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Pressure Coefficients on Sheltered Buildings

Summary of a report by Iain S Walker
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Sources of Pressure Coefficient Data

The effect of wind on building ventilation is determined by pressure coefficients that depend on many factors such as building geometry, wind direction, mean and turbulent atmospheric boundary layer velocity profiles, and the factor to be considered here : shelter by upwind obstacles. Pressure coefficients on the exterior of buildings are defined by normalising the pressure difference between that measured on the surface, $P_{surface}$, and a reference pressure (usually local atmospheric pressure, P_{atmos}) by an appropriate stagnation (or velocity) pressure. Stagnation pressure, P_{stag}, is defined as

$$P_{stag} = 0.5 \rho U^2 \qquad (1)$$

where U is the velocity in the undisturbed boundary layer at a reference height, usually the building eave or roof peak height and ρ is the air density. A pressure coefficient (Cp) is then defined as

$$Cp = (P_{surface} - P_{atmos})/P_{stag} \qquad (2)$$

Full scale measurements (e.g. Gustén (1989)) are not of much use for calculating ventilation rates as in most experiments there is only data for a few wind angles, windspeeds and shelter configurations. Also, in full scale tests it is difficult to maintain steady state conditions throughout a test and to eliminate stack effect pressures from the measurements. To capture all wind directions and to obtain enough measurements so that a reasonable average may be taken requires a long term program of testing which in most cases is both expensive and impractical.

Most sources of Cp are measured in wind tunnels as this allows for systematic variation of parameters such as wind angle, building geometry and shelter. Much of the data available in the literature is for specific buildings in specific urban environments and does not lend itself to a systematic analysis of building shelter effects. Some comprehensive measurements on exposed buildings have been made (e.g. Akins, Peterka and Cermak (1979)) to examine the effects of different boundary layer velocity profiles and wind angle (measurements were made every 10 degrees on average). Table 1 contains their wind tunnel results for Cp's with the wind direction perpendicular to the upwind wall.

In this issue

	Wall			Roof
	Upwind	Lee	Side	
Cp	0.6	-0.3	-0.65	-0.65

Table 1: Pressure coefficients on an isolated building in a turbulent boundary layer, with wind normal to the upwind wall. (From Akins, Peterka and Cermak (1979)

Most buildings are in urban areas and are not isolated therefore using Cp's from exposed buildings leads to overestimation of ventilation rates. Buildings are sheltered by surrounding buildings, trees, bushes etc. These obstructions change the local flow field around the building resulting in windspeed reductions and changes in pressure coefficients.

A possible future source of Cp's are Computational Fluid Dynamics (CFD) codes. These codes should be able to calculate surface pressures for any building shape or wind angle. Their use is probably restricted to a research level since they require large and expensive computers to run on; however, the results could be used to find simple algorithms that could be used in codes and standards.

The following sections describe the factors that affect sheltered building Cp's.

Upstream Flow

Mean velocity, turbulence and shear stress vary with height in the atmospheric boundary layer. This changes the flow around a building and other obstructions when compared to a uniform upstream flow. The mean velocity profile is commonly represented by power law relationship

$$U(z)/U(z_{ref}) = (z/z_{ref})^p \quad (3)$$

where U(z) is the mean velocity at height z above ground, U(zref) is the mean velocity at the reference height z_{ref} and the power p depends on terrain roughness and atmospheric stability, which itself is a function of windspeed and solar insolation. Values for p are given by Irwin (1979) and some typical values are given in Table 2. Figure 1 illustrates the change in boundary layer velocity profile with height and terrain roughness. The power law relationship (equation 3) allows meteorological tower windspeeds to be converted to other heights such as the building eave or roof peak height as used to calculate Cp's.

Terrain Class	Terrain Roughness	$U_{met} > 3$ m/s neutral stability Class D	$U_{met} < 3$ m/s stable Class E
1	Open Flat Terrain Rural Grassland z_o - 1 cm	0.12	0.34
2	Suburban Detached Housing Mixed Woods and Fields z_o - 10 cm	0.16	0.32
3	Dense Urban Housing with Multi Storey Buildings Heavy Forests z_o - 100 cm	0.27	0.38
4	High Rise Urban Centres z_o - 300 cm	0.37	0.47

Table 2: Windspeed power law exponent p (Irwin (1979))

Air Infiltration Review

Editor: Janet Blacknell

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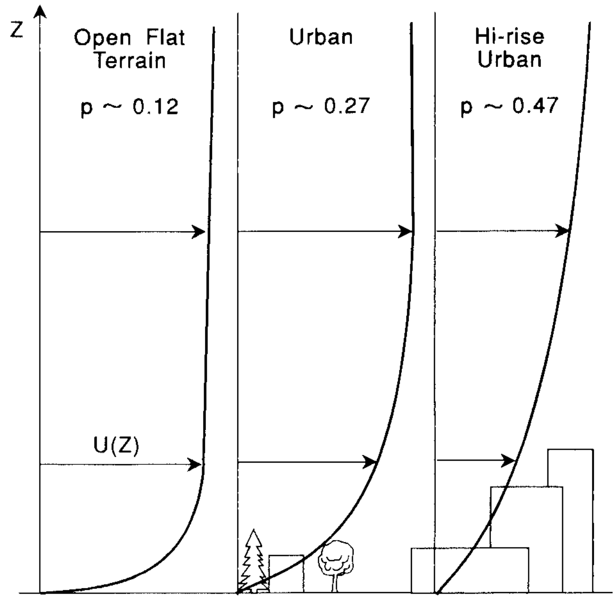

Figure 1: Change on boundary layer velocity profile with height and terrain roughness.

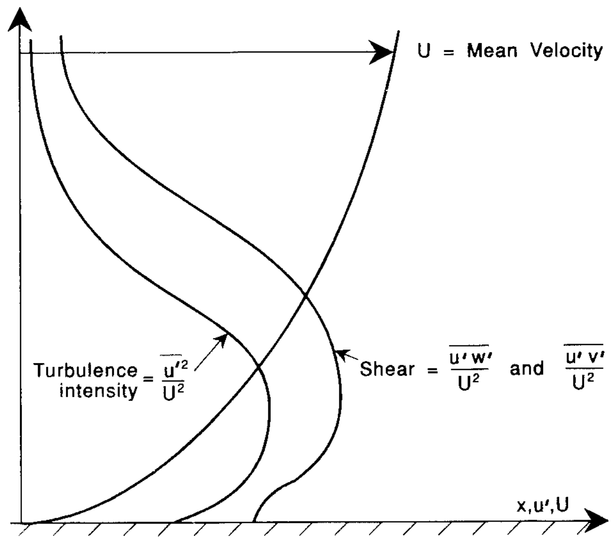

Figure 2: Typical velocity, shear and turbulence profiles

The variation of wind velocity with height creates shear in the flow which leads to a leading horseshoe vortex developed at the upstream side of the building. The turbulence in the atmospheric boundary layer also varies with height. Figure 2 is a sketch showing typical velocity, shear and turbulence profiles in which u', v' and w' are the turbulent fluctuations in velocity in the along wind (u'), horizontal (v') and vertical (w') directions.

This illustration gives the shape of the profiles only and not the magnitudes of the quantities involved. The horizontal fluctuations (v') are the cause of fluctuations in wind direction. Atmospheric turbulence is usually expressed as a root mean square quantity ($U_{r.m.s.}$) or as a turbulence intensity where the r.m.s. value is divided by the local mean velocity.

$$U_{r.m.s.} = ((u')^2)^{0.5} \quad (4)$$

$$\text{Turbulence intensity} = U_{r.m.s.}/U(z) \quad (5)$$

Typical values of turbulence intensity at the height of residential buildings are between 20% and 30% (Counihan (1973) and Tieleman, Akins and Sparks (1981)).

The scale of turbulence is also a major factor as it changes the pressure distribution in both time and space. Probably the most important scale for building surface pressures is that which matches the building size or the size of any large openings such as doors or windows. This scale of turbulence will interact with the flow around the building and effect the measured pressures. Turbulent scale interactions can be extremely complex and are beyond the scope of this report.

Increasing turbulence and shear tend to reduce the magnitude of all the Cp's on a building. The reduction in upstream velocity lowers the positive pressure coefficients on an upwind wall. Results from wind tunnel studies by Castro and Robbins (1977) and Corke and Nagib (1979) are shown in Table 3. Because of their effects on wake formation and growth and flow around the building it is important to model mean velocity, turbulence and shear correctly in wind tunnel and CFD experiments to find Cp's.

Shear and Turbulence	Wall			Roof
	Upwind	Lee	Side	
A] Low	0.9	-0.5	-0.65	-0.6
A] High	0.6	-0.15	-0.25	-0.4
B] Low	0.75	-0.3	-	-
B] High	0.5	-0.1	-	-

Table 3: Effect of boundary layer shear and turbulence on pressure coefficients (Castro and Robbins (1977) [A] and Corke and Nagib (1979) [B])

Wakes

Buildings experience shelter when they are in the wake of another building or some other upstream obstacle. Close behind an obstacle the mean wind velocity is near zero and there is a zone of recirculating flow where the turbulent velocities are of the same order or larger than the mean velocities. The recirculation zone extends about three building heights downstream at which point the mean velocity has recovered to 90% or more of the upstream value (Peterka and Cermak (1975)). Beyond the recirculation zone the mean velocity has recovered sufficiently to prevent flow reversals and the flow becomes self-preserving. The area of most importance for shelter effects on ventilation is in the recirculation zone where windspeeds are lowest.

Building Geometry

The relative size of each building dimension determines the flow pattern and thus the surface pressures. For example, a building whose along wind dimension is greater than its across wind dimension will experience greater pressure recovery on the sides roof and leeward walls thus making these pressure coefficients less negative.

The angle of roof pitch can change the flow as a flat roof will have a separation zone and experience highly negative pressures (Cp = -.6 from Akins et. al. (1979)) and a steeply pitched roof will have positive pressures on its upwind side and negative pressures on its downwind side (From Wirén (1985) Cp upwind = +0.2 and Cp downwind = -0.8). Wirén's data set for examining building shelter is one of the most comprehensive wind tunnel data sets to date including a boundary layer with shear and turbulence with Cp's measured on each surface. Most wind tunnel testing is performed on buildings of rectangular plan with no protuberances. For buildings that may shelter each other their relative sizes are important as a large building will completely immerse a smaller building in its wake whereas the wake from a smaller building will only partially shelter a larger one.

Wind Direction

With different wind directions the part of the building that is upstream changes. Akins, Peterka and Cermak (1979) show how the Cp's on an isolated building vary with wind angle for an isolated building. Other data sets covering fewer angles are to be found in ASHRAE (1989) and Liddament (1986).

Wirén (1985) measured the change in Cp with wind angle for a building with identical buildings to either side. An important parameter here is the building separation distance, S (measured form wall to wall), normalised by building height, H. Wirn's tests were performed with a separation equal to the side length of the building. Given the building dimensions this gives $S/H \approx 1.7$. Table 4 shows how the Cp's change as the wind direction is changed from being normal to the row of buildings to being parallel. Figure 3 illustrates the numbering convention used for the walls and roof. This numbering convention is also used in the other tables.

Wind Direction	Wall				Roof	
	1	2	3	4	Front	Rear
Normal to wall 1	.6	-.7	-.9	-.9	.2	-.8
Normal to wall 3	-.15	-.15	.15	-.15	-.15	-.15
Isolated building - normal to wall 1	.6	-.65	-.85	-.85	.2	-.8

Table 4:Effect of wind direction on shelter for C_p's on buildings in a row (Wiren (1985))

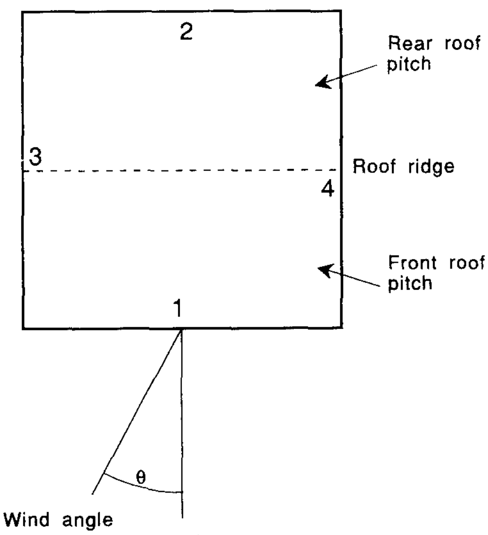

Figure 3: Numbering convention used for the walls and roof

The Cp's for flow along the row of buildings are the same on all but the upwind wall, which shows how the separation that produces the large negative pressures on leeward and side walls is suppressed due to the low velocities and high turbulence caused by the upstream building. The lower pressure on the upwind wall is a consequence of the reduced mean velocity in the wake. Table 4 also shows that when flow is normal to the row the Cp's on the side walls are more negative than for an isolated building. This is due to flow acceleration in the gaps between the buildings. The effect on air infiltration rates due to direction sensitive shelter on buildings in a row has been measured by Wilson and Walker (1991) and can cause up to a factor of five change in ventilation rate.

Figures 4 and 5 show more completely Wirén's data as a function of wind angle where 0 degrees is normal to wall 1. Figure 4 is for Wall 1 which is initially the upwind wall and Figure 5 is for Wall 3, one of the side walls (see Figure 1 for orientation). These two Figures also show data for an unsheltered building for comparison. It can be seen that the greatest effect is when the wind blows along the row (at wind angles of 90 and 270 degrees).

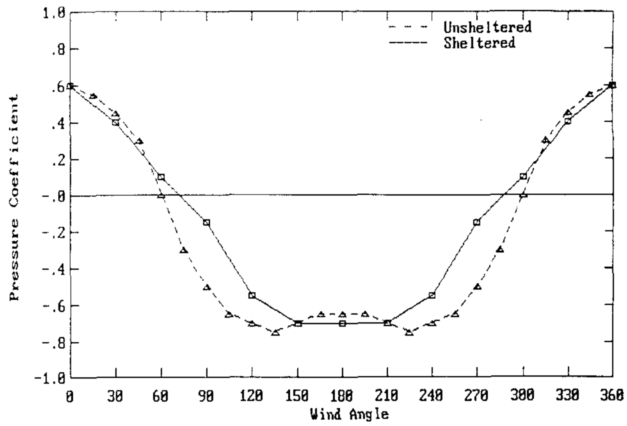

Figure 4: Comparison of sheltered and unsheltered pressure coefficients on the front wall (Wirén (1985))

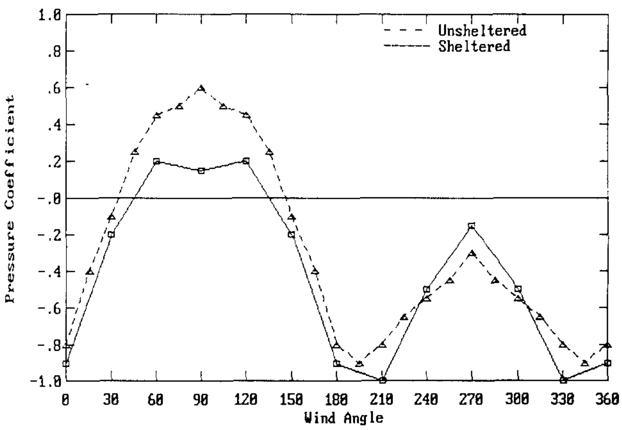

Figure 5: Comparison of sheltered and unsheltered pressure coefficients on the side wall (Wirén (1985))

Building Separation

Hussain and Lee (1980) described three flow regimes for shelter arrays that depend on building separation:

1 Isolated Roughness [S/H > 2.5] : Buildings are far enough apart that each building acts in isolation.

2 Wake Interference [2.5 > S/H > 1.5] : Buildings are closer together and the separation bubble is not fully developed because the front separation region (leading horseshoe vortex) of the downwind building is met before reattachment.

3 Skimming Flow [S/H > 1.5] : The separation bubble forms a stable vortex between the buildings.

Using H as the significant building dimension only applies to cubes. A more general effective building dimension (R) can be calculated using equation (6)

$$R = D_{small}^{2/3} D_{large}^{1/3} \qquad (6)$$

where D_{small} is the smallest building dimension and D_{large} is the largest building dimension.

In regions 1 and 2 the effect of shelter is to reduce the local windspeed. In region three the flow pattern changes and the high turbulence and low mean velocity reduce separation occurring on the top and sides of the building. This means that all but the upwind wall have almost exactly the same pressure coefficient, as shown in Table 4. In most urban environments buildings are arranged in rows and the shelter provided in region three is most applicable. Wilson and Walker (1992) have shown that the ventilation rates of terraced houses are reduced by a factor of three when the wind is parallel to the row.

Wirén's data for buildings in a row with varying separation is presented in Table 5, with the wind flow along the row parallel to walls 1 and 2. This shows how the pressures become more uniform as the separation is decreased. To calculate Cp's for values of S/H not shown in the table a linear interpolation between tabulated values may be used. For building separations below the lowest values (S/H = 1.7) in the table use these lowest values.

Separ-ation S/H	Wall				Roof	
	1	2	3	4	Front	Rear
Isolated	-.5	-.5	.6	-.3	-.4	-.4
4.25	-.4	-.4	.35	-.25	-.3	-.3
3.4	-.35	-.35	.3	-.25	-.25	-.25
2.55	-.25	-.25	.25	-.2	-.2	-.2
1.7	-.15	-.15	.15	-.15	-.15	-.15

Table 5: Influence of building separation on Cp's (Wiren (1985))

Combining Shelter from Several Obstacles

In most urban areas a building will be sheltered by more than a single obstacle. The effect of additional obstacles can be found by examining Wirén's data for buildings surrounded by uniform arrays of obstructions. In these experiments consecutive rings of obstacles were added to the sheltering array. Table 6 shows how the nearest ring of obstacles dominates the building shelter, with additional rings not contributing any significant extra sheltering effect. Comparing Table 6 to Table 4 also shows that there is little difference between the shelter provided by an array of buildings and buildings in a row when the wind is along the row. Thus a good initial estimate of sheltering effect can be found by only considering the nearest sheltering objects. Wirén's data for doubling the uniform separation to S/H = 3.4 confirms that only the closest obstacle has a significant effect on the building shelter.

Amount of shelter	Wall				Roof	
	1	2	3	4	1	2
Isolated	-.5	-.5	.6	-.3	-.65	-.65
1 ring S/H=1.7	-.2	-.2	.15	-.2	-.2	-.2
2 rings S/H=1.7	-.2	-.2	.15	-.2	-.2	-.2
3 rings S/H=1.7	-.2	-.2	.15	-.2	-.2	-.2
1 ring S/H=3.4	-.35	-.35	.25	-.3	-.25	-.25
2 rings S/H=3.4	-.3	-.3	.25	-.3	-.25	-.25
3 rings S/H=3.4	-.3	-.3	.25	-.3	-.25	-.25

Table 6: Effect of additional sheltering obstacles on C_p (Wirén (1985))

Conclusions

The best current method for obtaining pressure coefficients on sheltered buildings is to use wind tunnel models. In the future CFD codes may also be utilized, but currently they are expensive to run and it is not easy to obtain correct results for a broad range of conditions. To be useful for air infiltration analyses the test results need to fulfill the following criteria:

- The reference velocity used to calculate Cp's should be given in addition to the velocity profile.
- The velocity, and preferably the turbulence profile, should be within the range found in the atmospheric turbulent boundary layer.
- Cp's should be averaged over a wall by including as many points on the wall as possible that are equally weighted by area. An exception to this is for high rise buildings that may have large changes in Cp over their faces and different parts of each face are treated as different zones for ventilation calculations.
- Cp's should be defined as in equation (2) and not presented in terms of a windward-leeward or an inside outside pressure difference.
- The building and obstacle geometries and their location with respect to each other needs to be known.

Simple, physically realistic algorithms must be found to describe the Cp's to replace the massive number of lookup tables required if all parameters are to be sufficiently resolved. It is the surface pressure and not the Cp that is important for ventilation, thus the effect of shelter can be separated into the product of windspeed reduction and change of Cp's.

When a building is close to an obstacle (within approximately 1.5 obstacle heights) then the obstacle changes the flow pattern over the building so that a scaling of pressures by using a reduced windspeed no longer describes the surface pressures. In this case the separation zones on the top and sides of the building are reduced and the surface pressures become more uniform thus changing the Cp's.

The spread of wakes can be found by applying conservation of momentum across the wake once the wind speed in the wake is known. The results of windspeed reduction and changing Cp's measured in wind tunnel testing can be used to formulate the algorithms required to predict wind pressures on buildings for ventilation studies.

Guideline for Estimating Sheltered Cp's From Existing Data

A rule of thumb for sheltered Cp's can be estimated by assuming that most buildings are in urban surroundings and have other buildings within two building heights in all directions. The closest sheltering obstacle dominates the shelter experienced by a building. The most appropriate pressure coefficients to use are taken from Table 6 (from Wirén (1985)) where Cp = -.2 for all building surfaces except the upwind wall where Cp = .15. Buildings that are further apart or unsheltered have less uniform Cp's and are shown in Table 5. To calculate Cp's for values of S/H not shown in the table a linear interpolation between tabulated values may be used. For building separations below the lowest values (S/H = 1.7) in the table use these lowest values.
For buildings with non-uniform shelter Figures 4 and 5 can be used to estimate the change in Cp's on each wall.

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Sick Buildings Aired at ASHRAE

Report on Baltimore ASHRAE Meeting, June 1992

Martin W Liddament, Air Infiltration and Ventilation Centre

While formal Technical Sessions and Symposia continue to form an important aspect of ASHRAE meetings, in recent times, increased emphasis has been given to Seminars, Forums and Technical Committee meetings. Unlike the formal sessions, these other meetings do not produce published output, although they do much to drive the policy, standards and research programme of ASHRAE. Invariably, sessions on similar topics run concurrently, with the result that selecting appropriate meetings to attend is difficult and much can be missed. Nevertheless, a strength of ASHRAE is the freedom to attend and raise points at any of the meetings, no matter how specialist or small they may be.

A brief review of the programme clearly indicated that indoor air quality and ventilation remain dominant issues. In charting a course through the timetable, a decision was made to concentrate on the unreported sessions covering this topic.

Keeping Outside Contaminants Out - Forum-4

The first such session was a Forum entitled "Keeping Outside Contaminants Out". To stimulate the free flow of ideas at Forums, ASHRAE require the anonymity of contributors, therefore open reporting is restricted. However, general points were raised that have applications in almost any built environment. Pollutant problems were categorised in terms of:

- regional problems (such as local industrial areas).

- medium term transient (dominated by weather systems).

- short term transient (such as rush hour traffic).

- local problems (such as emissions from nearby exhausts).

Solutions for regional problems concentrated on cleaning exhaust emissions, statutory considerations and, in some cases, the use of filtration to clean the incoming air. Reference was also made to the guidelines already given for the siting of industrial stacks in Chapter 14 of the ASHRAE Fundamentals.

Weather dominated problems are those that might prevail for several days and be the cause of high ozone and other pollutant concentrations derived from high traffic pollution and the reaction of sunlight. Charcoal filtration systems were seen as a method of alleviating the problem in buildings.

Discussion on transient local traffic fumes focused on both the use of air quality controlled inlet dampers and on the siting of air inlets. Air quality controlled dampers were particularly seen as a possible cure for very transient air quality problems. Evidence was also cited on the effect of location of supply inlets. Inlets placed at roof level of one high rise building were found to have only 1% of the traffic pollutants found in the street level supply inlet of the same building.

Contamination or re-entry from adjacent exhausts was also identified as an important problem for which further design guidance was needed. This problem is especially complex because the risk of contamination is dependent on the proximity of adjacent exhausts or cooling towers, local topography and wind conditions. It was concluded that although some guidance was available in the ASHRAE Fundamentals, more guidance is needed. It was also reported that an ASHRAE Work Statement on this topic was currently being drafted.

Other topics included infiltration problems, the reliability of air quality monitors, the range of external pollutants that should be measured and requirements covering external air quality.

Ventilation for Acceptable Indoor Air Quality - SSPC 62

Standing Standard Project Committee (SSPC) on Ventilation for Acceptable Indoor Air Quality met from 13.00 to 21.00 on Sunday afternoon and evening. This session was split into several parallel subcommittee meetings followed by a marathon and general meeting which attracted approximately 100 participants.

ASHRAE Standard 62 is probably one of ASHRAE's most sensitive Standards. Last revised in 1989, it has been used by authorities both within the United States and throughout the world. It has also been used in litigation evidence when buildings have not performed. The implications related to health and indoor air quality as well as the concerns of many of the groups represented on the various subcommittees serve to make future revisions a very lively activity. In preparing for a future revision, a total of eight subcommittees have been formed. These are:

- Health and Comfort.

- Source Control and Air Cleaning.

- IAQ Procedure Group.

- Energy Impact of Ventilation.

- Residential Ventilation.

- Ventilation Efficiency.

- Operation and Maintenance.

- Editorial.

The principal purpose of the meeting was to review the activities of the various subcommittees. On health and comfort, the identified needs included evaluating knowledge on contaminant concentration limits, including the effects of exposure and problems associated with the interaction of multi-contaminants. A need to define acceptable indoor air quality was expressed.

Since requirements in dwellings differ from that of the work place, the residential subcommittee suggested a need for a separate standard or section in the standard to cover ventilation in the home. Aspects of concern included backdraughting from combustion appliances, climatic influences and the general relationship between IAQ and air change rate. An issue was also raised on whether natural ventilation was an acceptable means of ventilation. On this point, there was no consensus within the subcommittee. One suggestion was made that the rate of ventilation should be prescribed within the Standard rather than prescribing methods of achieving these rates. A reference level or definition of acceptable indoor air quality was also needed.

The IAQ subcommittee is attempting to determine comfort and health aspects of indoor air quality. They are also determining the feasibility of presenting an IAQ procedure in the form of Code Language. Other aspects include specifying criteria to deal with individual contaminants, providing guidance by examples and evaluating system requirements for good indoor air quality.

A report from the energy impact subcommittee reviewed and questioned current views on the energy and air quality impact of ventilation. It reviewed 70 research studies on ventilation rate and sick building syndrome and argued that, in each case, no statistical correlation between ventilation and SBS could be found. On the otherhand it suggested that the energy impact of increasing the intake of outdoor air could have a much greater energy impact than previous studies had revealed. Thus the energy impact committee placed firmly on the agenda the need to understand the role of ventilation in relation to indoor air quality and energy consumption.

Other items covered at this meeting included:

- the development of a manual of practice.

- European Guidelines for Ventilation Requirements in Buildings.

- organising a Forum on Standard 62.

Air Flow around Buildings - TC 2.5

Technical Committees coordinate activities within given subject areas and recommend to ASHRAE the priority in which tasks should be undertaken. They also manage the progression of ASHRAE funded research, the development of Standards and revisions to the ASHRAE Handbooks.

Technical Committee 2.5 is currently preparing a Work Statement on Design Criteria for Building Ventilation Inlets to avoid the ingress of contaminants. In the first instance, a review of current methods and needs is proposed which would then be followed by the development of specific design procedures. This committee met to finalise the Work Statement, incorporating the ideas presented at the Forum on keeping outdoor contaminants out. It also met to review other possible Work Statements including one on the effects of architectural screens on building ventilation systems.

Ventilation Requirements and Infiltration - TC 4.3

Technical Committee 4.3 is concerned with the identification of ventilation requirements for buildings and with the leakage characteristics of building components. As such, it is responsible for the progression of revisions to Standard 62 on ventilation for acceptable indoor air quality. The meeting reviewed progress on this Standard and on work on categorising component air leakage. It also received comments on proposed revisions to Chapter 23 of the Ashrae Fundamentals (Infiltration and Ventilation) and reviewed the progress of future Work Statements. Proposed Work Statement topics included:

- Radon and Below Grade Infiltration

- Air Leakage Test Procedures for Minimising Halon Discharges.

- The Impact of Leaks in Ducts on Energy Consumption.

- Designing Single Family Homes to Specific Airtightness Values.

- The Impact of High Use Automatic Doors on Infiltration.

- Infiltration Data for Model Validation Purposes.

- Validation of Interzonal Models.

Methods of Measuring Ventilation Rates - SPC 136

Standing Project Committees meet to draft and supervise, on behalf of the relevant Technical Committee, the progression of Standards. Standing Project Committee 136 met briefly to approve the final text of proposed ASHRAE Standard 136 on establishing a protocol for estimating ventilation rates in single family dwellings. This Standard combines climatic data for the United States and Canada with results from building pressurisation testing to infer an average ventilation rate under both naturally and mechanically ventilated conditions for dwellings in any North American location.

Indoor Air Quality Modelling - Seminar-25

ASHRAE Seminars take the form of presentations of ongoing research, without the requirement for presenters to produce written material.

Seminar-25 focused on the development of numerical modelling to predict indoor air quality in buildings. Presentations covered:

- multi-zone applications (IEA Annex 23).

- the prediction of ventilation effectiveness.

- the development of interfaces.

- smoke control simulation.

- transport through sub-floor ventilation systems.

Pilot Field Study of the Indoor Environment in Office Buildings - Seminar-26

This seminar reviewed current studies in assessing the role of the indoor environment on occupants. The discussion was chaired by Bjarne Oleson of the Virginia Polytechnic Institute and State University. Presentations concentrated largely on the results of questionnaire analysis and multi-parameter studies. Preliminary results from an eight building study indicated that it was difficult to relate specific parameters to environmental acceptability. Of the buildings studied, two were identified as "sick" and required remedial renovation, three had some complaints and the remaining three were free of complaints. Often job category or job stress had a significant influence on an occupants perception of satisfaction. There was little or no relation found between carbon dioxide concentration, an indicator of low ventilation rate, and complaints in the buildings studied. Equally, no significant correlations were found with other common pollutants. It was stressed, however, that while parameters were independently assessed against symptoms, very often parameters do not act independently of each other. Nevertheless, at this stage of the study, no clear information has been identified on the cause of building environmental problems.

Experiences Using Carbon Dioxide as an Indicator of Indoor Air Quality - Seminar-34

The monitoring of carbon dioxide in buildings as an indicator of air quality has been a popular concept. Metabolic carbon dioxide concentration for sedentary occupation can be closely correlated to the rate of outdoor air ventilation. Dick Grot of Lagus Technology illustrated that a steady state concentration of 2000ppm of carbon dioxide equated with a ventilation rate of 5cfm (2.5 l/s), while 1000ppm correlated with 15cfm (7.5 l/s) (ASHRAE minimum recommended ventilation rate), 800ppm with 20cfm (10 l/)s and 600ppm with 40cfm (20 l/s). It was recommended that carbon dioxide levels should be kept to below 600ppm to minimise air quality problems. William Fisk of the University of California cited the results of 9 surveys total approximately 8000 occupants and found no statistical correlation between carbon dioxide concentration and symptoms of sick buildings. In most instances, concentrations were below the 1000 ppm level but in a school study there was a perception of bad odour for concentrations above 1200ppm. Other contributors included Andy Persily of the US National Institute of Standards and Testing who illustrated methods by which the ventilation rate in a building could be determined by monitoring carbon dioxide concentrations

Other Sessions

In addition to the above "unreported" activities, the ASHRAE Programme included several relevant Technical and Symposium presentations. This included a Symposium entitled "Air Flow in Realistic Rooms - CFD and Physical Data". Papers from this and other sessions will be reviewed in "Recent Additions to Airbase".

For further information, contact Martin Liddament at the AIVC.

Application of Tracer Gas Techniques for Measurement of Friction-Factors of Rectangular Ducts

K W Cheong and S B Riffat

Nottingham School of Architecture, University of Nottingham, Great Britain

Abstract

This work examines the application of the constant-injection and pulse-injection tracer-gas techniques for measurement of airflow in rectangular ducts. Experiments were carried out in ducts with aspect ratios of 1, 2 and 4. Tracer-gas measurements were generally similar to measurements made using a pitot tube. Relationships for the friction-factor (f) and hydrodynamic entrance length are presented for Reynolds number between 73,300 and 395,000. Results indicated that f and Le are dependent on the aspect-ratio of the duct.

1.0 Introduction

Rectangular flow passages are commonly used in HVAC systems, heat exchangers, gas turbine regenerators and nuclear reactors. As a consequence, there is significant interest in the measurement of fluid flow through this type of passage. Accurate measurement of fluid velocity in flow passages is important but often difficult to achieve using traditional instrumentation such as hot-wire anemometers, pitot tubes and vane anemometers. Measurements may be restricted as a result of the short length of the duct or limited access to the flow passage. Furthermore, it is difficult to obtain reasonable measurement accuracy with a pitot tube or vane anemometer when flow velocities are less than 3 m/s.

Tracer-gas techniques offer an alternative approach for measuring airflow in ducts and unlike traditional instrumentations, are not limited by length or complexity of duct configuration. The following injection strategies were used for measuring airflow in ducts:

i) constant-injection: tracer-gas is injected into the duct at a constant rate and the resulting concentration response is measured.

ii) pulse-injection: tracer-gas is injected into the duct in separate, short duration pulses and the concentration response is measured.

This paper describes the application of tracer-gas techniques for measuring the friction-factor and hydrodynamic entrance-length of rectangular ducts of various aspect-ratios.

2.0 Theory

2.1 Constant-Injection Technique

This technique involves the injection of a tracer gas into the duct at a constant rate, q, using a mass flow controller. Assuming that the concentration of tracer gas, C, in the outside air is zero, the following equation can be used for steady-state conditions:

$$F = (q/C) \times 10^6$$

2.2 Pulse-Injection Technique

This technique is based on the injection into the duct inlet of a short-duration pulse of tracer gas at a rate G(t). The variation of concentration with time is measured at the duct exit. The amount of injected tracer gas is small, so it does not contribute significantly to the volume flow rate of air in the duct.

Applying the integral volume balance of tracer gas, we have:

$$F(\alpha) = \left[\int_{t1}^{t2} C_{(t)}\, dt\right]^{-1} \int_{t1}^{t2} G_{(t)} dt \quad (\text{for } t_1 \le \alpha \le t_2)$$

2.3 Friction-Factor and Entrance-Length

The wall shear-stress for steady incompressible fully-developed flow in a duct is given by:

$$\tau_w = \frac{-D_h}{4}(\Delta P/\Delta X)$$

The friction factor may be defined as:

$$f = 2\,\tau_w/\rho U_b.$$

The procedure used to obtain the relationship between f and Re is as follows:

Considering Re $= \rho U_b D_h/\mu$ and the above equation, it can be seen that the following measurements are required: air temperature, to obtain ρ and μ ; test section hydraulic diameter, D_h; bulk velocity, U_b; pressure drop, ΔP; and ΔX . The bulk velocity U_b, was estimated from tracer-gas measurements as outlined in section 2.1.

The hydrodynamic entrance-length was determined using the Bernoulli equation and tracer gas techniques were used to estimate the velocity profile of the ducts.

3.0 Experimental

The experimental work was carried out using ducts with cross-sections of 300 mm x 300 mm, 600 mm x 300 mm and 1200 mm x 300 mm (see Figure 1). The ducts were constructed from galvanised mild steel and were 9m long. The downstream end of the ducts was connected to an axial fan by means of a diffuser. The flow rate through the ducts was varied using a speed controller.

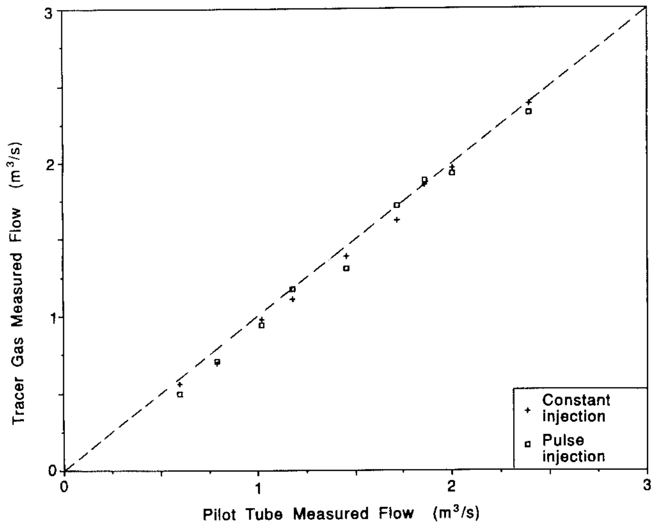

Figure 1: Experimental work carried out using ducts

Static, velocity pressure and tracer gas tappings were positioned along the duct. The velocity tappings allowed insertion of a pitot tube which could be traversed across the duct cross-section in order to measure velocity at various distances from the duct wall.

The concentration of tracer gas was measured using an infra-red gas analyser, type BINOS 1000. The accuracy of analyser was estimated to be within ±2%.

4.0 Results and Discussions

Airflow rates in the ducts were measured with a pitot tube and also using of the constant-injection and pulse-injection techniques. Figure 2 compares measurements of duct air-flow rate made with the tracer-gas techniques and a pitot tube.

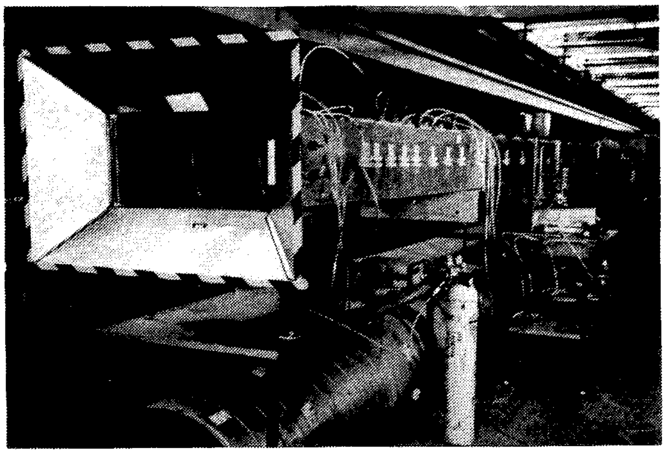

Figure 2: Measurement of duct air flow rate made with the tracer gas techniques and a pitot tube

The friction factor, f and entrance length, Le required to achieve fully developed flow were calculated using values for the average velocity (based on tracer gas measurement) and the pressure gradient. Table 1 shows the relationships of f/Re and Le/Re. It is clear from this table that f and Le are affected by the aspect-ratio of the duct. For Re = 110830, the values of f were found to be 5.19×10^{-3}, 6.24×10^{-3} and 6.59×10^{-3}, respectively while the values of Le were 2.29, 4.04 and 5.18 m respectively.

Aspect-Ratio	Friction-Factor (f)	Entrance-Length (Le)
1 :1	$0.0209\ Re^{-0.12}$	$1.894\ Re^{0.12}\ D_h$
2 : 1	$0.0637\ Re^{-0.20}$	$0.99\ Re^{0.20}\ D_h$
4 : 1	$0.3421\ Re^{-0.34}$	$0.208\ Re^{0.34}\ D_h$

Table 1 Relationships of f/Re and Le/Re

5.0 Conclusions

The constant-injection and pulse-injection techniques were applied successfully for measuring air flow in rectangular ducts. Results were in general agreement with pitot tube measurements.

Relationships were established for f and Le for rectangular ducts and these were found to be influenced by the aspect-ratio.

Acknowledgements

The authors wish to acknowledge the financial support of the Science and Engineering Research Council for this project.

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Advanced Ventilation Systems - State of the Art and Trends Bas Knoll, TNO Netherlands

Digest of AIVC Technical Note 35 by Mark Limb, Air Infiltration and Ventilation Centre

Increased health standards and the need to save energy, has resulted in modern residential buildings becoming more airtight and better insulated, and as such demands greater consciousness on the part of applied ventilation systems.

This report focuses on residential ventilation systems where the main pollutant sources are occupant dependent. However, consideration is not given to ventilation as a means of reducing the effects of highly avoidable pollutants, special ventilation appliances and techniques such as filtration and air cleaning.

The report deals with dwellings which display some, or all, of the following features:

- building materials used have emissions already limited at the production stage;

- the floor is airtight to prevent ingress of radon, methane or vapour;

- vapour barriers are applied to prevent vapour transport from the building shell;

- thermal bridges are avoided and reasonable insulation levels appear to prevent mould growth;

- no unvented combustion appliances are being used;

- additional ventilation means are applied to deal with incidental high internal heat loads, over occupancy, severe smoking and polluting household or hobby activities.

A review of advanced residential ventilation systems, design considerations and common and advanced approaches, especially in colder climates, is presented.

Chapters 1 and 2 outline the structure of the report and provides a resume of ventilation needs. This is followed by a National Standards and Systems summary, covering AIVC countries, and outlining official ventilation requirements for residential buildings in chapter 3. Also included is a review of most commonly used systems and ventilation trends in these countries. Appendices A and B contain additional information relating to these discussions.

In Chapter 4 the emphasis is on present ventilation systems, common and advanced approaches, based on a review of relevant literature. The majority of common and advanced systems are also classified in this Chapter employing an overall performance index as an arbitrary rate, as outlined in Appendix C. The author discusses what he considers are the most significant new developments for promoting further discussion and research, in Chapters 5 and 6.

In milder climates natural ventilation still dominates, and recent attempts to improve its control are highlighted. However, in more severe climates, that natural ventilation has been superceded by mechanical systems, which allow even greater control over the ventilation process.

The advanced systems are divided into four categories:

1. Air movement control system, subdivided into spot, room, inter room and dwelling in or outflow control systems.

2. Flow quantity control systems, subdivided into automatic setpoint maintenance and set point adjustment systems.

3. Ventilation heat recovery systems.

4. Alternative ventilation energy gain systems.

To establish the way in which different developments contribute to better ventilation, both from an energy and indoor air quality point of view, a categorisation system is developed. Each system is then compared with other systems, and also with an ideal system which combines all of their separate features.

A rating table has been devised, classifying each ventilation system's main characteristics according to the five categories shown below:

1. Application of ventilation flows taking into consideration the location, production and flow pattern of pollutants.

2. Energy input or recovery.

3. Cost of installation and operation.

4. Reliability (durability and risk of disorders).

5. Effect on comfort.

Following discussion of each of the points above, the report culminates in a categorisation of both common and advanced ventilation systems, as outlined in the attached Table.

Based on the results of this table the author concludes that:

- most ventilation systems do have a poor ability to direct ventilation air to polluted areas only;

- in addition to this, the application of decentralized flow-rate control is rare;

- in most systems no measures have been taken to improve the coefficient of air change performance;

- the advantage of mechanical ventilation systems is the applicability of heat recovery devices;

- in general, system costs are increased by ventilation or energy efficient measures. Therefore, the cost effectiveness of these measures have to be considered;

- the reliability of ventilation systems may be affected significantly by some types of advanced control;

- the thermal conditions of decentral supply systems need to be improved.

This technical note can be obtained from AIVC

Stop Press

Japan

ISRACVE Conference Attracts 230 Participants July 22-24 1992

The International Symposium on Room Air Convection and Ventilation Effectiveness, held at the University of Tokyo attracted over 230 participants from 20 countries. A total of 80 papers were presented during the three day period of this conference dealing with the measurement and simulation of air flow within buildings. Video demonstrations revealed the new graphic capabilities of the latest generation of CFD codes. These included the ability to plot air flow patterns and to track the age of air. Three-dimensional graphics was used in which air movement was depicted by the use of spheres. As these spheres passed through a space their age was represented by a gradual change of colour.

Much discussion concentrated on the definitions of ventilation, with one participant remarking that 32 different definitions of ventilation effectiveness had been presented within the first 24 hours of the conference. What makes good perceived air quality was also discussed.

CFD analysis has developed considerably and many examples of the use of CFD were presented with, in some instances, the comparison of results with measurement. The representation of buildings, however, was still highly idealised, these being airtight structures with well defined boundary conditions. Measurement systems, too, were well represented in the presentations and there was some discussion on the contrasting roles and capabilities of measurement and calculation techniques.

Papers from the conference will be reviewed in "Recent Additions to AIRBASE" and will be published shortly as an ASHRAE Publication.

New Zealand

The New Zealand electrical power supply organisation Electricorp has introduced a Medallion Award Home Specification System. This sets criteria for the standards of all-electric homes. To qualify for the highest "Medallion 2000 Award", the home must be constructed and tested to a maximum leakage of seven air changes per hour at 50 Pa. The dwelling must also be mechanically ventilated and incorporate air-to-air heat recovery.

Contacting the AIVC

For Literature Requests, Airbase Searches and other Technical Enquiries, please write, phone or fax as follows:-

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Fax: 44 203 416306

Air Infiltration and Ventilation Centre,
University of Warwick Science Park,
Sovereign Court,
Sir William Lyons Road,
Coventry CV4 7EZ,
Great Britain

New Technical Notes from the AIVC

Technical Note 37

A Strategy for Future Ventilation Research and Application

by Martin Liddament, Air Infiltration and Ventilation Centre, September 1992

The objective of this strategy is to identify the research needed to understand, develop and promote the role of ventilation in the control of energy use for optimum indoor air quality. To achieve this, the following tasks are proposed:

(i) evaluate the existing energy impact of ventilation.

The energy significance of ventilation heating and cooling loss, in both domestic and non domestic buildings, needs to be accurately identified. This is important for future energy policy planning and for use as a reference level against which future ventilation energy reductions can be compared.

(ii) establish indoor air quality needs.

Indoor air quality needs should be identified and pollutants should be categorised according to unavoidable and avoidable sources. Any extra energy and cost impact of ventilating to mitigate avoidable pollutant sources can then be found.

(iii) identify the role of ventilation in controlling IAQ.

The role of ventilation as a mechanism for controlling indoor air quality should be assessed. Where ventilation is inappropriate or expensive, other control measures should be identified.

(iv) evaluate optimum ventilation needs.

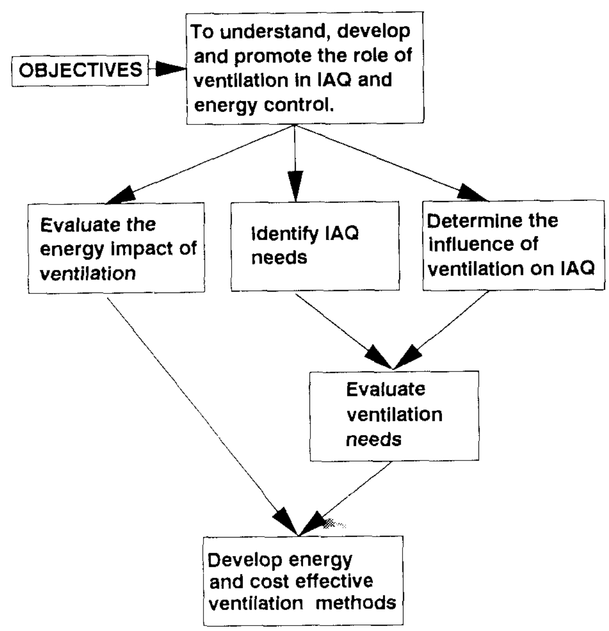
An evaluation of the optimum ventilation appropriate for the needs of occupants and for diluting and removing unavoidable pollutants should be undertaken.

(v) assess the energy impact of optimum ventilation.

The energy needed for providing optimum ventilation should be evaluated. This may then be compared with the results of task (i) to establish an energy reduction target.

(vi) achieve energy and cost effective ventilation

A Strategy for IEA Ventilation Analysis



Factors that influence energy and cost effective ventilation must be identified. These include climate, building type and size, occupant considerations, reliability and cost.

(vii) disseminate results through a guide to ventilation

Results should be published in a guide to ventilation. This publication should be aimed at policy makers, designers and other end users who can ensure the widespread use of results.

An important aim of this strategy is to provide a foundation for future ventilation analysis within the International Energy Agency. This should address energy and air quality aspects of ventilation and be integrated within an overall strategy for building energy planning.

New Technical Notes from the AIVC

Technical Note 38

Airguide: Guide to the AIVC's Bibliographic Database

by Mark Limb, Air Infiltration and Ventilation Centre, September 1992

"Airbase" is the Air infiltration and Ventilation Centre's bibliographic database, available as a suite of programs for distribution on diskettes to all participants of the AIVC. The abovementioned technical note is a new version of the installation and user guide originally distributed in photocopy format with the package, and is intended as a user-friendly booklet which guides the reader in easy stages through installation and search procedures.

The booklet is divided into ten sections which are briefly outlined below.

1. Before you start...

2. Installation procedure.

The first two sections outline the contents of the package (disk format, user guide, etc.), and directions on loading the Airbase database onto the user's computer.

3. How to enter Airbase

The third section outlines basic searching procedures, including:- a simple search; narrowing or widening the search; key field searching and recording and playing back a search. This section is divided into fifteen subsections.

4. How to export a search to a printer.

5. How to export a search to a file.

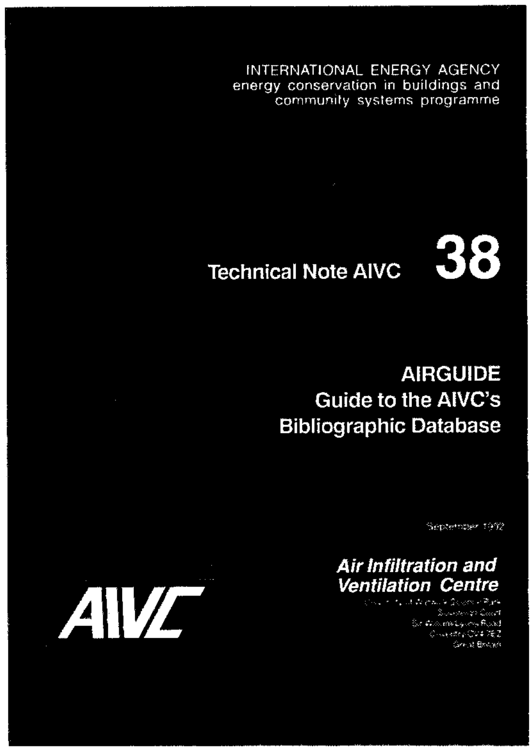
Sections four and five explain how to export a search to either a printer or a file.

6. Other features.

This section discusses other features of the operating software, "Idealist", such as DOS shell operations. It also indicates how to quit Airbase and how to edit the synonym list.

7. Updating Airbase

Section seven outlines how Airbase is updated and how the user can obtain updated copies.



8. Help (The on-board help facility)

9. The AIVC Helpline

Two help facilities are available which are outlined in sections eight and nine.

10. Thesaurus

The final section consists of a thesaurus which is divided into three subsections. The thesaurus is specially designed for Airbase, and is included to aid the user.

The booklet is available free of charge on purchase of the Airbase diskette package.

All enquiries regarding Airbase, including requests for free sample diskettes of the most recent additions to the database, should be directed to Mark Limb at the Air Infiltration and Ventilation Centre.

Forthcoming Conferences

Indoor Air Quality, Ventilation and Energy Conservation in Buildings. 5th Jacques Cartier Conference
DATE: October 7-9, 1992
VENUE: Queen Elizabeth Hotel, Montreal, Canada
CONTACT: Fariborz Haghighat, Centre for Building Studies, Concordia University, Montreal, Quebec, Canada H3G 1M8
Tel: (514) 848 3192
Fax: (514) 848 7965

Second International Course on Sick Building Syndrome
DATE: 12-16 October 1992
VENUE: Hotel Oranje Boulevard Hotel, Noordwijk-ann Zee, the Netherlands
CONTACT: Gunilla Ahlberg, NIVA, Topeliuksenkatu 41 a A, SF00250 Helsinki, Finland
Tel: +358 0 474 7498
Fax: +358 0 414 634

ASHRAE IAQ '92 Environments for People Symposium
DATE: October 18-21, 1992
VENUE: San Francisco, California, USA
CONTACT: Manager of Technical Services, ASHRAE, 1791 Tullie Circle NE, Atlanta, GA 303292306, USA
Tel: 404/6368400
Fax: 404/3215478

Building Airflow Simulation: BEPAC Task Group 1
22nd October 1992
VENUE: British Gas, Solihull, UK
CONTACT: John Kendrick, Air Infiltration and Ventilation Centre, Sovereign Court, University of Warwick Science Park, Sir William Lyons Road, Coventry CV4 7EZ
Tel: +44 203 692050
Fax: +44 203 416306

ECAM '92
A major international conference on the efficient use of energy
26-29 October 1992
VENUE: The Hotel Berlin, Lutzowplatz 17, D1000 Berlin, Germany
CONTACT: Mr John R Gillott, Director of Marketing and Business Development, Newcare, Newcare House, Grainger Park Road, Newcastle upon Tyne NE4 8RQ, UK
Tel: +44 91 273 2111
Fax: +44 91 272 4938

Innovations in Management, Maintenance and Modernisation of Buildings
DATE: 28-30 October 1992
VENUE: Rotterdam, Holland
CONTACT: CIB W70 Rotterdam Symposium, ROSTRA Congrescommunicatie PO Box 82345, 2508 EH The Hague, Netherlands
Fax: 31 70 356 28 78

ESS 92
European Simulation Symposium. Simulation in AI in Computer Aided Techniques
DATE: November 6-8, 1992
VENUE: Dresden, Germany
CONTACT: SCS International, c/o Philippe Geril, The European Simulation Office, Coupure Links 653, B9000 Ghent, Belgium

Quality Standards for the Indoor Environment: Scientific and Regulatory Aspects
13 December 1992
VENUE: Prague, Czechoslovakia
CONTACT: Professor M V Jokl, c/o Secretariat: Quality Standards for the Indoor Environment: Scientific and Regulatory Aspect, Society for Environmental Technology, CS 116 68 Prague 1, Czechoslovakia
Fax: +42 2 232 8611

Thermal Performance of the Exterior Envelopes of Buildings V
DATE: December 7-10, 1992
VENUE: Clearwater Beach, Florida, USA
CONTACT: Jeffrey E Christian, Building Thermal Envelope Systems and Materials, Oak Ridge National Laboratory, P O Box 2008, Oak Ridge, TN 378316070, USA
Tel: +1 615 574 5207

Building Design, Technology and Occupant Well Being in Cold and Temperate Climates
DATE: 17-19 February 1993
VENUE: Palais des Congres, Brussels, Belgium
CONTACT: Agitour, Avenue Louise, 265, B1050 Brussels, Belgium
Tel: 32 2 649 81 70
Fax: 32 2 649 32 62

EEB International Symposium
Energy Efficient Buildings
Design, performance and operation under the auspices of the CIB Working Group W67: energy conservation in the building environment
DATE: March 9-11, 1993
VENUE: University of Stuttgart, Germany
CONTACT: U Fadel, Nobelstr. 12, 7000 Stuttgart 80, Germany
Tel: +49 711 970 3360
Fax: +49 711 970 3395

Indoor Air '93 The 6th International Conference on Indoor Air Quality and Climate
DATE: July 4-8, 1993
VENUE: Helsinki, Finland
CONTACT: Indoor Air '93, Prof Olli Seppanen, Helsinki University of Technology, SF02150 Espoo, Finland
Tel: 358 0 451 3600
Fax: 358 0 451 3611

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Air Infiltration Review. Quarterly newsletter containing topical and informative articles on air infiltration research and application.
Recent Additions to AIRBASE. Quarterly bulletin of abstracts added to AIRBASE, AIVC's bibliographic database.

GUIDES AND HANDBOOKS

Applications Guide 1 (1986) Liddament, M.W. 'Air Infiltration Calculation Techniques - An Applications Guide'
Applications Guide 2 (1988) Charlesworth, P.S. 'Air Exchange Rate and Airtightness Measurement Techniques - An Application Guide'
Handbook (1983) Elmroth, A. Levin, P. 'Air infiltration control in housing. A guide to international practice.'

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TN 13 (1984) Allen,C. 'Wind pressure data requirements for air infiltration calculations'
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TN 17 (1985) Parfitt, Y. 'Ventilation Strategy - A Selected Bibliography'
TN 20 (1987) 'Airborne moisture transfer: New Zealand workshop proceedings and bibliographic review'
TN 21 (1987) Liddament, M.W. 'A review and bibliography of ventilation effectiveness - definitions, measurement, design and calculation'
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TN 24 (1988) 'AIVC Measurement Techniques Workshop: Proceedings and Bibliography'
TN 25 (1989) Blacknell,J. 'A subject analysis of the AIVC's bibliographic database - AIRBASE',
TN 26 (1989) Haberda,F and Trepte,L. IEA Annex IX 'Minimum ventilation rates and measures for controlling indoor air quality.
TN 27 (1990) Bassett, M. 'Infiltration and leakage paths in single family houses. A multizone infiltration case study.'
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TN30 (1990) Colthorpe, K 'A review of building airtightness and ventilation standards.'
TN31 (1990) Limb, M 'AIVC's fifth worldwide survey of current research into air infiltration, ventilation and indoor air quality.'
TN32 (1991) Harrje DT, Piggins JT 'Reporting guidelines for the measurement of airflows and related factors in buildings.'
TN33 (1991) Liddament M W 'A review of building air flow simulation.'
TN34 (1991) Roulet C-A, Vandaele L 'Air flow patterns within buildings: measurement techniques.'
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TN36 (1992) Limb M J 'Airgloss Air Infiltration Glossary.'
TN37 (1992) Liddament M W 'A Strategy for Future Ventilation Research and Application'.
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IEA ANNEX REPORTS

DCV (1990) Raatschen, W (ed.) Demand controlled ventilating system: state of the art review.' Annex 18 report.
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AIVC CONFERENCE PROCEEDINGS

1st 'Instrumentation and measuring techniques', 1980.
2nd 'Building design for minimum air infiltration', 1981.
3rd 'Energy efficient domestic ventilation systems...' , 1982.
4th 'Air infiltration reduction in existing buildings', 1982.
5th 'The implementation and effectiveness of air infiltration standards in buildings', 1984.
6th 'Ventilation strategies and measurement techniques', 1985.
7th 'Occupant interaction with ventilation systems', 1986.
8th 'Ventilation technology - research and application', 1987.
9th 'Effective Ventilation', 1988
10th 'Progress and trends in air infiltration and ventilation research' , 1989
11th 'Ventilation System Performance', 1990
12th 'Air Movement and Ventilation Control within Buildings',1991
13th 'Ventilation for Energy Effficiency and Optimum Indoor Air Quality' Nice, France, 1992, 2 volumes.
mf Proceedings of AIVC conferences numbers 1-13 are also available in microfiche form.

LITERATURE LISTS

1) Pressurisation - infiltration correlation: 1. Models.
2) Pressurisation - infiltration correlation: 2. Measurements.
3) Weatherstripping windows and doors.
4) Caulks and sealants.
5) Domestic air-to-air heat exchangers.
6) Air infiltration in industrial buildings.
7) Air flow through building entrances.
8) Air infiltration in commercial buildings.
9) Air infiltration in public buildings.
10) Carbon dioxide controlled ventilation.
11) Occupancy effects on air infiltration.
12) Windbreaks and shelterbelts.
13) Air infiltration measurement techniques.
14) Roofs and attics.
15) Identification of air leakage paths.
16) Sick buildings.
17) Flow through large openings.
18) Control of cross contamination from smokers.
19) Location of exhausts and inlets.

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[ ]	6th	£22	£22	[ ]	13th	£50	£50
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