An approximate correction equation to account for height difference and intervening terrain is given below. BS5925:1991 (British Standards Institution) suggests that in order to estimate wind speed in a particular terrain from Meteorological Office wind speed, U_m, the following conversion may be used:

$$U_z = U_m k z^a \; ,$$

where

U_z (m·s^{-1}) is building height wind speed,

U_m (m·s^{-1}) is wind speed measured in open country at a standard height of 10 m,

z (m) is building height, and

k, a are constants dependent on terrain (see Table 2).

The following conversion method is adopted in the LBL Effective Leakage Area Model (Appendix C):

$$U_z = U_{z'} \frac{\alpha (z/10)^\gamma}{\alpha'(z'/10)^{\gamma'}} \; ,$$

where

U_z (m·s^{-1}) is required site wind speed at level z (m) above ground,

$U_{z'}$ (m·s^{-1}) is measured wind speed at level z' (m) above ground,

α', γ' are constants dependent on offsite terrain conditions (see Table 3), and

α, γ are constants dependent on onsite terrain conditions (see Table 3).

Table 2 Terrain coefficients for use in BS5925 wind speed conversion

Terrain coefficients	k	a
Open flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

Table 3 Onsite and offsite terrain-dependent constants used in the LBL Model

Terrain description	γ or γ'	α or α'
Ocean or other body of water with at least 5 km of unrestricted expanse	0.10	1.30
Flat terrain with some isolated obstacles, e.g. buildings or trees well-separated from each other	0.15	1.00
Rural areas with low buildings, trees, etc.	0.20	0.85
Urban, industrial or forest areas	0.25	0.67
Centre of large city, e.g. Manhattan	0.35	0.47

Temperature data

Kimani (1998) has undertaken a survey of published algorithms for converting meteorological site weather data to urban locations, with particular emphasis on temperature. At present there appear to be few generally applicable simple algorithms, due to the underlying complexity of meteorological processes. So, any modelling of buildings located in urban areas relying on the use of rural or sub-urban meteorological data should be treated with particular care. His conclusions include that changes in the strength of the urban heat island effect at different times of day should be taken into account in temperature conversions.

In addition, it is commented that Lennon and Turner (1995) have developed a prediction method for interpolating between temperature measurements made at meteorological stations. Their method takes account of altitude, distance from the sea, slope and topographic roughness. Also, their predicted temperatures are calculated at real altitudes. However, their procedure does not take account of urban heat island effects.

2.2.5   The properties of moist air (psychrometric data)

There are three principal factors that determine the density of air. These are the air temperature, absolute pressure, and humidity, and any differences in these between the internal and external air will result in a driving force that causes air flow through a building. An appreciation of the variability of air density is also necessary because a conversion is often needed to convert air tightness characteristics of building components, which are generally quoted in terms of volume flow rates, to mass flow rates. In fact, this may take place automatically within a ventilation model. Psychrometric charts (e.g. CIBSE, 1986), may be used to relate how the properties of air change with varying temperature and humidity. These conversions may also be automatically handled by a model. For example, air at 5 °C and 90% relative humidity has a moisture content of 4.9 g·kg^{-1} and density 1.26 kg·m^{-3}, whereas air at 20 °C with the same moisture content has a relative humidity of 33% and density of 1.19 kg·m^{-3}.

2.3   Ventilation Provisions

Pressure loss factors ('K-values') for ductwork and other system components and characteristics of pressure sources (fans) are widely available and published. (See, for instance, ASHRAE, 1997, or CIBSE, 1986.)

2.4   Occupancy Data

Available occupant-related data are:
- default residential occupancy profiles (from the Annex 27 project),
- occupant behaviour (Annex 20) (Roulet et al, 1991), and
- an extensive occupant-related summary (42 references covering The Netherlands, United Kingdom, Australia, Belgium, France, Germany, Hong Kong, Hungary, Japan, Switzerland, USA).

Typical occupancy schedules will be dependent on building type. In particular, Annex 27 (1996) includes schedules for occupants and associated pollutant generation schedules, for a variety of dwelling types. Furthermore, Dubrul (1988) highlights work undertaken concerning occupant behaviour with respect to ventilation in dwellings. An example of the influence that occupants may have over ventilation is shown in Figure 2. The percentage of windows that were recorded to be open over a range of external temperatures in both sunny and cloudy conditions for a number of dwellings can be seen in this Figure. This may have a significant impact on the ventilation rate. In addition, Figure 3 presents a nomograph for determining

typical heating season ventilation rates in dwellings (Dubrul, 1988), showing the influence that window opening may have on the total air change rate.
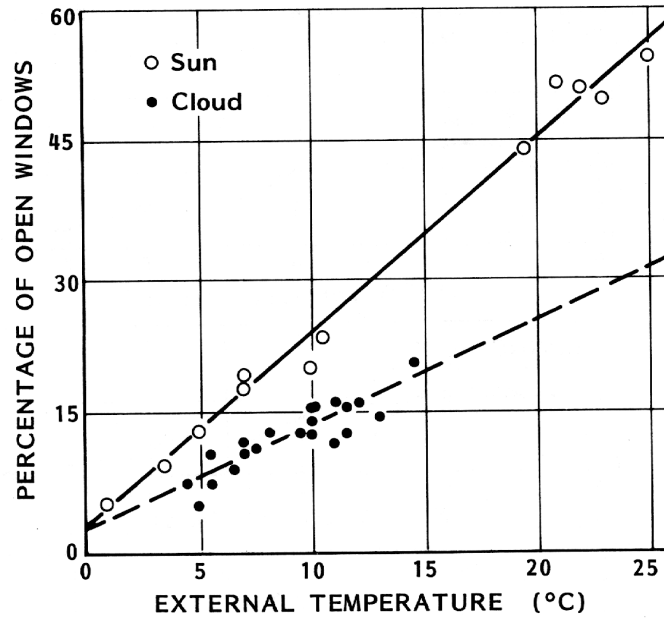
Figure 2 Window opening as a function of outdoor temperature and sunshine (from Dubrul, 1988)
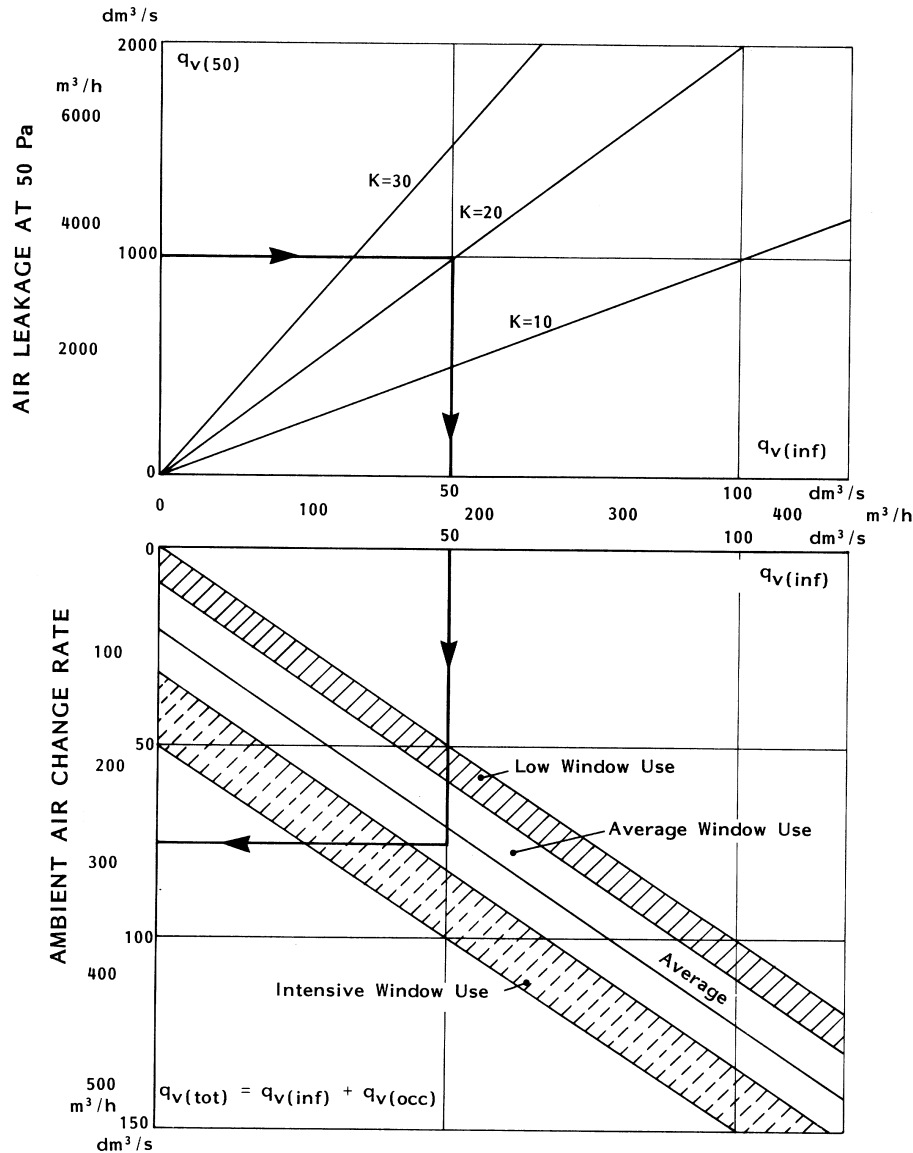
Figure 3 Nomograph for determining typical heating season ventilation rates in dwellings (from Dubrul, 1988)

2.5   Pollutant Data

- *211 references covering pollutant measurements and guidelines* have been summarised. Pollutant (contaminant) models make use of the air flow rates calculated as solutions to the air flow network when it is subject to certain driving forces. By equating pollutant source and sink strengths in each zone with pollutant gains from and losses to other zones (including the outside), the concentration in each zone is determined after a given time period, often with the assumption of uniform mixing. (In other words, conservation of mass of each pollutant leads to a particular concentration.) Occupant exposures can then be evaluated.

In pollutant transfer models, it is necessary to specify the strengths of sources and sinks at scheduled times. (Some models also allow sorption and re-emission, or decay to be

considered.) This information, when combined by the model with ventilation rates, is used to calculate pollutant concentrations in each zone after a given time interval. Certain models are now able to conveniently handle more than one pollutant at the same time, which removes the need for ventilation rates to be re-calculated each time, and hence reduces computation time.

2.5.1   Sources of Pollutants
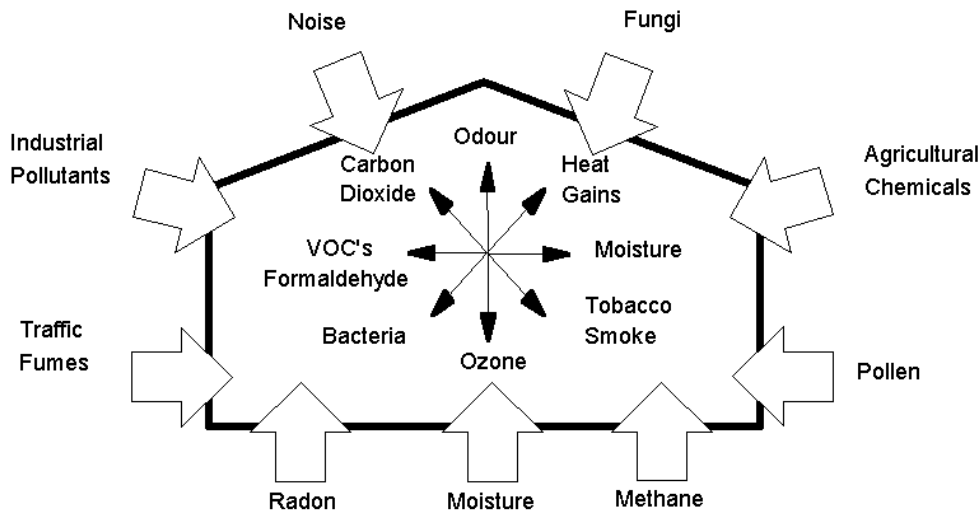
2.6   Evaluation Exercises

Model evaluation data available here are:
- the LESO dataset (an office building, Switzerland),
- the Bang & Olufsen building (an office building, Denmark),
- the ELA dataset (an atrium, Norway), and
- the de Montford dataset (an auditorium, UK),
- the Tånga dataset with wind pressure coefficient data (a school building, Sweden),
- the BRANZ dataset (single family houses, New Zealand),
- the SP dataset (apartments and single family houses, Sweden),
- the Alberta dataset (test houses, Canada),
- the Cauberg-Huygen dataset (low energy houses, the Netherlands), and
- the MIT dataset (displacement ventilation, suitable for CFD, USA).

Evaluation of a ventilation model is defined here to mean a comparison of predicted results from the model with measured data. (Sometimes this is known as 'validation'.) The purpose of evaluation is to confirm that the model results accurately reflect physical behaviour. This requires very well-documented data obtained from measurements made on real buildings, including the results themselves and also the characteristics of the studied building. Reporting guidelines for these kinds of results are provided in Harrje and Piggins (1991). As an example of this type of data set, Fürbringer et al (1989, 1990) describe the LESO office building, together with measured air flow rates and associated meteorological data. Brief details of evaluation exercises for COMIS and the LBL model are given in Sections 2.6.1 and 2.6.2 respectively.

2.6.1   COMIS

As part of the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems (ECBCS) Programme Annex 23, an evaluation of their multi-zone air

flow model, COMIS, was carried out (Fürbringer et al, 1996). The extent of this evaluation consisted of more than 50 comparisons with known exact solutions of the airflow network. It also involved inter-model comparisons with 14 other simulation codes, and an extensive experimental comparison involving measurement results from 9 monitored buildings.

2.6.2 LBL model

In a study of 10 air infiltration models, Liddament and Allen (1983) reported on the comparison of a number of air infiltration models, including the LBL model. Measurement results from 3 buildings, under a range of meteorological conditions, were compared with predicted results from the models. It was found that, for the LBL model, in most cases examined, the predicted air change rates for the buildings were within ±25% of the measured value.

2.7 Additional Data Considerations

It is useful to briefly refer to certain other types of data:

- Thermal transmittance data ('U-values') are widely available and published for an extensive range of construction elements. (See, for instance, ASHRAE, 1997 or CIBSE, 1986.)
- Data related to energy use.

Although they are not essential for calculations of ventilation rate, it is desirable to consider certain equipment-related data, in order to support calculations of delivered energy use. Examples of these include:

- furnace or boiler efficiencies,
- fan power characteristics (see Jagemar, 1996, for typical values of specific fan power),
- coefficients of performance for heat pumps or coefficients of refrigeration for cooling equipment, and
- efficiency of heat recovery devices.

Often, the above may be obtained from manufacturers' data sheets for known models.

2.7.1 Caution with summary output data

Problems and inconsistencies may not be immediately apparent from summary output data. This may be the case, for instance, when examining whole heating season simulations. So, it is advisable to make a number of 'spot checks' of instantaneous flow rates through defined leakage paths.

2.7.2 Sensitivity analysis

It is important to understand quantitatively how uncertainties in input data propagate through models, influencing confidence in the numerical results. Fürbringer (1996) gives an introduction to this significant topic, known as *sensitivity analysis*. Moreover, interactions between different input parameters can have unexpected consequences, so varying a single parameter in isolation (the 'one-at-a-time' approach), may not reveal sufficient information about the output errors. A proper treatment requires a carefully designed numerical experiment (involving a number of simulations), the outcome of which will reveal which input parameters have most influence on the results for a given model configuration.

3 Model Descriptions

The models considered in this report are described below. Tables 4 (i) to (iii) summarise their features. The use of these models is not exclusive. Each model may be best suited to different

applications, and so it may be most advantageous to simulate the same situation using a number of models, which may individually highlight important results. For example, consider simplified models, which can produce results more quickly than other model types (although sometimes at the expense of detail and accuracy). If a large number of cases are to be investigated, perhaps for an optimisation problem, then initial studies may be performed rapidly. More complex models may then be applied to cases of particular interest. If two or more models produce similar answers based on input data that are as identical as possible, then the user may be reasonably confident in the results. Of course, this confidence should be restricted by the limitations of the models themselves, as well as the reliability of the input data. Contact details for obtaining the models are presented in Appendix A.

Table 4(i) Summary of model features and characteristics

	AIDA	AIM-2	AIOLOS	BREEZE	CEN	
					Explct	Implct
Simplified	No	Yes	No	No	Yes	No
Single zone/ Multi-zone	Single	Single	Multi-	Multi-	Single	
Modelling of air handling systems	Fixed air flows	Not applicable	Not applicable	Partial	Fixed air flows	
Component airtightness database	No	Not applicable	No	No	No	
Airtightness data format	Power law	Equivalent leakage area	Orifice (large vertical), power law (cracks)	Power law or quadratic	Power law	
Two-way flow modelled in large openings	No	No	Yes	Yes	No	
Default wind pressure coeffs. - calculated - database	No	Simplified	Yes Yes	No	(Yes)	
Pollutant generation schedules	Not applicable	Not applicable	Not applicable	(Yes)	Not applicable	
Occupancy schedules	No	No	No	No	No	
Opening schedules	No	No	Yes	(Yes)	No	
Long term meteorological data input files	No	No	Yes	(Yes)	No	
Type of user interface	Mini-spreadsheet MS-Windows™	Paper based	Menu MS-Windows™	Graphical DOS	Paper based	Algor-ithm only
Output format	Numerical	Numerical	Numerical + graphical	Numerical + graphical	Paper based	Algor-ithm only
Availability	Public domain	Public domain	Commercial	Commercial	Public domain	

Table 4(ii) Summary of model features and characteristics

	CIBSE	COMIS	CONTAMW	LBL	NatVent®
Simplified Single zone/ Multi-zone	Yes Single	No Multi-	No Multi-	Yes Single	Yes Single
Modelling of air handling systems	Not applicable	Yes	Yes	Not applicable	Not applicable
Component airtightness database	Not applicable	User defined	User defined	Not applicable	Not applicable
Airtightness data format	Orifice equation	Power law or quadratic	Power law or quadratic	Effective leakage area	Equivalent leakage area
Two-way flow modelled in large openings	No	Yes	Yes	No	No
Default wind pressure coeffs. - calculated - database	No	Yes	Yes	Simplified	Simplified
Pollutant generation schedules	Not applicable	Yes	Yes	Not applicable	Not applicable
Occupancy schedules	Not applicable	Yes	Yes	No	Yes
Opening schedule	No	Yes	Yes	No	No
Long term meteorological data input files	No	Yes	Yes	No	Yes
Type of user interface	Paper based	Graphical MS-Windows™	Graphical MS-Windows™	Paper based	Menu MS-Windows™
Output format	Paper based	Numerical	Numerical and graphical	Numerical	Graphical
Availability	Public domain	Eventually commercial ?	Public domain	Public domain	Commercial

Table 4(iii) Summary of model features and characteristics

	NatVent® NaVIAQ	NiteCool	PASSPORT Plus	Summer Build.	Summer Tech.	VENT
Simplified	Yes	Yes	No	Yes	No	Yes
Single zone/ Multi-zone	Multi-	Single	Multi-	Single	Multi-	Single
Modelling of air handling systems	Not applicable	Fixed air flows	Fixed air flows	Not applicable		Fixed air flows
Component airtightness database	Not applicable	Not applicable	No	No		No
Airtightness data format	Not applicable	Opening area	Opening area	Opening dimensions	Opening + crack dimensions	Quadratic
Two-way flow modelled in large openings	No	No	Yes	No	Yes	No
Default wind pressure coeffs. - calculated - database	Simplified	Yes	No	No		No
Pollutant generation schedules	(Yes)	Not applicable	Not applicable	Not applicable		Not applicable
Occupancy schedules	No	Some	Yes	No		No
Opening schedule	Yes	Yes	Yes	Yes		No
Long term meteorological data input files	No	Summary only	Yes	Yes		No
Type of user interface	Menu MS-Windows™	Menu MS-Windows™	Menu DOS	Menu MS-Windows™		DOS
Output format	Graphical	Graphical + numerical	Numerical	Graphical + numerical		Numerical
Availability		Commercial	Commercial	Commercial		Public domain

3.1   AIDA

AIDA (Air Infiltration Development Algorithm) is a single zone model devised at the AIVC (Liddament, 1989) and is written in BASIC. The original version relies on balancing volume flow rates, although a version designed to take account of mass flow and density variations has since been produced (Palmiter, 1990). The original algorithm is presented in Appendix B of this report, together with the extension. In AIDA, the general form of the air flow path input data involves specifying a volume flow coefficient, a flow exponent, the height of the path above a reference level, and a wind pressure coefficient. It is also necessary to define both internal and external air temperatures, as well as external wind speed at the building location. The output from the model is presented in numerical form. In addition, Mobsby (1997) has developed an MS-Windows version of the programme, which is shown in Figure 4.

Figure 4 Example AIDA input and output screen

3.2   AIM-2

The Alberta Infiltration Model (AIM-2), described in Walker and Wilson (1990, 1998), enables a flue leakage characteristic to be incorporated into a simplified air infiltration model. This then allows for the significantly increased air infiltration rates often encountered when a flue is present. AIM-2 is a 'paper-based' model and therefore does not require the use of a computer. However, it may be implemented on a spreadsheet if desired in a straightforward manner, as it does not require iterative solution.

3.3   AIOLOS

The AIOLOS software has been designed for the calculation of natural ventilation air flow rates, under the framework of EC-DG XVII, ALTENER Programme. The software is described in Allard (1998) and also UoA (1997). The user interface of AIOLOS is menu-based and runs under MS-Windows. It is a multi-zone model that allows the calculation of ventilation rates through both internal and external user defined openings and cracks (air leakage paths) in the building envelope. Output from AIOLOS is either in numerical or graphical format, in the form of times series for the air flow rates through openings. Also, it contains a simple thermal model ("AIOLOS Building"), which can determine the total cooling load and the number of hours of overheating for the time period covered by the meteorological input data. In addition, it includes the capability to perform sensitivity analyses on certain input data. Figure 5 shows an example of an output screen from AIOLOS. A climatic pre-processor is available for a statistical treatment of the climatic input data. Statistical treatment of results is also a feature of the tool. AIOLOS also includes the following features:

- the CPCALC+ wind pressure coefficient generator (see Section 2.3.1),
- schedules for opening status (open/closed),
- optimisation analysis, and
- sequential coupling with AIOLOS Building (see Section 8.1).
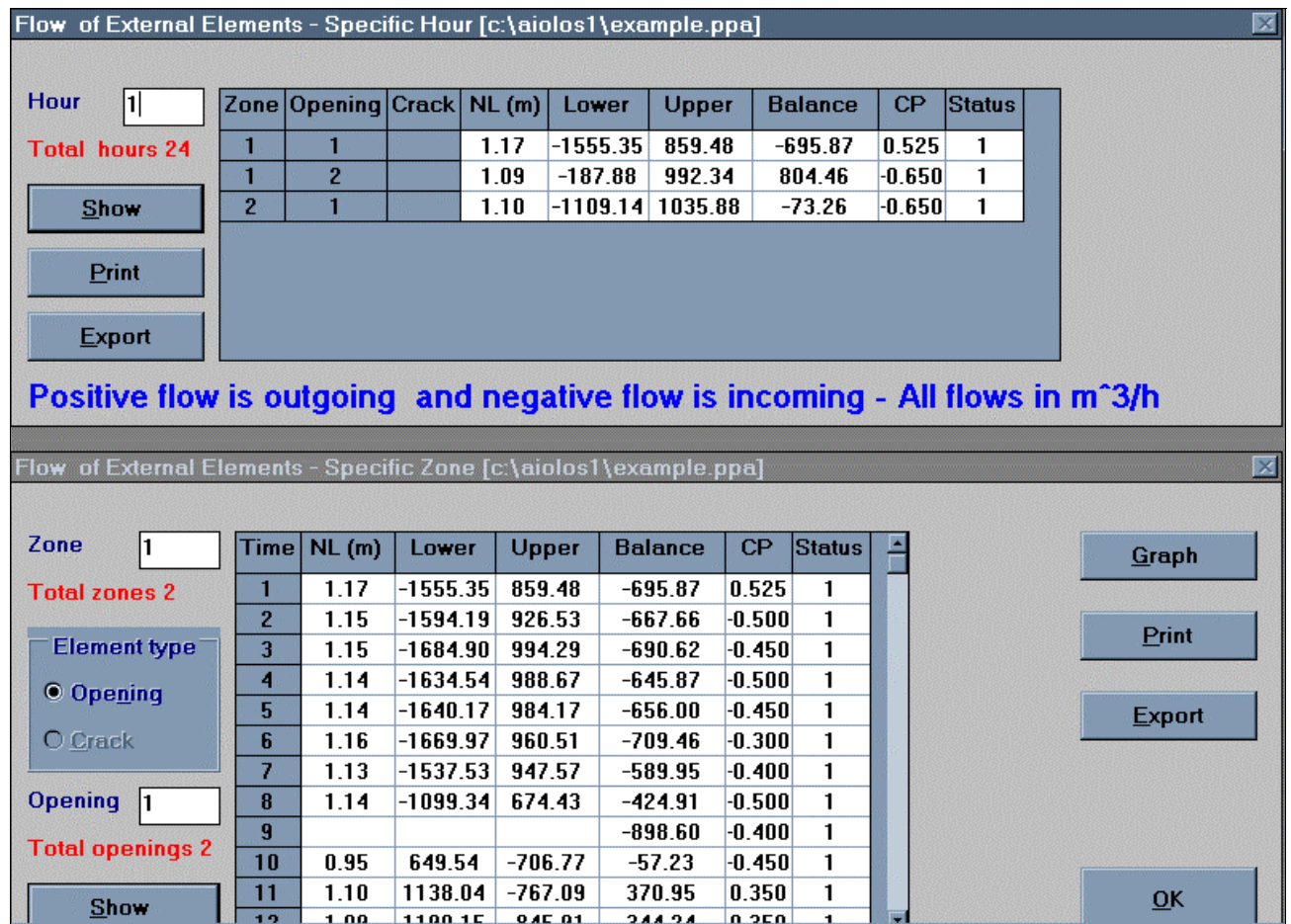
Figure 5 Example AIOLOS output screen

3.4   BREEZE

BREEZE is a PC based computer programme (running under DOS) for estimating the ventilation and inter-zonal air flows in multi-zone buildings. Definition of the zones and the air flow paths is by means of a floor based graphical representation. The User Manual describes the operation of the programme (BRE, 1994). In addition to the calculation of air flow rates, it allows pollutant concentrations to be determined (contaminant analysis). Wind pressure coefficient tables may also be defined, to allow for multiple wind directions.

Figure 6 shows a sample BREEZE input screen, in which the building is seen in plan view. The layout may be drawn with a 'sketchpad' type of entry to place walls and leakage paths. Output from BREEZE is in either graphical or numerical format. BREEZE has the facility to include a number of opening types, including simple vents, cracks, duct vents, fans, doors and windows, leakage elements, and remote connections. Two-way flow through large openings is also incorporated.
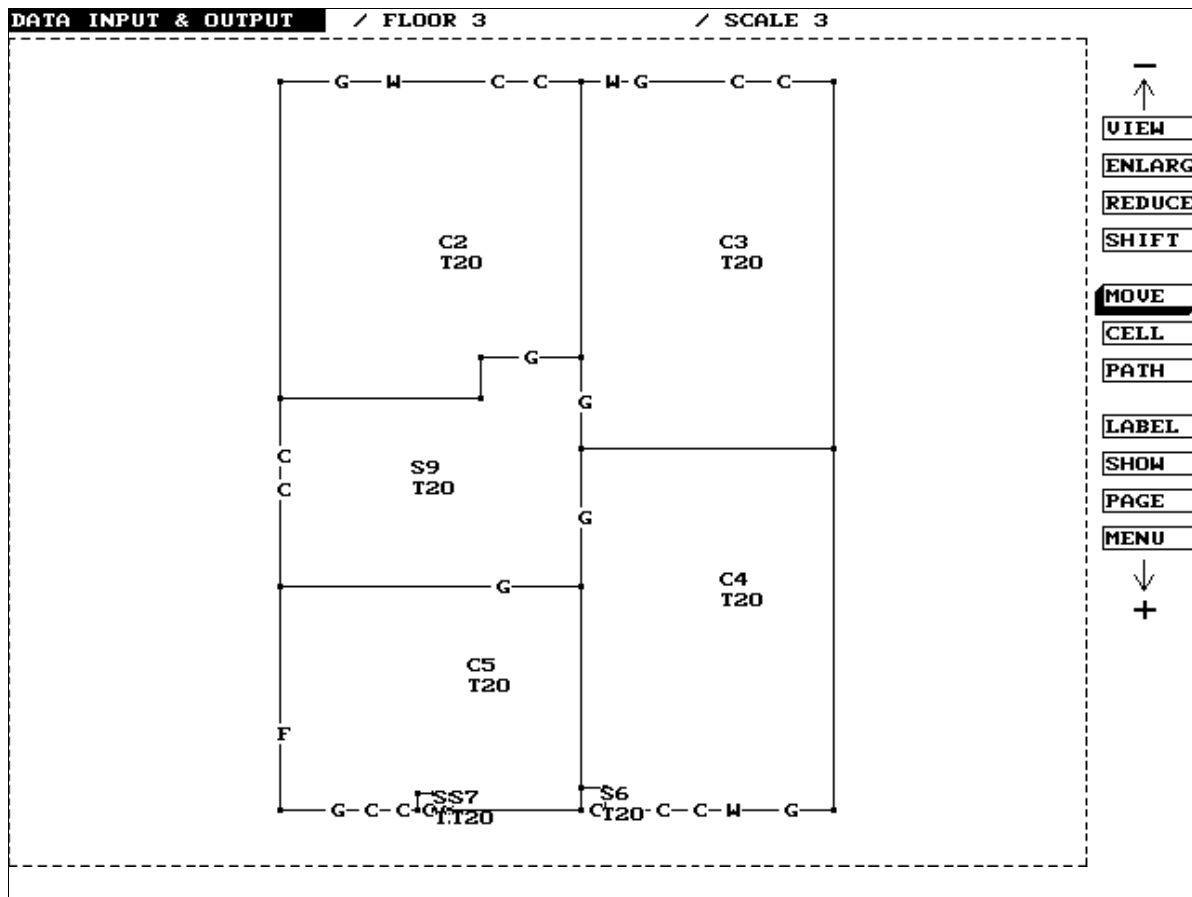
Figure 6 Example BREEZE input screen

3.5   CEN simplified calculation procedures

Cripps (1996) describes standardised techniques for estimating ventilation rates in dwellings. These have been developed by Ad Hoc Group 4 of CEN TC156 (Ventilation), Working Group 2. The motivation behind this (currently draft) standard is that different people carrying out calculations with the same input data should obtain the same result. Two versions of the calculation techniques have been produced, one explicit and the other implicit, and both based on air flow equations for a single zone model. The explicit method is designed to avoid the need for iterative solution and makes certain assumptions in order to achieve this simplicity. The implicit method, however, is based on a representation of a dwelling as a single zone at a uniform temperature. A solution with this technique is obtained iteratively. The explicit calculation procedure is paper based, while the implicit procedure must in practice be computer based.

3.6   CIBSE 'inverse sizing' model

When designing for natural ventilation, an initial estimate is necessary for the opening area that needs to be provided. Briefly, this involves using the minimum required ventilation rates and solving the 'inverse problem' of finding the minimum area of opening to achieve this. CIBSE (1997) outlines an inverse sizing design tool for this purpose. It is a paper-based tool, relying on the orifice equation (see Section 2.1.1 and Appendix E), together with expressions for natural driving forces of wind and temperature difference.

3.7   COMIS

COMIS is a multi-zone air flow model developed within IEA ECBCS Annex 23 ("Multi-Zone Modelling"). The FORTRAN code was originally developed at the Lawrence Berkeley National Laboratory, USA in the framework of the COMIS one year workshop. Significant further development of the model has taken place since then. Furthermore, the most accurate features of two building energy simulation programs, BLAST and DOE-2 are being combined into a new simulation tool, EnergyPlus. (See Crawley et al, 1998.) It is also planned to integrate COMIS as a module of this new tool.

The COMIS programme allows users to simulate air flow and pollutant patterns in multi-zone buildings. Air flow components for natural as well as mechanical ventilation can be modelled. It includes cracks, duct systems, fans, volumes, layers, vertical large openings, sources and sinks of pollutants, and pressure coefficients of facades. Facilities also exist in the programme for the definition of various 'schedules', which enable transient characteristics of the input data to be modelled. Schedules can be defined for the outdoor climate, indoor room temperatures, pollutant sources and sinks, and air flow component operation schedules, e.g. for window opening or for fan operation. Feustel and Smith (1997) describe the use of these features.

Output from the COMIS programme itself is in numerical format. It is possible to customise the output content so that only quantities of interest are presented. User interfaces for input and output processing are available for PC, for both DOS and MS-WINDOWS. Additionally, a graphical user interface, IISiBat, has also been developed for COMIS. An example input screen for IISiBat is shown in Figure 7.

3.8   CONTAMW

CONTAMW (Dols et al, 2000) is a multi-zone air flow and contaminant transfer model. It is accessed by means of a graphical user interface, that allows entry of the input data and provides a display of the output data. CONTAMW is updated as part of an on-going process. Output from CONTAMW is in either graphical or numerical format. Figure 8 illustrates a typical CONTAMW graphical output screen, with the building shown in plan view. As can be seen in Figure 8, the air flow rates are represented at each leakage path using a vector, indicating both the magnitude and the direction of the flow (which can either be into or out from each zone). The input screen has a similar format, except that only zones and leakage paths are shown. Many characteristics can be assigned in detail to the building, with a number of menus accessible at a relevant location on the floor plan. Duct systems may also be drawn and simulated with this model. Another feature is that exposure of occupants to pollutants may be determined as they move among the different zones in a building, for up to one simulated year.
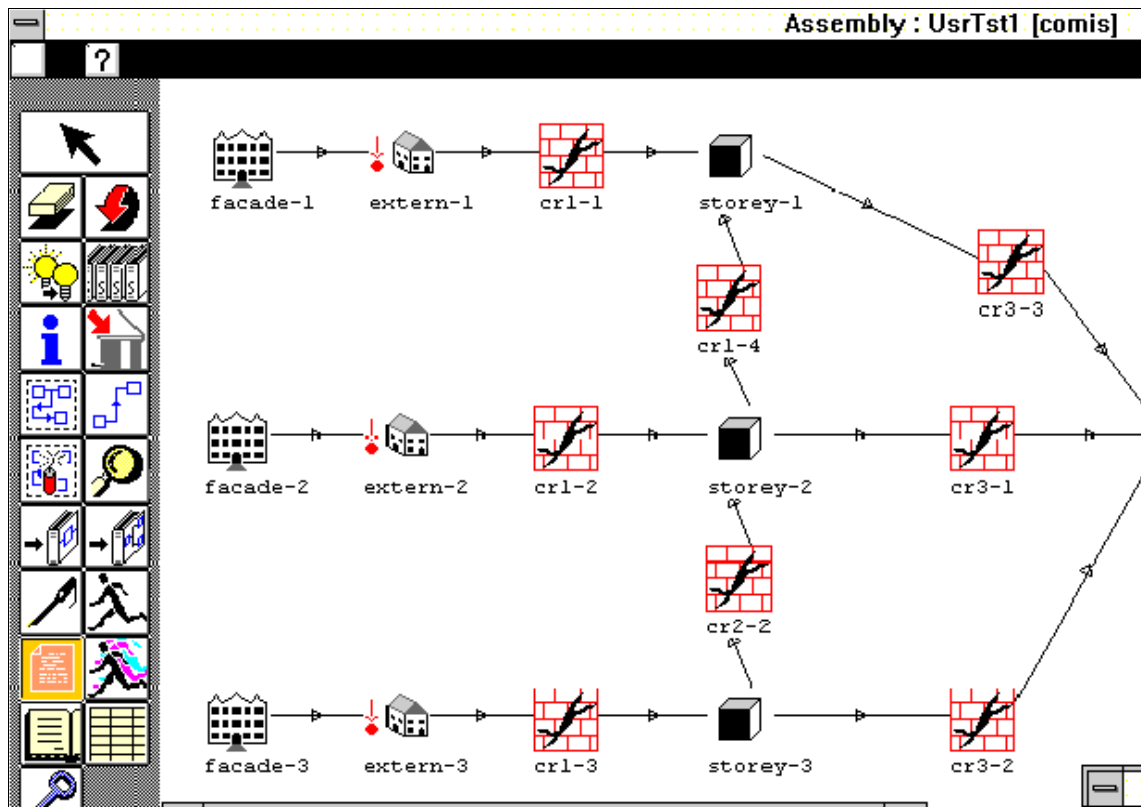
Figure 7 IISiBat Interface for COMIS - example input screen
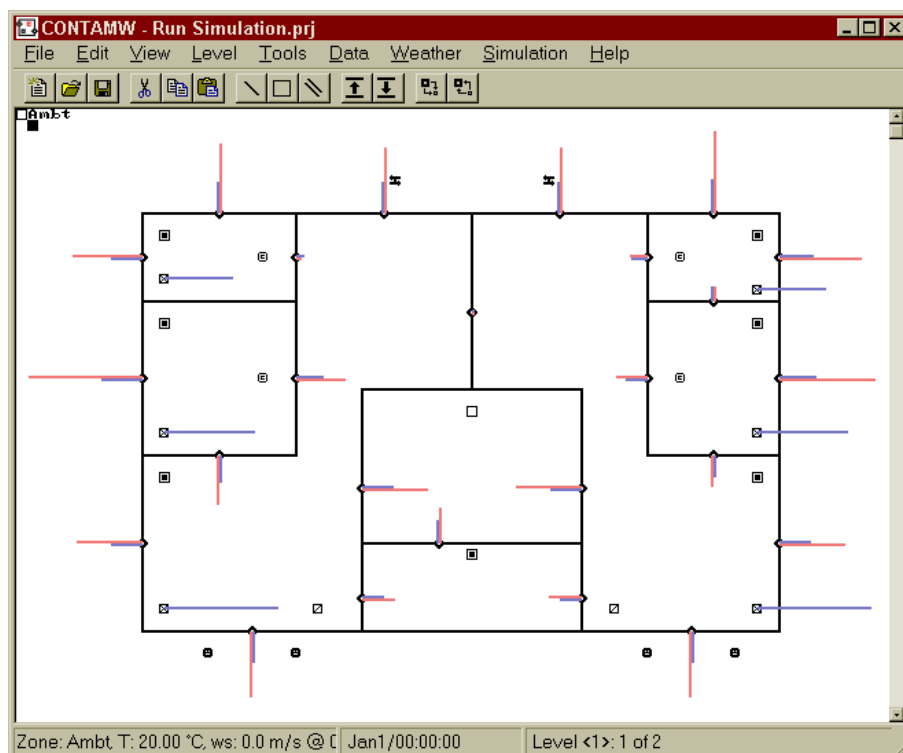
Figure 8 Example CONTAMW output screen

3.9 LBL

The LBL (Lawrence Berkeley Laboratory) model is a simplified single zone model, developed by Sherman and Grimsrud (1980). By a careful choice of tabulated input parameters, the model explicitly calculates an estimated air infiltration rate. A description of the model and its algorithm is included in Appendix C of this report. The LBL model does not require iterative solution, and is therefore suitable as a 'paper-based' model (or, of course, as a computer-based model if required). Figure 9, based on the LBL model, gives a graphical method for calculating air infiltration. (The notation used in Figure 9 is explained in Appendix C.)
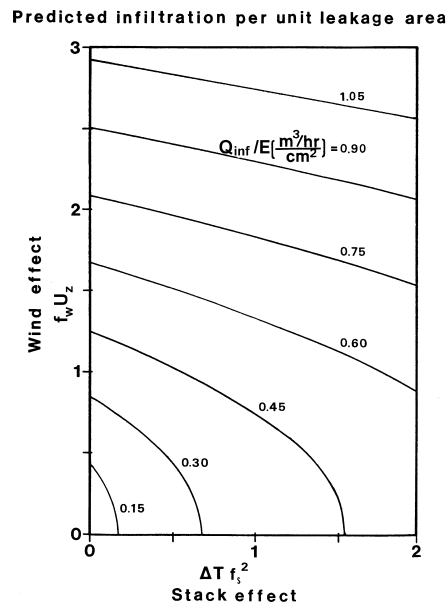
Figure 9 Predicted infiltration per unit leakage area based on the LBL model (from Sherman and Grimsrud, 1980)

3.10 LESOCOOL

LESOCOOL is a computer programme for the evaluation of the risk of overheating and the potential of cooling. It provides a simplified interface for this purpose. The interface is shown in Figure 10.
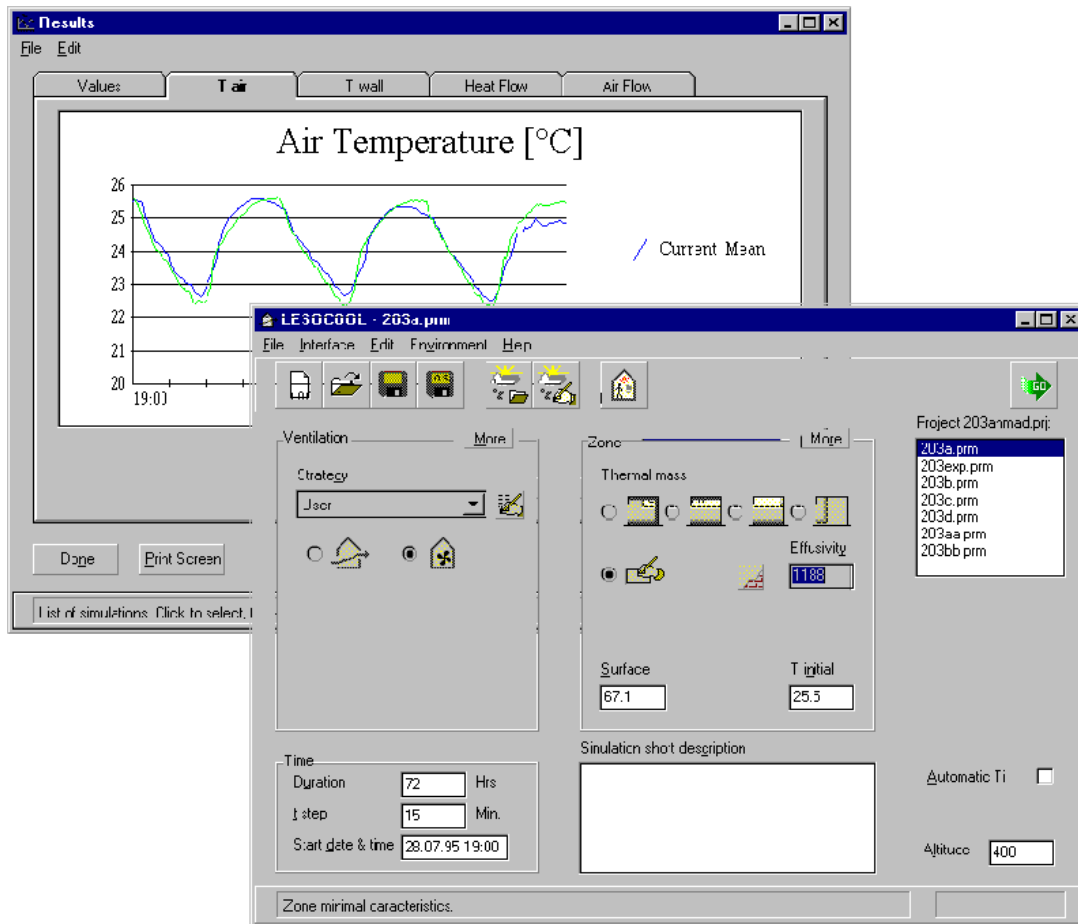
Figure 10 LESOCOOL interface

3.11 NatVent[®]

The NatVent[®] programme is a simplified design tool accessible through a menu-driven computer code designed for assessing internal temperatures and air flow rates in naturally ventilated buildings, particularly offices. It has been developed as part of the European NatVent[®] project, within the Joule III Programme of EC-DG XII. As an example of one important application, it allows the potential for night-time cooling by ventilation to be evaluated.

The data input screens for the NatVent[®] programme can be seen in Figure 11. Data entry is achieved via a series of menus. Output from the tool is presented as on-screen graphs. Re-calculated output data can be obtained in a straightforward manner, if adjustments to the input data are required. Default climatic data is provided for a number of European locations, for both summer and winter design. (In general, for office buildings, summer design focuses on indoor temperatures, while winter design focuses on indoor air quality.)

3.12 NatVent[®] NaVIAQ

Another tool developed as part of the NatVent[®] project, NaVIAQ provides a simplified design tool for investigating indoor air quality in naturally ventilated office buildings. The program models a single level of an office building, in which the number of rooms is adjustable. Simulations may be run over a length of time, to allow for modelling of the transient nature of pollutant concentrations in offices. It has been developed as part of the European NatVent[®] project, within the Joule III Programme of EC-DG XII. Figure 12 shows an example of the

user interface for NaVIAQ, showing both input settings and the output, which are presented on the screen simultaneously. Changes to the input data can be made easily, and the consequent effects on the output data observed immediately.

Various strategies for office ventilation, including self-regulating grilles, may be examined. Furthermore, not only is the pollutant modelling transient, but the ventilation modelling is also.
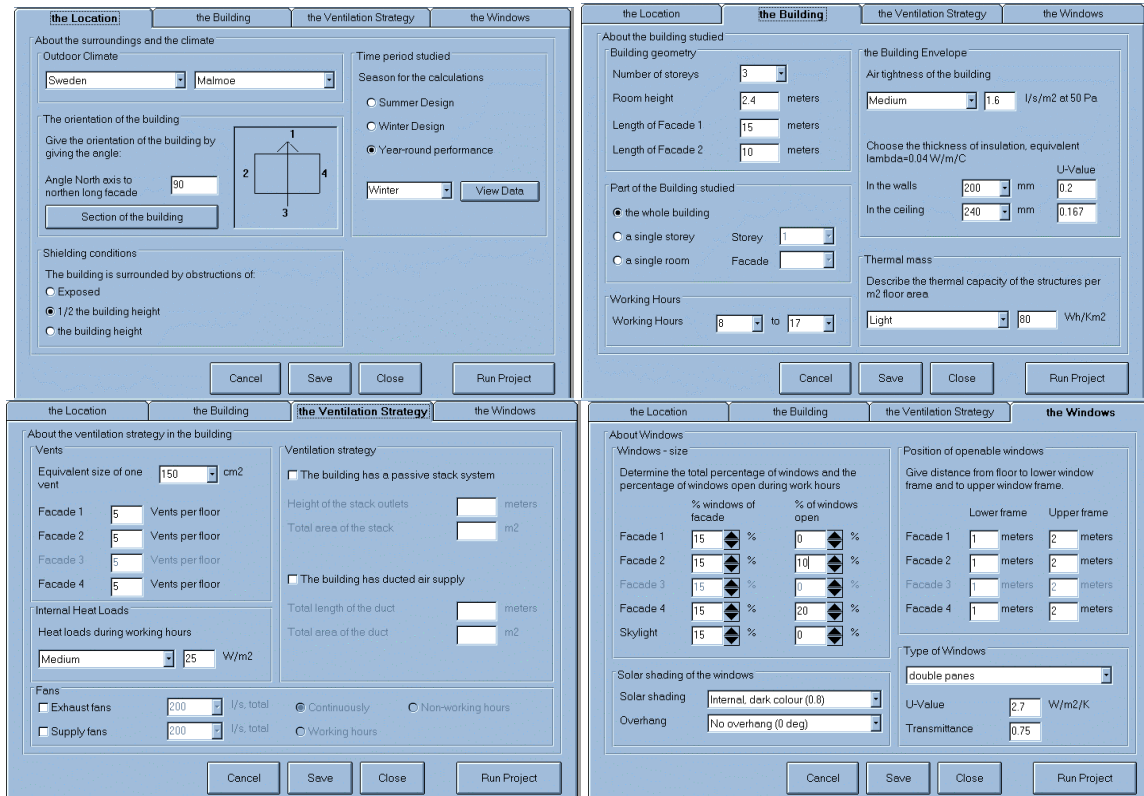
Figure 11 NatVent® input screens
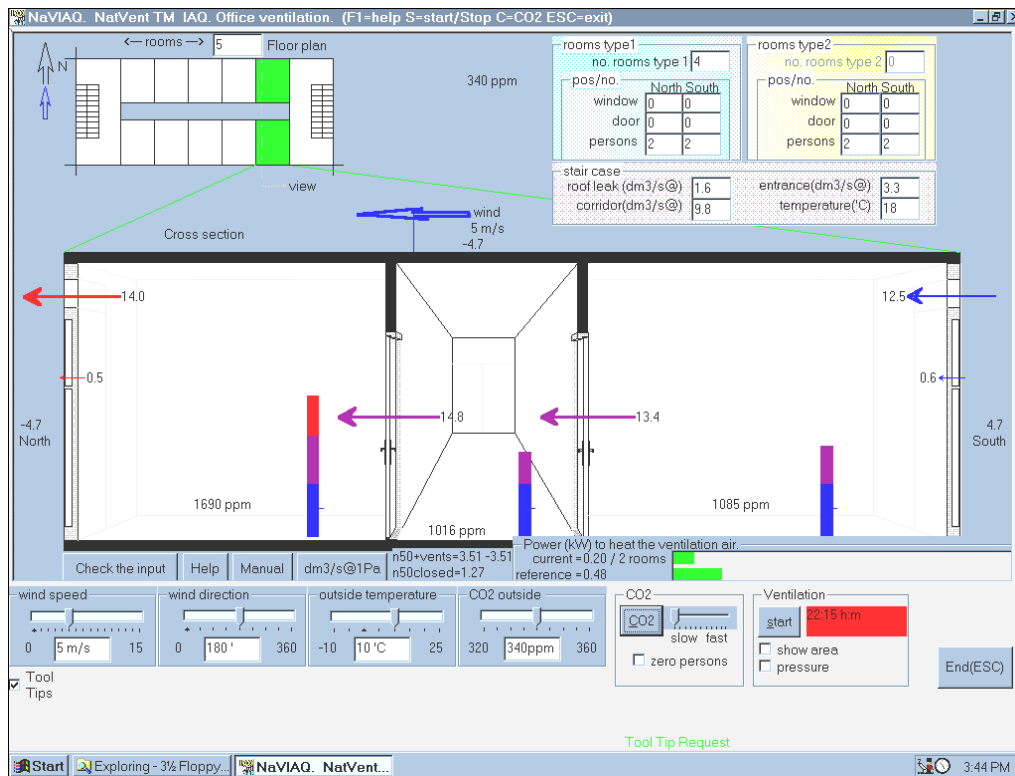
Figure 12 Example NatVent® NaVIAQ combined input and results screen

3.13 NiteCool

The NiteCool program has been developed under the UK DOE Environmental Issues in Buildings (EnREI) Programme. It is specifically designed to assess the feasibility of using night-time cooling of the fabric of office buildings, achieved with natural or mechanical ventilation, for day-time sensible cooling of the indoor air. It is a simplified design tool for predicting internal temperatures and energy savings relative to a reference system (Kolokotroni et al, 1997). The user interface for NiteCool is implemented in MS-Windows and Figure 13 shows one of the combined input and results screens.

A number of possible ventilation systems are considered by the tool: mechanical supply only, mechanical extract only, balanced, single-sided with single or double opening, cross ventilation, stack ventilation, fan coil with 100% fresh air, and displacement ventilation. The default designs for the single-sided, cross, and stack ventilation systems may be adjusted. Also, the night cooling control strategy for all systems may be varied. Additionally, the CIBSE 'inverse sizing' model (described in Section 5.6) has also been incorporated into NiteCool.
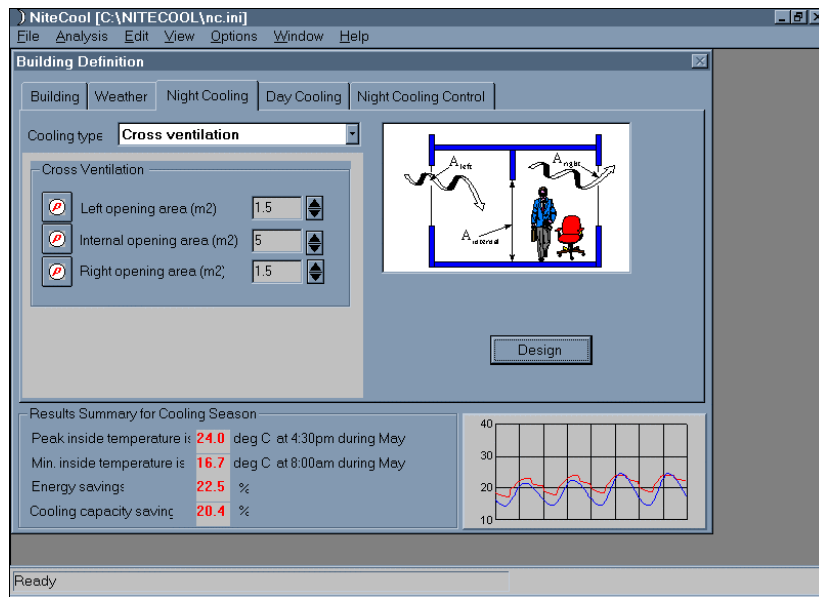
Figure 13 Example NiteCool combined input and results screen

3.14 PASSPORT Plus

PASSPORT Plus is a thermal model that includes a calculation subroutine for determining natural ventilation flow rates, PASSPORT-AIR. Combination of the thermal and air flow results is by means of 'sequential coupling', in which the schedule of air flows is calculated for each point in the weather and occupant-related (i.e. window opening) schedules. Fixed (mechanical) ventilation rates may also be specified. Hence the ventilation air flows may influence the calculated indoor temperatures. The program performs thermal simulations of buildings and calculates hourly indoor air and wall surface temperatures, indoor air flows, cooling or heating loads, and indoor thermal comfort conditions. It was developed under the EC-DG XII Joule II Programme. PASSPORT Plus is menu driven, and principally designed as a thermal model.

3.15 SUMMER

There are two programmes in the SUMMER package (Klitsikas et al, 1996): BUILDINGS and TECHNIQUES. They were developed under EC-DG XVII, as part of the SAVE Programme and are both intended for investigating passive cooling of buildings. SUMMER-BUILDING is a simplified design tool, which may be applied to solar control, thermal mass, natural ventilation, night ventilation, buried pipes, and combinations of these techniques. SUMMER-TECHNIQUES includes more detailed simulation tools for: ground cooling, radiative cooling, evaporative cooling, ventilative comfort, natural ventilation, and solar control. Furthermore, the natural ventilation simulation tool in TECHNIQUES contains a multi-zone air flow model. Both BUILDING and TECHNIQUES have MS-Windows based user interfaces and Figure 14 displays an example SUMMER-BUILDING output screen.
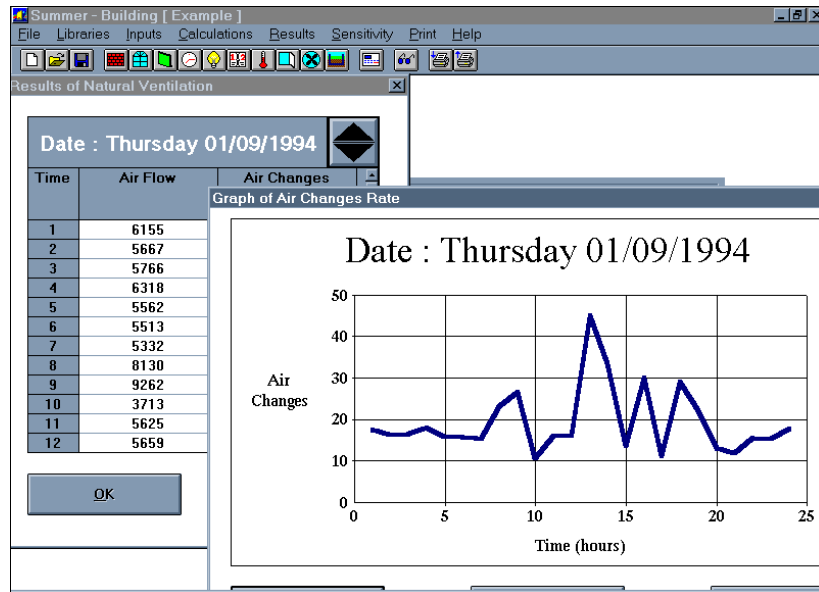
Figure 14 Example SUMMER output screen

3.16 VENT

Appendix D contains a flow chart for the operation of VENT. In this model a distinction is made between purpose-provided openings (which have a square-law flow characteristic) and adventitious openings (which follow the quadratic flow equation). In this simplified version of the single-zone model the adventitious openings are assumed to be uniformly distributed over the walls with a fixed value of the shape factor (a/b2), such that the user need only input the adventitious leakage at 50 Pa. VENT has a simple computer user interface, and output from the programme is provided in numerical format. The output can either be in the form of the whole building air change rate, or more detailed, with flow rates for each opening presented. It also allows the inclusion of fixed mechanical supply or extract air flow rates.

4   Example Applications

4.1   Example simulation using COMIS, BREEZE and CONTAM93

The simulation discussed here is very simple and well-defined. All the necessary input data have been stated, so no judgements are needed from the user in order to configure the model.

4.1.1   General information about the building

The building has 3 storeys together with a connecting enclosed stairwell. A section is shown in Figure 15. Each floor has a volume of 150 m^3 excluding the stairwell

Wind speed (roof height) = 2 m·s^{-1}
Outside temperature 10°C

4
Height = 9 m
$C = 0.02$ kg·s^{-1}·Pa^{-n}
$n = 0.66$
$c_p = -0.4$

3
Height = 8 m
$C = 0.02$ kg·s^{-1}·Pa^{-n}
$n = 0.66$
$c_p = 0.5$

10
Height = 6 m
$C = 0.004$ kg·s^{-1}·Pa^{-n}
$n = 0.66$

C

17.5°C   D

23°C

8
Height = 7 m
$C = 0.04$ kg·s^{-1}·Pa^{-n}
$n = 0.66$

2
Height = 5 m
$C = 0.02$ kg·s^{-1}·Pa^{-n}
$n = 0.66$
$c_p = 0.4$

9
Height = 3 m
$C = 0.004$ kg·s^{-1}·Pa^{-n}
$n = 0.66$

B

20°C

7
Height = 4 m
$C = 0.04$ kg·s^{-1}·Pa^{-n}
$n = 0.66$

9 m

1
Height = 2 m
$C = 0.02$ kg·s^{-1}·Pa^{-n}
$n = 0.66$
$c_p = 0.2$

A

5
Height = 1 m
$C = 0.02$ kg·s^{-1}·Pa^{-n}
$n = 0.66$
$c_p = -0.3$

3 m

18 °C

6
Height = 1 m
$C = 2$ kg·s^{-1}·Pa^{-n}
$n = 0.66$

Figure 15 Cross-section of the simulated building

(zones A, B, and C in Figure 15) and the stairwell itself has a volume of 135 m^3 (zone D in Figure 15). The total building volume is therefore 585 m^3. Flow characteristics of the leakage paths have been represented using power law expressions (with the mass flow coefficients, C, and flow exponents, n). Wind pressure coefficients, c_p, have been given for external openings. Atmospheric pressure is taken to equal 101.325 kPa, with an outdoor air temperature of 10 °C. The wind speed at the roof height of the building (9 m), at the building location, is 2 m·s^{-1}.

Both the indoor and outdoor humidity ratios were assumed to equal 0.0 g·kg^{-1} (completely dry air). The reason for this was in order to use identical air density profiles in all of the models, although such a situation would be extremely unlikely to occur in reality. The physical arrangement of leakage paths in the building structure is shown in Figure 15.

4.1.2   The solution

The results found using COMIS, CONTAM93 (an earlier version of CONTAMW), and BREEZE are shown in Figure 16. In this Figure, mass flow rates are listed for each leakage opening in the order COMIS, CONTAM93, and then BREEZE. It can be seen that the results obtained are very close for this well-defined problem.
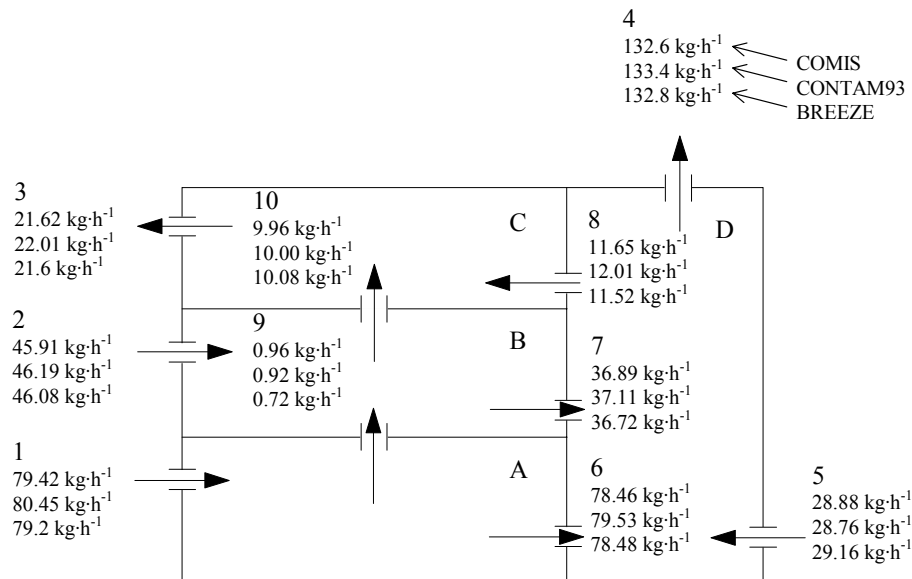
Figure 16 Results of the simulations - mass flow rates through the leakage paths

4.2   Example application using BREEZE (office building)

BREEZE was used to calculate local ventilation rates in a complex naturally ventilated office building situated in the United Kingdom, during design and construction (described in Walker et al, 1996). A cross section of the building is shown in Figure 17. The building incorporates the following key architectural features: a central atrium (covered street); deep offices with ventilation openings to the outside on only one face, with the other face opening to the atrium; multi-storey, with significant vertical ventilation routes; 4 storeys on one side of the atrium and 5 on the other. Ventilation is provided by windows to the outside and to the atrium, with trickle ventilators installed in each external window. The internal air temperature was assumed to be either 18 ºC or 21ºC.

In order to predict the local mean ages of air, the uniform emission of a tracer gas was simulated using the contaminant prediction capabilities of the model. The local ventilation rate, *r*, is defined as the reciprocal of the local mean age of air and the normalised flow rate per unit area, Q_{eq}, is the local ventilation rate multiplied by the room height. Q_{in} is the total inflow divided by the zone area and *acr* is the air change rate, which is the total inflow divided by the zone volume. Selected results from the simulation are shown in Table 5.
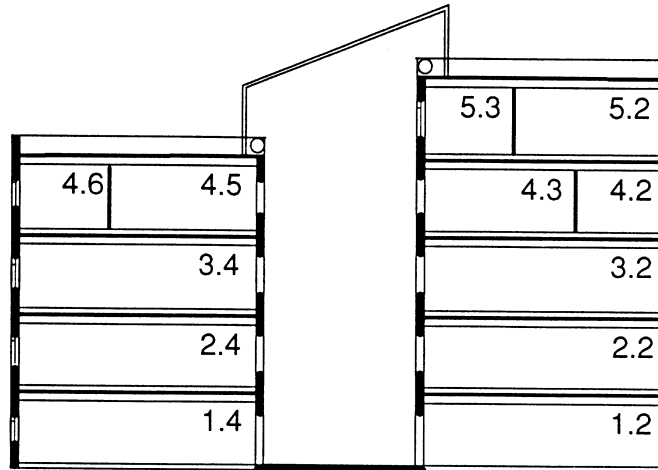
Figure 17 Cross section of the building showing zone numbers (from Walker et al, 1996)

The study focused on how local ventilation rates might vary throughout the building and whether they would meet minimum requirements in conditions when windows are closed. Three basic cases were considered as follows:

(i)   buoyancy dominated - no wind, with the air temperature outside lower than inside,
(ii) buoyancy and wind combined - prevailing wind, with air temperature outside lower than inside, and
(iii) wind dominated - prevailing wind, but with equal air temperatures inside and outside.

Table 5 Selected ventilation rates calculated from the model study

Location	1.2	1.4	4.6	5.2
Area (m^2)	910	839	150	750
Buoyancy Only				
r (h^{-1})	0.77	0.72	0.19	0.22
Q_{eq} ($dm^3 \cdot s^{-1} \cdot m^{-2}$)	1.01	0.94	0.22	0.25
Q_{in} ($dm^3 \cdot s^{-1} \cdot m^{-2}$)	0.95	0.88	1.72	1.03
acr (h^{-1})	0.73	0.68	1.47	0.88
Combined buoyancy and wind				
r (h^{-1})	0.18	0.50	1.25	0.24
Q_{eq} ($dm^3 \cdot s^{-1} \cdot m^{-2}$)	0.24	0.65	1.46	0.28
Q_{in} ($dm^3 \cdot s^{-1} \cdot m^{-2}$)	0.42	0.61	1.29	0.62
acr (h^{-1})	0.32	0.47	1.11	0.53
Wind only				
r (h^{-1})	0.15	0.21	1.86	0.60
Q_{eq} ($dm^3 \cdot s^{-1} \cdot m^{-2}$)	0.19	0.27	2.17	0.70
Q_{in} ($dm^3 \cdot s^{-1} \cdot m^{-2}$)	1.06	0.53	2.13	0.76
acr (h^{-1})	0.82	0.41	1.83	0.65

4.3   Example application using COMIS (residential building)

Measurements have been made in a two-storey Japanese detached single family house (Fürbringer et al, 1996b). The house is 7.5 m high, and the house has a net volume of 350 m^3. Equivalent leakage areas for the different rooms in the house can be seen in Table 6. The average wind speed, measured at the building location, was 2.32 $m \cdot s^{-1}$, and the average outdoor temperature was -6.86 ºC.

The air change rates calculated using COMIS for each zone are presented in Table 7, and the simulated air flow rates are indicated in Figure 18.
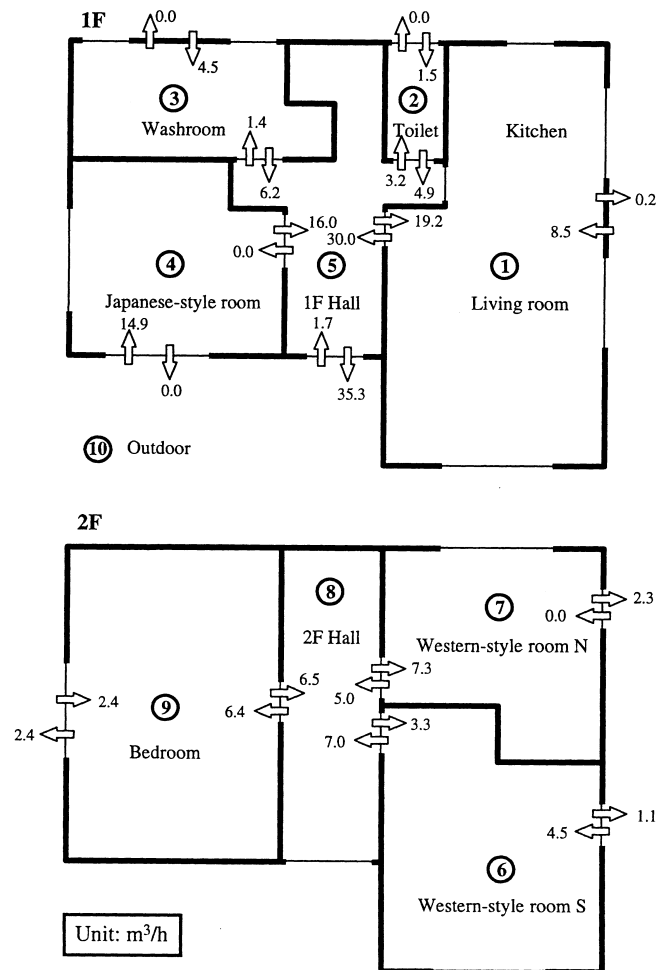
Figure 18 Simulated air flow rates (from Fürbringer et al, 1996b)

4.4   Example application using LBL model (residential building)

Measurements of air infiltration have been performed for a 3 storey single family row house in the Netherlands, and also the leakage with pressure difference has been determined (de Gids, 1979). From the experimental results, it can be determined that the total effective leakage area of the building at 4 Pa pressure difference, *L,* is 1180 cm^2. This includes the leakage area at ceiling level, $L_{ceiling}$, of 810 cm^2, including stacks, and leakage area at floor level, L_{floor} of 28.1 cm^2.

The local terrain is very flat and the house is partially shielded by surrounding buildings approximately 10 m high. The building shielding parameter, *C'* is therefore assumed to be 0.25 (from Table C1, Appendix C). Meteorological data was obtained from Rotterdam Airport, 9 km east of the building location. The meteorological site wind speed, $U_{z'}$, is 2 m·s^{-1}, measured at 10 m above ground level. Furthermore, it is judged that the offsite terrain constants, α', γ', 0.85 and 0.20 respectively and onsite terrain constants, α, γ, 0.67 and 0.25 respectively, are most suitable. By the conversion stated in Section 3.2.1, with the building height equal to 7.9 m (also assumed to be the height from the lowest to highest leakage site)

this implies an onsite wind speed of 1.49 m·s^{-1}. The average internal temperature is 17.7 ºC, and the average external temperature is 3.7 ºC.

We now have sufficient information to evaluate both the temperature driven flow characteristic, f_s = 0.148, and the wind driven flow characteristic, f_w = 0.165, from the defining equations stated in Appendix C. Substituting into the expression for the air infiltration rate produces

$$Q_{inf} = 0.118 \times (0.148^2 \times 14 + 0.165^2 \times 1.49^2)^{\frac{1}{2}} = 0.0715 \text{m}^3 \cdot \text{s}^{-1} \equiv 257 \text{m}^3 \cdot \text{h}^{-1}.$$

Table 6 Equivalent leakage area (9.8 Pa ELA) of the Japanese house

Element/Component	ELA	1/n
Building envelope	33.50	1.25
Living Room South Window	3.44	1.27
Living Room East Window	0.00	1.25
Windows of Toilet, Washroom and Bathroom	17.49	1.50
Windows of Japanese-style Room	19.66	1.53
South Window of Western-style Room (S)	6.06	1.50
Windows of Western-style Room (S), (N) and Bedroom	9.28	1.42
Top Light Windows (Ventilating Opening Closed)	11.29	1.56
Vestibule Door	0.00	1.50
Air Conditioner Outlet	0.00	1.20
Air Supply Opening (Closed)	0.00	1.21
Air Supply Opening (Open)	51.26	1.62
Air Exhaust Opening (Open)	20.86	1.55
Kitchen Door	103.47	1.78
Living Door	106.51	1.69
Toilet Door	113.82	1.60
Washroom Door	120.31	1.76
Door of Japanese-style Room	106.18	1.80
Door of Western-style Room (S)	119.24	1.81
Door of Western-style Room (N)	135.23	1.77
Bedroom Door	106.18	1.80

n: flow exponent of leakage

Table 7 Calculated air change rate [h^{-1}] and measured temperature in each zone [ºC]

Zone	1	2	3	4	5	6	7	8	9	10
ach	0.42	0.97	0.22	0.44	1.32	0.14	0.17	1.32	0.18	0.11
Temp [ºC]	33.89	19.57	14.63	11.81	16.04	13.60	13.03	16.16	11.24	-6.86

The gross volume of the building is 310 m^3, which implies that the net building volume is 248 m^3, assuming that net volume is 80% of gross volume. Therefore the infiltration-related building air change rate is estimated to be 1.04 ach, by the LBL model. In fact, the measured value for this building was found to equal 1.30 ach, under identical meteorological conditions.

5   Complementary Modelling Techniques

5.1   Coupling of Thermal and Ventilation Models

Kendrick (1993) gives an overview of combined modelling of energy and mass transport. The most basic form of coupling between ventilation and thermal models is known as 'sequential coupling'. In this method the mass flow rates are calculated first, with assumed internal temperatures, and these values are then fed into the thermal model. There is no feedback from the thermal model to the ventilation model. Hensen (1995) describes two additional approaches to coupling thermal and ventilation models, 'ping-pong' and 'onions'. The first of these approaches, 'ping-pong', involves the air flow rates from the ventilation model being used by the thermal model. The calculated air temperatures are then fed back into the ventilation model at the next time step. In the 'onions' approach, air flow rates are passed from the ventilation model to the thermal model, and air temperatures are passed back from the thermal model to the ventilation model. This process is repeated until 'convergence' is reached. In this case, convergence means that steady-state (constant) values of air flow rates and temperatures are reached for each time step.

Figure 19, adapted from a figure presented in Hensen (1995), gives a schematic representation of each of the three approaches previously mentioned. (In the case of both the 'ping-pong' and 'onions' approaches, it is possible to reverse the situation, so that the heat balance is calculated first, with assumed air flow rates.) Hensen (1995) argues that, "When used improperly in terms of time step, the onion method will have implications in terms of computing resources, but - more seriously - the ping-pong method may generate substantial errors." He concludes, "Which method to choose depends on the required accuracy. In general it is advisable to be careful with the ping-pong approach in combination with long time steps for problems with strongly coupled heat and air flow." A further approach is coupling by 'full integration'. This means that the ventilation model equations are solved simultaneously with the thermal model equations, by incorporating both into the system of equations covering heat transfer processes (Kendrick, 1993).
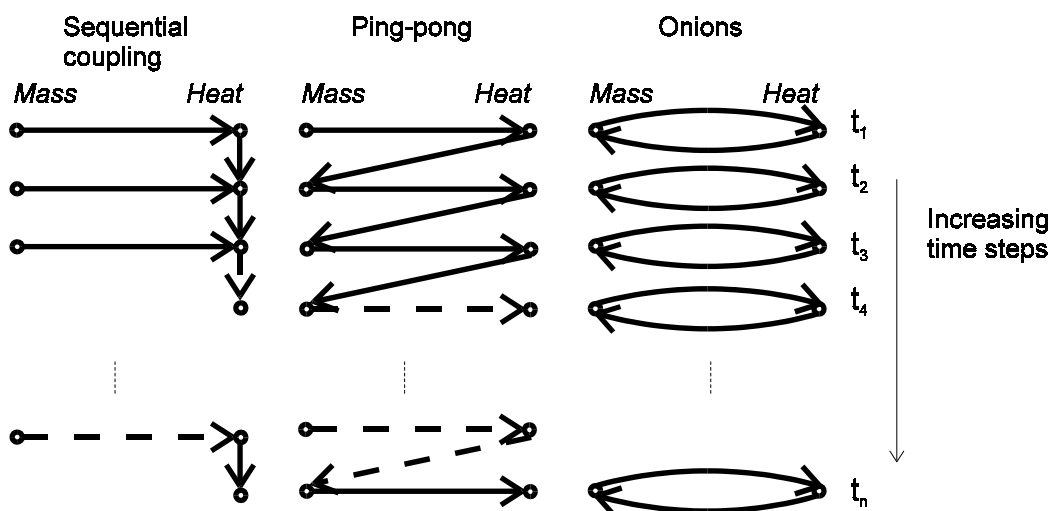
Figure 19 Preferred Methods for coupling thermal and ventilation models

A compromise method for coupling thermal and ventilation models may sometimes be adopted, when none of the methods presented in Figure 19 are possible. The 'poison ball' approach only requires that each model is run independently, but over an identical number of time steps. The resulting final flow rates from the ventilation model then become inputs for

the thermal model, which is then run and the final temperatures from the thermal model are used as input for the ventilation model, and so on. This approach is potentially more time-consuming than the previous ones, as well as having severe limitations concerning the weakness of the coupling. The poison ball method is depicted schematically within Figure 20.
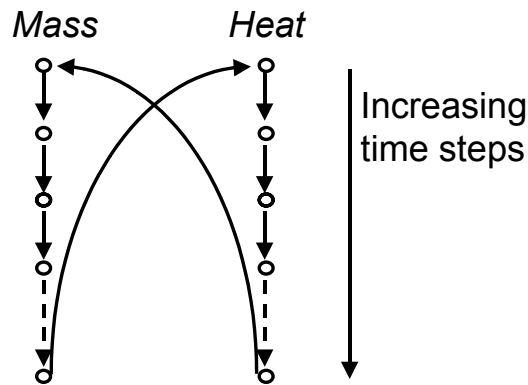
Figure 20 'Poison ball' coupling for thermal and ventilation models

5.1.1   Input data for coupled modelling

In Figure 21 can be seen the type of input data that are necessary to configure both ventilation models (mass balance) and thermal models (heat balance). The critical step for combining these two kinds of model (with the 'ping-pong' and 'onions' approaches) is that adjustment is made to the calculated internal air temperature (for each zone) according to the results of each model.
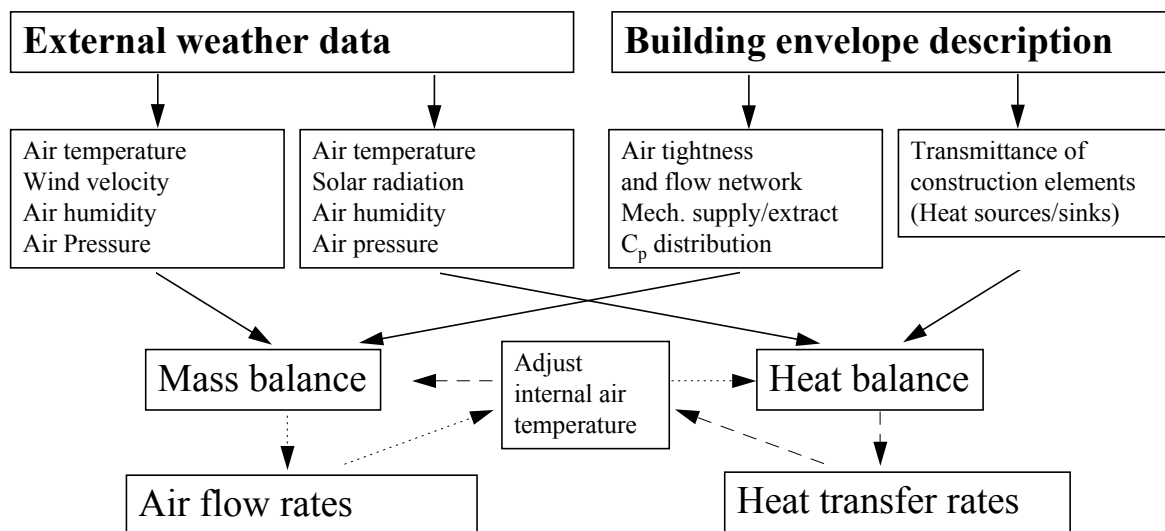
Figure 21 Applicable input data for coupled modelling of mass and heat transport

5.2   Computational fluid dynamics models

Computational fluid dynamics (CFD) is a numerical modelling technique that predicts temperature and velocity fields in detail throughout a single ventilated space. It is a powerful tool that has been applied for ventilation-related issues. Figure 22 illustrates an example of the kind of results that may be found. This contrasts with the ventilation models discussed in this report, which provide information about mass flows through pre-specified openings and leakage paths in single- or multi- zone buildings. These ventilation models are concerned with

bulk air flow rates, and do not predict air flow patterns within ventilated spaces, only between them. It could be considered that CFD and mass balance models are complementary techniques. The former provides detailed information about particular aspects of the building ventilation, while the latter gives an overview of the bulk air flow through large parts of a building.

The detailed information that can be obtained using CFD relies on specifying a similarly detailed level of input data, including initial and boundary conditions. If the input data are known with a high degree of certainty, then CFD is able to provide very useful predictions. However, CFD modelling of naturally ventilated spaces may be a challenge if realistic wind-related boundary conditions are required, due to the constantly changing nature of real wind. Liddament (1991) provides an introduction to the application of computational fluid dynamics to building ventilation, while Awbi (1991) presents the theoretical background in more detail, together with a number of case studies. Furthermore, Emmerich (1997) has undertaken an extensive literature review of the application of CFD to building ventilation and indoor air quality (IAQ) issues.
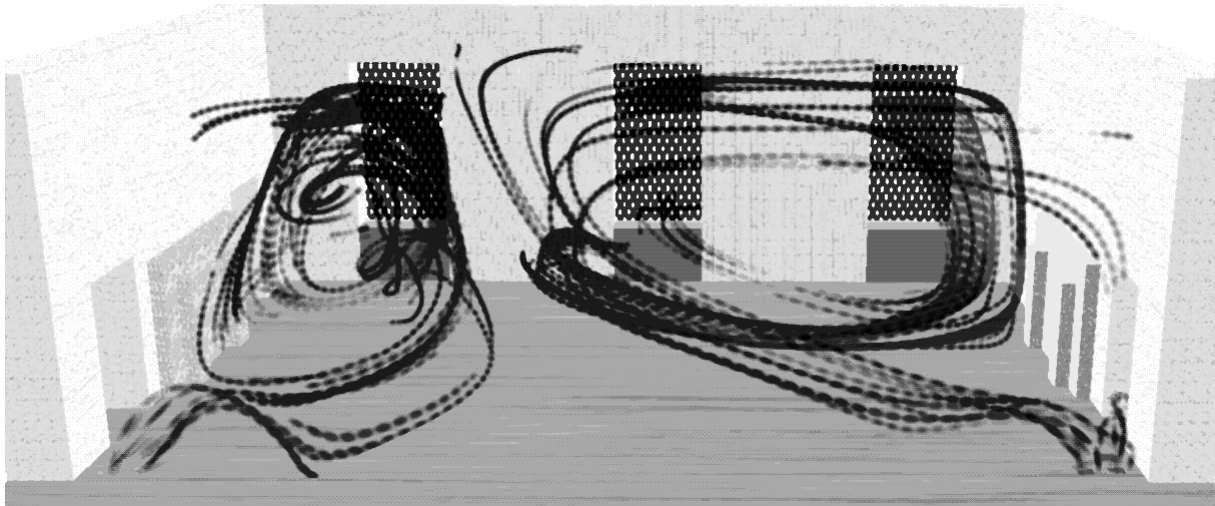
Figure 22 Example of air distribution prediction using CFD (Palmer, 1998)
- air distribution from two groups of swirl diffusers.

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7 Appendix A - Contact Information for the Ventilation Models

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Reference: BRE (1994)

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COMIS Homepage:
http://www.empa.ch/englisch/erg/comis/comis.htm
Excel Interface: http://www.byggforsk.no/hybvent/comis.htm
EnergyPlus version 1.0 (Crawley et al, 1998):
http://www.eren.doe.gov/buildings/energy_tools/energyplus/

Ftp: COMIS User Guide (Postscript)
epb1.lbl.gov/package/
USER NAME:ftp
PASSWORD: <your email address>

Availability:	Public domain

Fully supported commercial versions of COMIS are also envisaged and details will be announced at a later date.

Reference:	Allard et al (1990), Feustel and Smith (1997)

IISiBat Graphical User Interface for COMIS

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Fully supported commercial versions of COMIS are also envisaged and details will be announced at a later date.

Reference:	Annex 23 (1997a and 1997b)

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Reference:	See Appendix C. Also Sherman and Grimsrud (1980)

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Reference:	Roulet et al (1996)

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Availability:	Public domain
Reference:	Svensson (1998)

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Reference:	Phaff (1998)

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Availability:	Commercial
Reference:	Kolokotroni et al (1997)

PASSPORT Plus

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Availability:	Commercial
Reference:	Balaras and Alvarez (1995)

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Reference:	See Appendix D

8   Appendix B - AIDA (Air Infiltration Development Algorithm)

Introduction

AIDA is a basic infiltration and ventilation calculation procedure intended for the calculation of air change rates in single zone enclosures. It also resolves flow rates for up to any number of user defined openings and calculates wind and stack pressures. This program is very easy to use but, nevertheless, provides an accurate solution to the flow balance equation. As its name suggests this is a development algorithm which may be adapted to suit individual needs.

Theoretical outline

Solution is based on the iterative balancing of the volumetric flow balance equation given by

$$\sum_{i=1}^{j} Q_{v_i} = 0 \, ,$$

where Q_{v_i} = volume flow rate of air through the i'*th* flow path (m^3/s), j = the total number of flow paths into the zone, and

$$Q_{v_i} = C_i (P_i - P_{int})^{n_i} \ \text{if} \ P_i > P_{int}$$

or

$$Q_{v_i} = -C_i (P_{int} - P_i)^{n_i} \ \text{if} \ P_i < P_{int} \, ,$$

where C_i = flow coefficient of i'*th* flow path, n_i = flow exponent of i'*th* flow path, P_i = external pressure of i'*th* flow path (Pa), and P_{int} = internal pressure of zone (Pa).The stack pressure is given by

$$P_s = -\rho_0 g \, 273 (h_2 - h_1) \left[\frac{1}{T_{ext}} - \frac{1}{T_{int}} \right] \ \text{(Pa)},$$

where ρ_0 = air density at 273 K (1.29 kg/m^3), g = acceleration due to gravity (9.81 m/s^2), T_{ext} = outdoor air temperature (K), T_{int} = indoor air temperature (K), h_1 = height of opening 1 (m), h_2 = height of opening 2 (m), and the wind pressure is given by

$$P_w = \frac{\rho c_P v^2}{2} \, ,$$

where c_P = wind pressure coefficient, v = local wind velocity at a specified reference (building height) (m/s), and ρ = air density (kg/m^3).

For each flow path, the user enters appropriate flow characteristics and wind pressure coefficients, drawing data from knowledge about the building or from the default data presented in Appendix E.

Program operation

AIDA is written in BASIC. A full listing of this is presented in Table B1. Initiation of the code will be machine dependent but in the BASIC environment, will normally be achieved by using the "RUN" command. Once the response "Welcome to AIDA" appears on the screen, then the "EXE" or "ENTER" key is pressed sequentially with the user responding accurately to each of the input questions identified by a "?".
Data entry is largely self explicit. The order of entry is (for each flow path):

- building volume (m^3),
- number of flow paths,
- height of flow path (m),
- flow coefficient (m^3/s at 1 Pa), and
- wind pressure coefficient.

Once the flow path data is entered, climatic data are requested, these items are:
- outdoor temperature (^{o}C),
- internal temperature (^{o}C), and
- wind speed at building height (m/s).

On completion of data entry, the computer responds with the message "Calculation in Progress". After iteration is completed, the infiltration rate is displayed on the screen. With this 'PC' version, the air change rate and request for further climatic data is automatically displayed, break out of the program by using "CTRL BREAK". At the completion of a session, the most recent data remains in store and can be recovered by using the "PRINT" command followed by variable name, e.g.:
PRINT Q displays infiltration rate
PRINT F(2) displays flow in path 2

All the variables used in the algorithm are listed in Table B2.

Data must be inserted with care since there is no error trapping or editing facility. If an error is made, then it is necessary to restart the program.

Clearly, since this is a demonstration algorithm, the interactive Input/ Output routine is very rudimentary. It is assumed that if wider use is made of this code, then the user will amend these routines to suit individual requirements.

Solution technique

The flow balance equation is solved iteratively using a combination of "bi-section" and "addition". An internal pressure, known to be substantially negative with respect to the true pressure, is selected as a starting condition. For most applications a value of -100 Pa should be satisfactory and is automatically introduced at line 320. Successive iterations improve upon the internal pressure value until a flow balance within 0.0001 m^3/s is achieved. The flow balance criterion is established in line 450. An understanding of the technique may be gleaned from an analysis of lines 320 to 470 of the program. While this approach may not necessarily be the most numerically efficient, it is extremely robust and should not fail under normal circumstances over a wide range of flow conditions and leakage characteristics.

Example

Input data and results for a 3 flow path network are presented in Table B3. Although this is an arbitrary example, it has been selected to show that AIDA can handle differing flow coefficients, flow exponents, flow path heights and wind pressure coefficients within the same network.

Table B1: Program listing

```
20 PRINT "Welcome to AIDA"
    30 PRINT "Air Infiltration Development Algorithm"
40 PRINT "M Liddament - AIVC Guide to Ventilation 1995"
    50 DIM H(50),C(50),N(50),P(50),T(50),W(50),S(50),F(50)
55 PRINT:PRINT:PRINT
60 D=1.29 : REM Air Density at 0 Deg C
    70 PRINT "Enter Building Data:"
    80 INPUT "Building Volume (m3) = ";V
    85 PRINT:PRINT:PRINT
    90 PRINT "Enter Flow Path Data:"
    100 INPUT "Number of Flow Paths = ";L
    110 FOR J=1 TO L
    115 PRINT:PRINT:PRINT
    120     PRINT "Height (m)(Path";J;") = ";: INPUT H(J)
    130     PRINT "Flow Coef (Path";J;") = ";: INPUT C(J)
    140     PRINT "Flow Exp (Path";J;") = ";: INPUT N(J)
    150     PRINT "Pres Coef (Path";J;") = ";: INPUT P(J)
    160 NEXT J
    165 PRINT:PRINT:PRINT
    170 PRINT "Enter Climatic Data:"
    175 PRINT:PRINT:PRINT
    180 INPUT "Ext Temp (Deg C)   =" ;E
    190 INPUT "Int Temp (Deg C)   =" ;I
    200 INPUT "Wind Spd(Bldg Ht)(m/s)=" ;U
    210 REM Pressure Calculation
    220 FOR J=1 TO L
    230     REM Wind Pressure Calculation
    240     W(J)=.5*D*P(J)*U*U
    250     REM Stack Pressure Calculation
    260     S(J)=-3455*H(J)*(1/(E+273)-1/(I+273))
    270     REM Total Pressure
    280     T(J)=W(J)+S(J)
    290 NEXT J
    300 REM Calculate Infiltration
    305 CLS:PRINT:PRINT:PRINT
    310     PRINT "Calculation in Progress"
    320 R=-100
    330 X=50
    340 Y=0
    350 B=0
    360 R=R+X
    370 FOR J=1 TO L
    380     Y=Y+1
    390     O=T(J)-R
    400     IF O=0 THEN F(J)=0: GOTO 430
    410     F(J)=C(J)*(ABS(O)^N(J))*O/ABS(O)
    420     B=B+F(J)
    430 NEXT J
    440 IF B<0 THEN R=R-X: X=X/2: GOTO 350
    450 IF B<.0001 THEN GOTO 470
    460 GOTO 350
    470 Q=0
    480 FOR J=1 TO L
    490     IF F(J)>0 THEN Q=Q+F(J)
    500 NEXT J
    505 PRINT:PRINT:PRINT
    520 PRINT "infiltration rate (m3/s) = ";Q
    530 A=Q*3600/V
    540 PRINT "air change rate (ach)  = ";A
    545 PRINT:PRINT:PRINT
    550 GOTO 170
```

Table B2: AIDA list of variables

A	= Air change rate (ACH)
B	= Flow balance
C(J)	= Flow coefficient (Path J)
D	= Air density (kg/m³)
E	= External temperature (°C)
F(J)	= Calculated flow rate (Path J) (m³/s)
H(J)	= Height of flow path (Path J) (m)
I	= Internal temperature (°C)
J	= Flow path number
L	= Total number of flow paths (Max = 10)
N(J)	= Flow exponent (Path J)
O	= Pressure difference across flow path (Pa)
P(J)	= Wind pressure coefficient (Path J)
Q	= Infiltration rate (m³/s)
R	= Internal pressure (Pa)
S(J)	= Stack induced pressure (Path J) (Pa)
T(J)	= Total external pressure on flow path (Path J) (Pa)
U	= Wind speed at building height (m/s)
V	= Volume of building or enclosure (m³)
W(J)	= Wind induced pressure (Path J) (Pa)
X	= Iteration pressure step (Pa)
Y	= Iteration counter

Table B3: Example data and results

Building volume = 250 m³
Number of flow paths = 3

	Path 1	Path 2	Path 3
Height of path (m)	2	4	7
Flow coef (m³/s at 1 Pa)	0.03	0.06	0.02
Flow exponent	0.7	0.5	0.6
Wind pressure coefficient	0.3	-0.25	-0.4

Climatic data

	Outside temp. (°C)	Inside temp. (°C)	Wind speed (m/s)
Run 1	0	20	0
Run 2	5	15	2
Run 3	18	18	3

Results

Infiltration rate (m³/s)	Air change rate	Flow rate (m³/s) (path 1)	Flow rate (m³/s) (path 2)	Flow rate (m³/s) (path 3)
0.0437	0.63	0.0437	-0.0081	-0.0356
0.0511	0.74	0.0511	-0.0224	-0.0287
0.0615	0.80	0.0615	-0.0382	-0.0232

Program developments

Developments covering mechanical ventilation, additional flow paths, automatic wind pressure distributions and wind speed correction equations may be readily incorporated. For example, mechanical ventilation can be incorporated by expressing the ventilation rate as a 'C' value and setting the flow exponent to zero.

Mass Flow version of AIDA

Palmiter (1990) developed AIDA further to take account of mass flow rates. The following is his extension of the programme:
AIDA (Liddament, 1989) is strictly speaking only valid for mild climates, since the less accurate volumetric form of the flow equation is used. Suggested changes to the original algorithm are presented in order to solve for mass air flow.

In some regions it is also useful to link air density to elevation above sea level, rather than include it as a fixed value. At the elevation of Denver (Colorado, USA), for example, absolute pressure is reduced by 20%, thus, for a given temperature difference, stack pressure is also reduced by 20%. A variable density modification has therefore also been introduced. The necessary modifications to the Code are presented in Table B4, where

Y = absolute pressure (Pa),
D = outside air density (kg·m^{-3}), and
G = inside air density (kg·m^{-3}).

Table B4   Modifications to AIDA for mass flow and density variations

```
175 INPUT "Elevation above sea level (m) = ", Z
176 Y = 101325! * (1 - .0065 * Z / 288.15)^5.2559
195 D = Y / (287.044 * (E + 273.15))
196 G = Y / (287.044 * (I + 273.15))
```

The stack pressure calculation can then be simplified to:

```
260 S(J) = -9.80665 * H(J) * (D - G)
410 IF O > 0 THEN F(J) = C(J) * (ABS(O)^N(J)) * D
```

```
415 IF O < 0 THEN F(J) = C(J) * (ABS(O)^N(J)) * (-G)
```

```
505 Q = Q / D
```

With these adjustments, the model will give the correct flows for all temperatures and elevations.

Using a larger and more sophisticated version of the same one-zone flow model, we have found that eleven vertical holes, equally spaced, are required to model the stack flow through a uniformly porous wall to an accuracy of 3% - 4%. The four faces of a simple building then require 44 holes to obtain reasonable accuracy. Use of only three or four holes to model walls can result in errors of 100% or more. You may wish to share these guidelines with users of your program.

9   Appendix C - LBL Model

This Appendix presents the calculation method used in the full LBL Model. In the full LBL Model, a series of equations are used to approximate the total air infiltration rate into a space, Q_{inf}. These are based on 'effective leakage area' (a measure of the leakage characteristics of the building), temperature driven flow characteristics, f_s, and wind driven flow characteristics, f_w. The resultant equations are:

$$Q_{inf} = E\left(f_s^2 \Delta T + f_w^2 U_z^2\right)^{\frac{1}{2}}$$

$$f_s = \left(\frac{1+\dfrac{R}{2}}{3}\right)\left(1 - \frac{X^2}{(2-R)^2}\right)^{\frac{3}{2}}\left(\frac{gh}{T_o}\right)^{\frac{1}{2}}$$

$$f_w = C'(1-R)^{\frac{1}{3}}$$

$$R = \frac{E_{ceiling} + E_{floor}}{E} ; X = \frac{E_{ceiling} - E_{floor}}{E}$$

where

C'	=shielding parameter,
U_z	=building site wind speed at height z $(\mathrm{m \cdot s^{-1}})$,
ΔT	=indoor to outdoor air temperature difference (K),
T_0	=indoor air temperature (K),
E	=effective leakage area $(\mathrm{m^2})$,
h	=height from lowest to highest leakage site (m), and
g	=acceleration due to gravity $(9.81\,\mathrm{m \cdot s^{-2}})$.

$E_{ceiling}$ is the leakage area associated with gaps and cracks at ceiling level. E_{floor} is the leakage area associated with floor level openings. The derivation of the effective leakage area, E, using the power law and orifice equations is discussed in Appendix E.

Table C1

Shielding parameter	I (No shielding)	II (Light)	III (Moderate)	IV (Heavy)	V (Very heavy)
C'	0.34	0.3	0.25	0.19	0.11

The following conversion from measured to site wind speed is adopted in the LBL Effective Leakage Area Model:

$$U_z = U_{z'} \frac{\alpha(z/10)^\gamma}{\alpha'(z'/10)^{\gamma'}} \, ,$$

where U_z (m·s^{-1}) is required site wind speed at level z (m) above ground, $U_{z'}$ (m·s^{-1}) is measured wind speed at level z' (m) above ground, α', γ' are constants dependent on offsite terrain conditions (see Table C2), and α, γ are constants dependent on onsite terrain conditions (see Table C2).

Table C2 Onsite and offsite terrain-dependent constants used in the LBL Model

Terrain description	γ or γ'	α or α'
Ocean or other body of water with at least 5 km of unrestricted expanse	0.10	1.30
Flat terrain with some isolated obstacles, e.g. buildings or trees well-separated from each other	0.15	1.00
Rural areas with low buildings, trees, etc	0.20	0.85
Urban, industrial or forest areas	0.25	0.67
Centre of large city, e.g. Manhattan	0.35	0.47

10 Appendix D - VENT Flow Chart

Figure D1 contains a flow chart, which explains the operation of VENT. The source code for VENT itself can be found here.
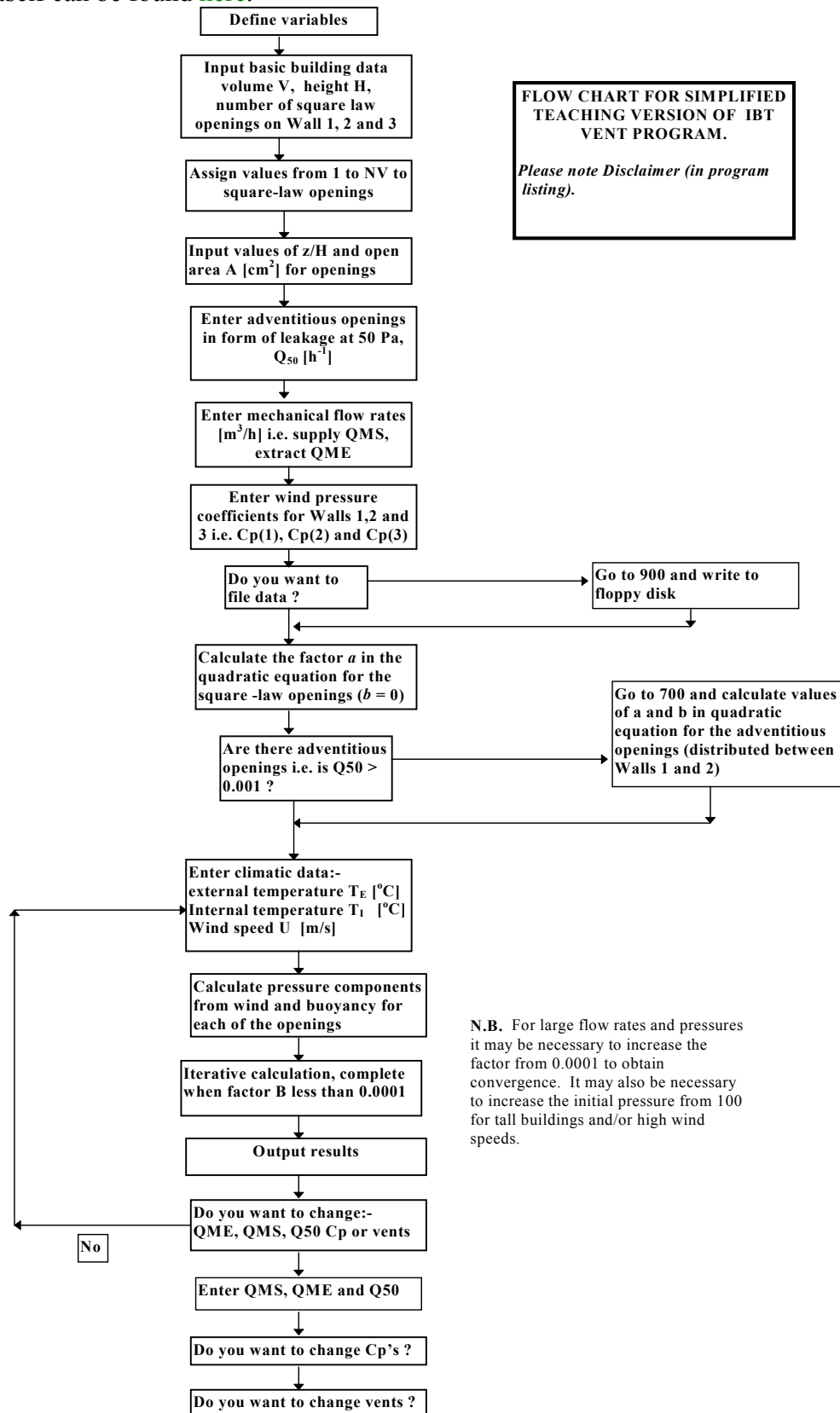

Figure D1 VENT Flow Chart (from Etheridge, 1998b)

11 Appendix E - Air Leakage Characteristics of Building Components

Power law equation

For a given applied pressure difference across an opening, the rate of air flow through it is a function of its size and geometry. The power law equation is a commonly used empirical expression that relates the air flow rate through gaps or cracks in the building fabric to the pressure difference across them. Its general form is

$$Q = K\Delta P^n \, ,$$

where Q is the volume flow rate ($dm^3 \cdot s^{-1}$), K is the flow coefficient ($dm^3 \cdot s^{-1} \cdot Pa^{-n}$), n is the (dimensionless) flow exponent, and ΔP is pressure difference across the opening (Pa). (Note that 1 dm^3 equals 0.001 m^3.)

The combination of K and n characterises the *airtightness* of an opening. The mass flow rate, $\dot{m}$ ($kg \cdot s^{-1}$), is found from the volume flow rate by multiplying by the air density (often assumed to equal the density on the higher pressure side of the opening), giving,

$$\dot{m} = 0.001\rho K\Delta P^n \, ,$$

where ρ is the air density ($kg \cdot m^{-3}$).

When tabulating component airtightness values, it is often convenient to normalise the flow coefficient by dividing by an appropriate component dimension, such as length, L (m), or area, A (m^2). The power law relationship can then be re-expressed as,

$$Q = LC\Delta P^n \, ,$$

for the flow coefficient, C ($dm^3 \cdot s^{-1} \cdot m^{-1} \cdot Pa^{-n}$), normalised by component length, or

$$Q = AC\Delta P^n \, ,$$

for the flow coefficient, C ($dm^3 \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-n}$), normalised by component area. Tables E1 to E13, contained within this Appendix, express currently available component airtightness data in either of these two ways.

Orifice equation

For relatively large openings (for example, purpose-provided vents, visible gaps around service penetrations, and very ill-fitting components) the air flow can sometimes be best represented by an equivalent flow through a flat plate orifice. The orifice flow equation is given by

$$Q = C_d A\left(\frac{2\Delta P}{\rho}\right)^{0.5} \, ,$$

where Q is the volume flow rate ($m^3 \cdot s^{-1}$), C_d is the (dimensionless) discharge coefficient (approximately 0.6 for a sharp-edged rectangular opening), ρ is the air density ($kg \cdot m^{-3}$), which is about 1.21 $kg \cdot m^{-3}$, at 20 ºC and standard atmospheric pressure, A is the area of the opening (m^2), and ΔP is pressure difference across the opening (Pa).

Calculation of effective leakage area

Combining the orifice equation with the power law equation (by equating the right hand sides of these equations and rearranging) produces an expression for the effective leakage area, *E*, at pressure difference $\Delta P = 4$ Pa in terms of the flow coefficient and flow exponent,

$$E = K'4^{n-0.5}\left(\frac{\rho}{2}\right)^{0.5} \text{ (m}^2\text{)},$$

in which, for use in the LBL Model, the discharge coefficient is assumed, $C_d = 1.00$. Note that the flow coefficient, K', has the units (m^3·s^{-1}·Pa^{-n}) in this equation.

Quadratic flow equation

Another air flow to pressure difference relationship is known as the quadratic formulation. One of the models discussed in this report (VENT) relies solely on this formulation, while others will allow building component airtightness values to be entered on this basis. It is given by

$$\Delta P = \alpha Q + \beta Q^2,$$

where Q and ΔP are as above, and α and β are constants. Further discussion of this approach is supplied in Etheridge and Sandberg (1996). Conversion between the power law and quadratic formulation relies on equating the volume flow rate at two pressure differences, and using simultaneous solution to convert from one to the other. Etheridge (1998a) describes how this may be achieved.

Table E1 Standards, Recommendations and Legal Codes of Practice - Windows

Country/Standard Ref.	Description	Quoted Leakage Value	Leakage at 1 Pa (Flow Exponent assumed 0.66)
Belgium STS 52.0	Building Height 0-10 m Building Height 10-18 m Building Height >18 m	$3.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 100 Pa $3.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 100 Pa $2.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 100 Pa	$0.040 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.040 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.027 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$
Canada CAN 3-A440-M84	A1 Low Rise Buildings (<3 storeys, <600 m^2) A2 Medium to High Rise Buildings A3 High Performance, Institutional & Commercial Fixed Storm (Max) Storm (Min)	$2.79 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 75 Pa $1.65 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 75 Pa $0.55 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 75 Pa $0.25 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 75 Pa $8.35 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 75 Pa $5.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 75 Pa	$0.045 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.027 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.009 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.004 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.134 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.080 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$
Denmark DS-418	Assumed Value (When True Value Not Known)	$0.50 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 30 Pa	$0.053 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$
Finland SFS 3304	Class 1 (Max) Class 2 (Min) Class 2 (Max) Class 3 (Min)	$0.50 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 50 Pa $0.50 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 50 Pa $2.50 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 50 Pa $2.50 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 50 Pa	$0.011 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $0.011 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $0.053 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $0.053 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$
France NF P20 302	A1 A2 A3	$20\text{-}60 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 100 Pa $7\text{-}20 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 100 Pa $<7 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 100 Pa	$0.266\text{-}0.798 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $0.093\text{-}0.266 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $<0.093 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$
Germany DIN 18055	A Building Height 0-8 m Above Grade B-D Building Height > 8 m Above Grade	$6.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 50 Pa $3.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 50 Pa	$0.126 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.063 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$
Netherlands NEN 3661	Normal Exposure: Building Height up to 15 m Building Height 15-40 m Building Height 40-100 m Coastal Exposure: Building Height up to 15 m Building Height 15-40 m Building Height 40-100 m	 $2.50 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 75 Pa $2.50 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 150 Pa $2.50 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 300 Pa $2.50 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 300 Pa $2.50 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 300 Pa $2.50 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 450 Pa	 $0.145 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.092 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.058 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.058 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.058 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.044 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$
New Zealand NZS N4211:1987	Airtight Moderate Air Leakage Low Air Leakage	$0.60 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 150 Pa $2.00 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ at 150 Pa $2.00 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 150 Pa $8.00 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ at 150 Pa $4.00 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 150 Pa $17.00 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ at 150 Pa	$0.022 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.073 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $0.073 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.293 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $0.147 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.623 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$
Sweden	All Buildings Buildings >8 Storeys	$1.70 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 50 Pa $5.60 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 300 Pa $7.90 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$ at 500 Pa	$0.036 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $0.036 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ $0.036 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$
Switzerland SIA 331	Building Height 0-8 m Building Height 8-20 m Building Height 20-100 m	$5.65 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 150 Pa $8.95 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 300 Pa $14.25 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 600 Pa	$0.056 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.056 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.056 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$
United Kingdom BS6375: Part 1: 1989	Openable - Design Wind Pressure (Exposure) <1600 Pa Openable - Design Wind Pressure (Exposure) > = 1600 Pa Fixed - Design Wind Pressure (Exposure) <1600 Pa Fixed - Design Wind Pressure (Exposure) > = 1600 Pa Fixed - High Performance Openable - High Performance	$6.34 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 50 Pa $4.84 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 50 Pa $1.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 200 Pa $1.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 300 Pa $1.00 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 600 Pa $6.60 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$ at 600 Pa	$0.133 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.102 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.008 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.006 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.004 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ $0.02 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$
USA ASHRAE 90-80	All	$0.77 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at 75 Pa	$0.045 \text{ dm}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$

Table E6 Standards, Recommendations and Legal Codes of Practice - Walls, Ceilings and Floors

Country/Standard Ref.	Description	Quoted Leakage Value	Leakage at 1 Pa (Flow Exponent assumed 0.66)
Netherlands Building Decree. Issued December 16, 1991	Flooring	20×10^{-6} $m^3 \cdot s^{-1} \cdot m^{-2}$ at 1 Pa	0.020 $dm^3 \cdot s^{-1} \cdot m^{-2}$

Table E7 Leakage Characteristics - Walls, Ceilings and Floors

Data expressed for each m^2 of surface. Includes joints	Lower Quartile		Median $dm^3 \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-n}$		Upper Quartile		Sample Size
	C	(n)	C	(n)	C	(n)	
Brick (bare) - Laboratory and Field Tests	0.022	(0.84)	0.043	(0.80)	0.094	(0.76)	5
Brick (plastered)	0.016	(0.86)	0.018	(0.85)	0.021	(0.84)	3
Brick (wall board panelling) - Laboratory test	0.010	(0.88)	0.042	(0.81)	0.18	(0.72)	2
Cladding (ungasketed)	0.010	(0.88)	0.032	(0.82)	0.10	(0.76)	2
Cladding (gasketed) - Laboratory test	6.9×10^{-3}	(0.90)	0.012	(0.87)	0.015	(0.86)	3
Concrete block (bare)	0.082	(0.77)	0.13	(0.74)	2.0	(0.59)	10
Concrete block (plastered, internal) - Laboratory test	0.021	(0.84)	0.021	(0.84)	0.021	(0.84)	2
Concrete panels (pre cast)	0.050	(0.80)	0.11	(0.75)	0.12	(0.74)	6
Concrete panels (pre cast, gasketed) - Laboratory test			0.026	(0.83)			1
Metal panels (walls)	0.076	(0.77)	0.090	(0.76)	0.13	(0.74)	3
Curtain walling	0.089	(0.76)	0.12	(0.74)	0.14	(0.74)	3
Plaster board (ceiling)	0.042	(0.81)	0.11	(0.75)	0.20	(0.72)	3
Fibre board (ceiling)			0.094	(0.76)			1
Timber panel (with wall board)	0.27	(0.70)	0.52	(0.67)	2.7	(0.58)	6
Timber panel (with air barrier) - Laboratory test			0.066	(0.78)			1
Timber floor (suspended)	0.11	(0.75)	0.15	(0.74)	0.45	(0.67)	15

Sources: #40, #86, #91, #142, #176, #177, #214, #311, #597, #1357, #3880, #5746, Wouters (1987), Brunelli (1969), BRE Unpublished.

Table E8 Leakage Characteristics - Wall to Floor/Ceiling Joints

Data expressed for each metre length of joint		Lower Quartile		Median $dm^3 \cdot s^{-1} \cdot m^{-1} \cdot Pa^{-n}$		Upper Quartile		Sample Size
Wall Material	Ceiling Material	C	(n)	C	(n)	C	(n)	
Caulked: Masonry	Timber/ Fibre Board			No data				
Masonry/ Concrete	Concrete	5.0×10^{-3}	(0.6)	0.024	(0.6)	0.11	(0.6)	2
Timber	Timber/ Fibre Board	6.6×10^{-3}	(0.6)	0.011	(0.6)	0.015	(0.6)	9
- Laboratory test Timber	Concrete	0.052	(0.6)	0.083	(0.6)	0.11	(0.6)	4
Uncaulked: Masonry/ Concrete	Timber/ Fibre Board	0.45	(0.6)	0.49	(0.6)	0.53	(0.6)	2
Masonry	Concrete			No data				
Timber	Timber/ Fibre Board	0.008	(0.6)	0.023	(0.6)	0.030	(0.6)	5
Sources: #1105, #1261, #1357, #1607, #5693.								

Table E9 Leakage Characteristics - Wall to Wall Joints

Data expressed for each metre length of joint	Lower Quartile		Median $dm^3 \cdot s^{-1} \cdot m^{-1} \cdot Pa^{-n}$		Upper Quartile		Sample Size
	C	(n)	C	(n)	C	(n)	
Caulked: Timber/Timber	6.7×10^{-4}	(0.6)	1.6×10^{-3}	(0.6)	3.4×10^{-3}	(0.6)	40
- Laboratory test Masonry/Timber			No data				
Uncaulked: Timber/Timber			No data				
Masonry/Timber			No data				
Sources: #1105, #5378.							

Table E10 Leakage Characteristics – Service Penetrations

Data expressed for each metre length of perimeter joint	Lower Quartile		Median $dm^3 \cdot s^{-1} \cdot m^{-1} \cdot Pa^{-n}$		Upper Quartile		Sample Size
	C	(n)	C	(n)	C	(n)	
Discharge pipes	1.1	(0.6)	1.2	(0.6)	1.4	(0.6)	2
Sealed spiral ducts	0.027	(0.6)	0.14	(0.6)	0.78	(0.6)	2
Vent			0.80	(0.6)			1
Pipes	0.63	(0.6)	0.74	(0.6)	0.84	(0.6)	3
- Laboratory Test							
Sources: BRE Unpublished, #1104, #1294, #5693.							

Table E11 Leakage Characteristics - Roofing

Data expressed for each m^2 of surface. Includes joints	Lower Quartile		Median $dm^3 \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-n}$		Upper Quartile		Sample Size
	C	(n)	C	(n)	C	(n)	
Shingles (roofing)	0.60	(0.66)	0.70	(0.65)	1.1	(0.63)	3
Tiles (roofing)	2.1	(0.59)	2.3	(0.58)	4.0	(0.55)	9
Metal (roofing	0.49	(0.67)	0.63	(0.66)	0.98	(0.63)	6
Sources: #1529, #3880.							

Table E12 Leakage Characteristics - Chimneys

Data expressed for each m² of chimney flue area	Lower Quartile C	(n)	Median dm³·s⁻¹·m⁻²·Pa⁻ⁿ C	(n)	Upper Quartile C	(n)	Sample Size
Fireplace opening bare - Laboratory and field tests	670	(0.5)	750	(0.5)	790	(0.5)	3
Pegboard baffle (Sealed) - Laboratory tests			300	(0.5)			1
Pegboard baffle (Unsealed) - Laboratory tests			410	(0.5)			1
Plywood baffle (Unsealed) - Laboratory test	180	(0.5)	180	(0.5)	180	(0.5)	2
Sources: BRE Unpublished, #1259.							

Table E13 Leakage Characteristics (expressed by the ratio of 'closed' flow to 'open' flow) - Trickle Ventilators

	Lower Quartile	Median	Upper Quartile	Sample Size
Trickle Ventilators- Laboratory test	0.06	0.08	0.23	8
To determine the flow characteristics of a closed trickle ventilator when its 'open' flow is given by size $Q = C \Delta P^n$, multiply by value given above, to give e.g. $Q = 0.06 \ C \ \Delta P^n$, the flow equation of the trickle ventilator when the vents are closed.				
Data Source: BRE Unpublished.				

12 Appendix F - Wind Pressure Coefficient Data

Figure F1 (Orme et al, 1998) shows wind pressure coefficients derived from wind tunnel tests performed on a 1:1200 scale model of a tall building with a flat roof and a central lightwell, located in an array of flat-roof low rise buildings. The low rise buildings were of random orientation and one third of the height of the tall building. The high rise building had dimensions 60 m × 50 m × 33 m (**W**idth × **L**ength × **H**eight) to scale. The lightwell measured 30 m × 20 m × 33 m to scale, was centrally placed and was completely open to the wind.

The wind pressure coefficients were referenced to the undisturbed wind velocity at the height of the roof. An atmospheric boundary layer was simulated in the wind tunnel and the incoming wind was given a velocity profile with a power exponent of 0.23. (See Section 3.2.1.) The pressure coefficients of the external building surface, including the lightwell, are indicated within Figure F1, in which **aa** is the lightwell wall adjacent to outer wall **AA** of the building, etc. The wind direction is normal to and towards wall **AA**.
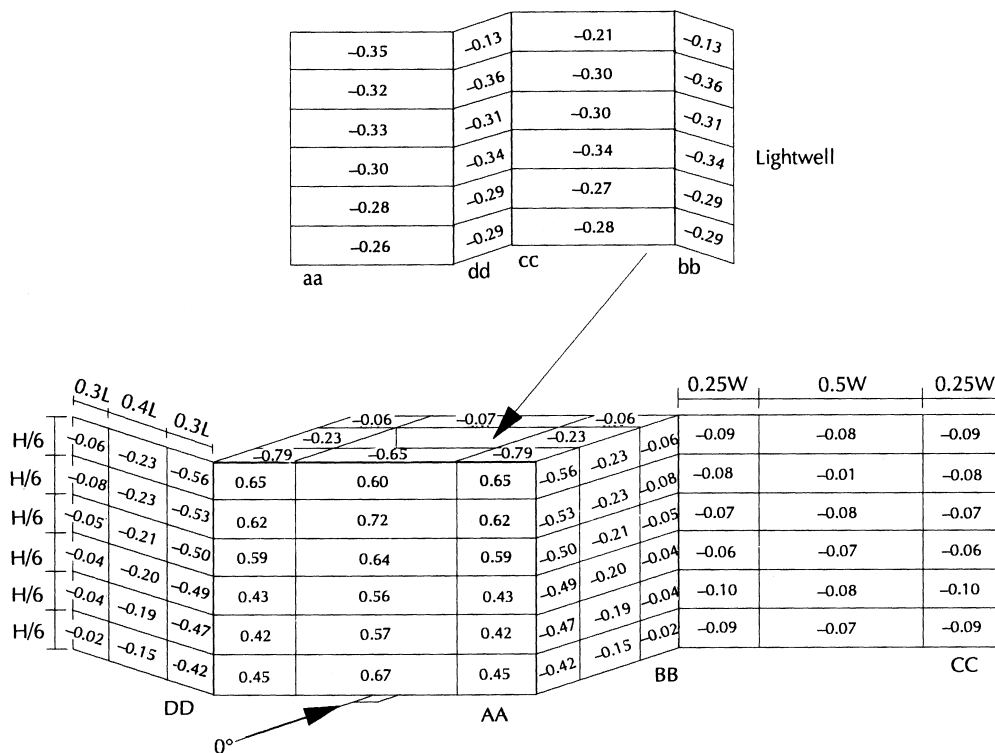

Figure F1 Wind pressure coefficients for a three-level office with lightwell

Tables F1 to F6 (Liddament, 1986) give single value wind pressure coefficients for each face of low rise buildings, for a range of shielding conditions.

Table F1 Wind Pressure Coefficient Data

Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.7	0.35	-0.5	-0.4	-0.2	-0.4	-0.5	0.35
Face 2		-0.2	-0.4	-0.5	0.35	0.7	0.35	-0.5	-0.4
Face 3		-0.5	0.35	0.7	0.35	-0.5	-0.4	-0.2	-0.4
Face 4		-0.5	-0.4	-0.2	-0.4	-0.5	0.35	0.7	0.35
Roof (<10° pitch)	Front	-0.8	-0.7	-0.6	-0.5	-0.4	-0.5	-0.6	-0.7
	Rear	-0.4	-0.5	-0.6	-0.7	-0.8	-0.7	-0.6	-0.5
Average		-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Roof (11-30° pitch)	Front	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5
	Rear	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5
Average		-0.4	-0.5	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5
Roof (>30° pitch)	Front	0.3	-0.4	-0.6	-0.4	-0.5	-0.4	-0.6	-0.4
	Rear	-0.5	-0.4	-0.6	-0.4	0.3	-0.4	-0.6	-0.4
Average		-0.1	-0.4	-0.6	-0.4	-0.1	-0.4	-0.6	-0.4

Low-rise buildings (up to 3 storeys)
Length to width ratio: 1:1
Shielding condition: Exposed
Wind speed reference level: Building height

Table F2 Wind Pressure Coefficient Data

Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.4	0.1	-0.3	-0.35	-0.2	-0.35	-0.3	0.1
Face 2		-0.2	-0.35	-0.3	0.1	0.4	0.1	-0.3	-0.35
Face 3		-0.3	0.1	0.4	0.1	-0.3	-0.35	-0.2	-0.35
Face 4		-0.3	-0.35	-0.2	-0.35	-0.3	0.1	0.4	0.1
Roof (<10° pitch)	Front	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5
	Rear	-0.6	-0.5	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5
Average		-0.6	-0.5	-0.4	-0.5	-0.6	-0.5	-0.4	-0.5
Roof (11-30° pitch)	Front	-0.35	-0.45	-0.55	-0.45	-0.35	-0.45	-0.55	-0.45
	Rear	-0.35	-0.45	-0.55	-0.45	-0.35	-0.45	-0.55	-0.45
Average		-0.35	-0.45	-0.55	-0.45	-0.35	-0.45	-0.55	-0.45
Roof (>30° pitch)	Front	0.3	-0.5	-0.6	-0.5	-0.5	-0.5	-0.6	-0.5
	Rear	-0.5	-0.5	-0.6	-0.5	0.3	-0.5	-0.6	-0.5
Average		-0.1	-0.5	-0.6	-0.5	-0.1	-0.5	-0.6	-0.5

Low-rise buildings (up to 3 storeys)
Length to width ratio: 1:1
Shielding condition: Surrounded by obstructions
                                equivalent to half the height of the building
Wind speed reference level: Building height

Table F3 Wind Pressure Coefficient Data

Location		Wind Angle							
		0º	45º	90º	135º	180º	225º	270º	315º
Face 1		0.2	0.05	-0.25	-0.3	-0.25	-0.3	-0.25	0.05
Face 2		-0.25	-0.3	-0.25	0.05	0.2	0.05	-0.25	-0.3
Face 3		-0.25	0.05	0.2	0.05	-0.25	-0.3	-0.25	-0.3
Face 4		-0.25	-0.3	-0.25	-0.3	-0.25	0.05	0.2	0.05
Roof (<10º pitch)	Front	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.4	-0.5
	Rear	-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.4	-0.5
Average		-0.5	-0.5	-0.4	-0.5	-0.5	-0.5	-0.4	-0.5
Roof (11-30º pitch)	Front	-0.3	-0.4	-0.5	-0.4	-0.3	-0.4	-0.5	-0.4
	Rear	-0.3	-0.4	-0.5	-0.4	-0.3	-0.4	-0.5	-0.4
Average		-0.3	-0.4	-0.5	-0.4	-0.3	-0.4	-0.5	-0.4
Roof (>30º pitch)	Front	0.25	-0.3	-0.5	-0.3	-0.4	-0.3	-0.5	-0.3
	Rear	-0.4	-0.3	-0.5	-0.3	0.25	-0.3	-0.5	-0.3
Average		-0.08	-0.3	-0.5	-0.3	-0.08	-0.3	-0.5	-0.3

Low-rise buildings (up to 3 storeys)
Length to width ratio: 1:1
Shielding condition: Surrounded by obstructions equal to the height of the building
Wind speed reference level: Building height

Table F4 Wind Pressure Coefficient Data

Location		Wind Angle							
		0º	45º	90º	135º	180º	225º	270º	315º
Face 1		0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
Face 2		-0.7	-0.8	-0.5	0.25	0.5	0.25	-0.5	-0.8
Face 3		-0.9	0.2	0.6	0.2	-0.9	-0.6	-0.35	-0.6
Face 4		-0.9	-0.6	-0.35	-0.6	-0.9	0.2	0.6	0.2
Roof (<10º pitch)	Front	-0.7	-0.7	-0.8	-0.7	-0.7	-0.7	-0.8	-0.7
	Rear	-0.7	-0.7	-0.8	-0.7	-0.7	-0.7	-0.8	-0.7
Average		-0.7	-0.7	-0.8	-0.7	-0.7	-0.7	-0.8	-0.7
Roof (11-30º pitch)	Front	-0.7	-0.7	-0.7	-0.6	-0.5	-0.6	-0.7	-0.7
	Rear	-0.5	-0.6	-0.7	-0.7	-0.7	-0.7	-0.7	-0.6
Average		-0.6	-0.65	-0.7	-0.65	-0.6	-0.65	-0.7	-0.65
Roof (>30º pitch)	Front	0.25	0	-0.6	-0.9	-0.8	-0.9	-0.6	0
	Rear	-0.8	-0.9	-0.6	0	0.25	0	-0.6	-0.9
Average		-0.18	-0.45	-0.6	-0.45	-0.18	-0.45	-0.6	-0.45

Low-rise buildings (up to 3 storeys)
Length to width ratio: 2:1
Shielding condition: Exposed
Wind speed reference level: Building height

Table F5 Wind Pressure Coefficient Data

Location		Wind Angle							
		0º	45º	90º	135º	180º	225º	270º	315º
Face 1		0.25	0.06	-0.35	-0.6	-0.5	-0.6	-0.35	0.06
Face 2		-0.5	-0.6	-0.35	0.06	0.25	0.06	-0.35	-0.6
Face 3		-0.6	0.2	0.4	0.2	-0.6	-0.5	-0.3	-0.5
Face 4		-0.6	-0.5	-0.3	-0.5	-0.6	0.5	0.4	0.2
Roof (<10º pitch)	Front	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
	Rear	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Average		-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Roof (11-30º pitch)	Front	-0.6	-0.6	-0.55	-0.55	-0.45	-0.55	-0.55	-0.6
	Rear	-0.45	-0.55	-0.55	-0.6	-0.6	-0.6	-0.55	-0.55
Average		-0.5	-0.6	-0.55	-0.6	-0.5	-0.6	-0.55	-0.6
Roof (>30º pitch)	Front	0.15	-0.08	-0.4	-0.75	-0.6	-0.75	-0.4	-0.08
	Rear	-0.6	-0.75	-0.4	-0.08	0.15	-0.08	-0.4	-0.75
Average		-0.2	-0.4	-0.4	-0.4	-0.2	-0.4	-0.4	-0.4

Low-rise buildings (up to 3 storeys)
Length to width ratio: 2:1
Shielding condition: Surrounded by obstructions
                            equivalent to half the height of the building
Wind speed reference level: Building height

Table F6 Wind Pressure Coefficient Data

Location		Wind Angle							
		0º	45º	90º	135º	180º	225º	270º	315º
Face 1		0.06	-0.12	-0.2	-0.38	-0.3	-0.38	-0.2	0.12
Face 2		-0.3	-0.38	-0.2	-0.12	0.06	-0.12	-0.2	-0.38
Face 3		-0.3	0.15	0.18	0.15	-0.3	-0.32	-0.2	-0.32
Face 4		-0.3	-0.32	-0.2	-0.32	-0.3	0.15	0.18	0.15
Roof (<10º pitch	Front	-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
	Rear	-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Average		-0.49	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Roof (11-30º pitch)	Front	-0.49	-0.46	-0.41	-0.46	-0.4	-0.46	-0.41	-0.46
	Rear	-0.4	-0.46	-0.41	-0.46	-0.49	-0.46	-0.41	-0.46
Average		-0.45	-0.46	-0.41	-0.46	-0.45	-0.46	-0.41	-0.46
Roof (>30º pitch)	Front	0.06	-0.15	-0.23	-0.6	-0.42	-0.6	-0.23	-0.15
	Rear	-0.42	-0.6	-0.23	-0.15	-0.06	-0.15	-0.23	-0.6
Average		-0.18	-0.4	-0.23	-0.4	-0.18	-0.4	-0.23	-0.4

Low-rise buildings (up to 3 storeys)
Length to width ratio: 2:1
Shielding condition: Surrounded by obstructions
                            equal to the height of the building
Wind speed reference level: Building height

13 Appendix G – Overview of available additional documents

13.1 Building-Related Input Data

13.1.1 Whole dwelling airtightness

- Air-tightness of U.S. dwellings (pdf file) + Set of data (Excel file)
- Field measurement results of the airtightness of 64 French dwellings (pdf file) + Set of data (Excel file)
- Airtightness of French dwellings - Results from field measurement studies (pdf file)
- Ventilation performances in French dwellings : Results from field observations and measurements (pdf file)
- Set of data from The Netherlands (Excel file)

13.1.2 Air leakage paths

- Component data from a variety of sources (Excel file)

13.1.3 Whole building airtightness data

- Whole building data from numerous references (Excel file)

13.1.4 Wind pressure corfficient

- Summary of wind pressure coefficient measurements from 50 references (pdf file) + Set of data (Excel file)
- Detailed measurements from the 'Tånga School' (pdf file) + Set of data (Excel file)
- Wind Pressure Data Requirements For Air Infiltration Calculations (AIVC TN 13) (pdf file)
- Knoll B, Phaff J C, and de Gids W F (1995), "*Pressure simulation program*", Air Infiltration and Ventilation Centre, UK, *Proceedings of 16th AIVC Conference*, "Implementing the results of ventilation research", held Palm Springs, USA, 18 - 22 September, 1995, Volume 1, pp 233-242. #9060
- Walker I S and Wilson D J (1994*), "Practical methods for improving estimates of natural ventilation rates*", Air Infiltration and Ventilation Centre, UK, *Proceedings of 15th AIVC Conference*, "The Role of Ventilation", held Buxton, UK, 27 - 30 September 1994, Volume 2, pp 517-526. #8001

13.2 Meteorological Data

- London, UK - coincidence of wind speed, direction and air temperature (pdf file)
- EC Test Reference Years (principally for thermal calculations) (pdf file) + Set of data (Excel file).
- A compression technique for meteorological data (pdf file)
- Driving forces in several European locations from the EU NatVent project (Excel file).
- A condensed ventilation weather year for the Netherlands (pdf file)
- Data collated through the IEA ECBCS Annex 27 project (pdf file)
- International Surface Weather Observations (ISWO) station list (pdf file)
- ISWO data format (pdf file)
- Engineering weather data handbook (pdf file)

13.3   Occupancy Data

- Assumptions for the Simulations, Draft, 19th November, 1996, IEA-ECBCS Annex 27, "Evaluation and Demonstration of Domestic Ventilation Systems"
- Default residential occupancy profiles (from the Annex 27 project) (pdf file)
- Occupant behaviour (Annex 20) (Excel file)
- Extensive occupant-related summary (42 references covering The Netherlands, United Kingdom, Australia, Belgium, France, Germany, Hong Kong, Hungary, Japan, Switzerland, USA) (pdf file) + Set of data (The Netherlands, UK, other countries) (Excel files)

13.4   Pollutant Data

- 211 references covering pollutant measurements and guidelines (pdf file) + Set of data (Building materials, Residential buildings, Commercial and residential buildings, Commercial buildings, Guidelines) (Excel files)

13.5   Evaluation Exercises

- Weather and aeraulic data set for validation – The LESO building – Part 1 : Content of the data set (pdf file)
- Weather and aeraulic data set for validation – The LESO building – Part 2 : Building description and measurement report (pdf file)
- The LESO dataset (an office building, Switzerland) (Excel file)
- Measurements at B&O HQ, Struer, Denmark - Presentation of detailed short term measurements (pdf file)
- Pilot study report : Bang & Olufsen - Struer, Denmark (pdf file)
- Background information : B&O Headquarters, Struer, Denmark (pdf file)
- Bang & Olufsen HQ - BEMS Monitoring (pdf file) + Set of data (long term measurements, short term measurements)
- Measurements of the ELA-atrium under summer conditions (pdf file) + Set of data (Excel file)
- Data for modelling internal conditions in the De Montford Auditorium (pdf file) + Set of data (Summary, Mid season, Summer, Winter) (Excel files)
- Description of ventilation principles in the Tånga School (pdf file)
- Pilot study report : Tånga - Falkenberg, Sweden (pdf file) + Set of data (Excel file)
- Tånga School Data Summary (pdf file) + Set of data (Damper positions and temperatures, Pressure drop over air supply ducts, Fan operation and meteorological conditions, Various parameters) (Excel files)
- Infiltration and leakage paths in single family houses - A multizone infiltration case study (AIVC TN 27) (pdf file)
- Multi-Zone Calculations and Measurements of Air Flows in Dwellings - IEA Annex 27 (pdf file)
- Infiltration data from the Alberta home heating research facility (AIVC TN 41) (pdf file) + Set of data (Excel file)
- Performances of a new generation high efficiency heat recovery units for domestic ventilation (pdf file)
- A Critical Review of Displacement Ventilation (pdf file)