SIZING AND LOCATION OF PASSIVE VENTILATION OPENINGS

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Contractor

Oscar Faber Applied Research

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Report under Contract S/N5/00142

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1 EXECUTIVE SUMMARY

Solar driven natural ventilation is becoming an increasingly important strategy for the design of commercial buildings in the U.K. Such buildings are becoming increasingly attractive to the market because they offer a combination of reduced environmental impact whilst offering the user an increased facility for individual control.

One of the barriers to the further uptake of naturally ventilated buildings is the problem associated with the sizing of natural ventilation openings. Current design methods rely on rather complex computer based design tools which require skill and experience to use effectively. The purpose of this project was to develop some simpler design guidance and/or procedures which would assist the design team to get the fundamentals of the building design right. This requires a method which can be used at the concept design stage. In order to ensure a wide uptake of the results, the method has been developed in parallel with the drafting of the CIBSE Applications Manual on Natural ventilation in Non-Domestic Buildings. The results of this project have now been summarised in chapter 5 of that manual.

The project started out with the intention of developing a series of design charts or nomograms which would cover the range of parameters typical of non-domestic building designs in the U.K. Initial analysis soon demonstrated that such an approach would be very time consuming, and the results would probably be rather limiting for use in practice. Consequently the project concentrated on developing a design oriented methodology which placed no restrictions on built form or input parameters. This methodology has become known as the "inverse solver".

The inverse solver is a method which turns the current approach to design on its head. Rather than seeking to size ventilation openings by an iterative procedure using simulation tools, it establishes a means of calculating opening sizes directly. This means that the method is very fast and direct, and ideally suited to concept design. The methodology has been developed in two forms -

a) a series of worksheets covering the principal design strategies (buoyancy driven and wind driven)

b) a computerised implementation of the method in a standard spreadsheet.

The method has then been "proven" by designing a series of generic buildings using the inverse solver, and then testing the performance of the design by analysing the building performance using an established multi-zone ventilation program. The results showed maximum deviations of about 1%, which establishes a high degree of confidence in the method.

A second phase of the project was to demonstrate the robustness of selected ventilation strategies to occupant interaction (i.e. how they might use their windows). This demonstrated that for the particular buildings studied, the designs were fairly robust to misuse by occupants. Although there is inevitably some interaction between different flowpaths, the user normally has the ability to adjust his own window opening to restore acceptable ventilation rates.

The final phase of the project was to summarise available information on related issues (shading, glare etc), to enable designers to take into account all the interacting features which make up a good naturally ventilated and daylit design.

2 INTRODUCTION

Natural ventilation, assisted by passive solar design, is an increasingly important design strategy for a range of non-domestic buildings. One of the main challenges facing the designers of such buildings is to determine the size and distribution of natural ventilation openings in order to ensure adequate ventilation rates for all design conditions. This report summarises work carried out for ETSU under the Passive Solar Programme; the report seeks to provide simple but robust tools which will enable the designer to size and distribute the openings as part of the concept design stage. Detailed design stages and design optimization may well require the use of more sophisticated tools (e.g. multi-zone ventilation models).

The design of an effective natural ventilation strategy must go beyond a consideration of size and location of ventilation openings. It must be properly integrated into the overall design concept for the building. This will include other environmental performance issues like daylighting, how the occupants of the building will interact with the systems, through to non-technical issues like security. Although this report concentrates on the sizing and location of the ventilation openings, the other issues are discussed briefly, and reference is made to other relevant publications.

2.1 Project Description

The use of solar driven natural ventilation is a strategy which is being applied increasingly in the design of non domestic buildings. Although naturally ventilated buildings are relatively simple in terms of engineering systems, the effort required to achieve an acceptable design can be considerable.

In particular, the sizing and location of passive ventilation openings is a significant design challenge. Designers want to know what size of openings they should use and where they should be placed to obtain specified ventilation within the building. For a good overall design, a carefully evaluated compromise is necessary between the number and area of openings for ventilation, the admission of daylight and the avoidance of glare and excess solar gains. At the moment, this cannot be done without recourse to relatively complex design tools. Judgement has to be made *a priori* on the size and location of the openings and the ventilation flows then calculated. An iterative procedure on a 'trial and error' basis is then used to home in on the acceptable (rather than the required) ventilation performance for the building. This project has developed a set of much simpler design tools which the designer can use quickly and easily, even for the earliest stage of design development.

2.2 Objectives

The specific objectives of the work described in this report were :

a) to prepare guidance and a designer–orientated procedure that would enable the required size and distribution of passive ventilation openings to provide specified ventilation rates in multi–storey, non–domestic buildings.

b) to develop guidance with due regard given to daylighting and the avoidance of glare and overheating.

These objectives were to be achieved in such a way as to be easily integrated into the parallel work being undertaken by CIBSE and BRECSU in the development of a CIBSE Design and Applications Manual for Natural Ventilation in Non–Domestic Buildings.

2.3 Background

There is an increasing interest in controlled passive ventilation in commercial buildings. There are two main reasons for this:

a) A need to ensure adequate ventilation to provide acceptable indoor air quality without excessive use of non– renewable energy.

b) A move away from air conditioning for the cooling of buildings because of;

   i) the need to reduce energy consumption (and hence CO_2 production)

   ii) concerns over the environmental issues associated with the use of CFC and HCFC refrigerants, and

   iii) a perception that sick building syndrome may be more prevalent in air conditioned buildings.

Passive ventilation is not a soft option for designers. Designing a building for controlled passive ventilation requires a sound grasp of the fundamental building physics associated with air flow. In general, it is not expected that architects and designers should need to have such a sound grasp; but what would be useful would be usable guidance prepared in a form for immediate design application. This project aims to provide the basis for such guidance.

The main result of the work is a simplified design method which can be implemented either as manual worksheets or as a simple computer program (an illustrative spreadsheet tool has been prepared). This will provide designers with a simple entry route to designing natural ventilation schemes, particularly at the early design stage when the basic form and organisation of the building is being established.

2.4 Methodology

In developing calculation methods, a distinction should be drawn between two distinct classes of tools – design and simulation. The distinction between these two classes of tool is very important, and has a very significant influence on the natural progression of the design process.

2.4.1 Design Tools

Design tools are procedures which inform the designer directly about the systems or equipment he needs to specify. The meaning is best illustrated by examples. A "classical" heating design calculation will explicitly determine the size of radiators and boilers required to keep a building up to temperature under assumed design conditions of constant external temperature. Similarly, a lumen method lighting calculation will tell the designer how many light fittings of a certain type will be required to achieve a target illuminance level.

This type of information is essential in developing the design concept for a building. The calculations are simple and direct. They enable different strategies to be explored very quickly, and provide information on which the design can be developed further. However, such tools do not answer every question that a designer may wish to know. The examples quoted cannot predict annual heating energy use or the variation in lighting intensity across a space. This is the domain of the simulation tool.

2.4.2 Simulation Tools

Simulation tools require as input the specification details of the system being analysed – the size of the heat emitters and the power of the boiler. In the lighting example it would require the position of each luminaire, its light distribution characteristics, room reflectances etc. The simulation program will then inform the user on how the system will perform under a defined set of boundary conditions. A simulation tool can therefore provide much more detailed information about the performance of a system that has already been sized.

Simulation tools can be used to size systems by a "guess and test" process – inputting assumed sizes and testing to see if performance is acceptable and iterating around the loop until satisfactory conditions are obtained. In order to gain maximum benefit, simulation tools also require a level of expertise of the user, which many individuals do not have the time or inclination to acquire. Use of simulation methods can be a time consuming process, and this is further complicated by the fact that most simulation tools require quite detailed data inputs. At the concept design stage, much of this data is not easily obtained, and the time to prepare the data and execute the analysis is never available.

Design and simulation tools should therefore be seen as distinct elements in the process of design development. The Design tool is used at the early stage – it is quick and simple to use, and it indicates whether the chosen strategy is workable or not. It provides "starting values" for the simulation tool which can then be used to refine and optimize the design during the detailed design phase.

2.4.3 A Design Tool For Passive Ventilation Openings

A number of tools are available for analysing ventilation performance of buildings [1]. These tools, although varying in sophistication and complexity, are in fact all simulation tools. They require as input data the size and position of ventilation openings, and based on prevailing weather conditions etc., will predict the air flow rates through the structure. The problem facing the designer of a naturally ventilated building is the converse of this. Based on fresh air requirements or the analysis of overheating risk, a required flowrate of outside air through each notional building zone will have been defined. The task is to determine the size and position of the passive ventilation openings to achieve this flow distribution using natural driving forces. This project is aimed at helping the designer to solve this problem.

At the outset, it was the intention to use a simulation tool to run a series of parametric studies to develop a number of design charts which could provide the basis of selecting opening sizes. This is a very time consuming and tedious process, especially given the wide range of building form and organisation, terrain conditions, shielding effects etc. Consequently the effort in the project concentrated on developing and proving a simplified calculation model which would predict the required opening sizes based on inputs of required flowrates. This calculation model became known as the "inverse solver". The following section describes the development of this procedure, and demonstrates its usefulness by comparing the answers it predicts with the results of the Building Research Establishment's (BRE) multi-zone ventilation model BREEZE [2].

3 DEVELOPMENT OF DESIGN EQUATIONS

Natural ventilation design strategies fall into two main categories, stack driven and wind driven [3]. In reality, there is always an interaction between these two driving forces for natural ventilation. In terms of the design process, it is convenient to consider first the dominant driving force, and then adjust the design for the effect of the other. In this section, there is a description of the philosophy behind the development of the inverse solver and a demonstration of its application. The detailed development of the equations is given in Appendix 1.

3.1 <u>Stack Driven Ventilation</u>

Stack driven ventilation systems rely on the buoyancy of a warm column of air to drive flow vertically upward through a building to be replaced by fresh air at a lower level. The pressure differences which drive the airflow are generated by density differences between the air inside and outside the stack. There is a point at which the internal and external pressures are equal; this level is called the neutral pressure level (NPL). Below the NPL, the pressure difference is from outside to inside, and in the opposite sense above the NPL (for the normal case when outside conditions are warmer than inside). Figure 1 shows the relationship between the pressure gradients and the NPL.

The internal and external pressure gradients are defined by the normal hydrostatic relationship

$$\frac{dP}{dh} = -\rho . g \qquad (1)$$

where P = Pressure (Pa)
ρ = Air density (kg/m³)
g = gravitational constant (m/s²)
h = vertical distance above datum height (m)

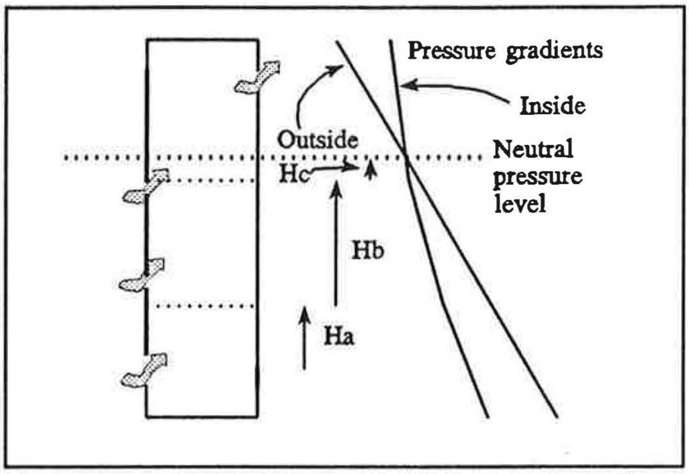


Figure 1 Calculation of driving pressure in a stratified stack

Using the ideal gas laws, a simple relationship between air density and air temperature can be derived, and from this, the inside–outside pressure difference at any level relative to the neutral pressure level can be derived (see appendix 1). Once the pressure difference between inside and outside is known, the size of any opening can be determined using the normal equation for flow through a sharp edged orifice.

$$Q = C_d . A . \sqrt{(\frac{2.\Delta P}{\rho})} \qquad (2)$$

where Q = Volumetric flowrate (m^3/s)
C_d = Discharge coefficient (–) {Typically a value of 0.61 is used}
A = Opening area (m^2)
ΔP = Pressure difference across the opening (Pa)

If these simple relationships are examined, there is only one parameter which prevents the equations being explicitly solved for every opening in the system. The position of the neutral pressure level is not known *a priori*. Consequently the pressure differences and opening areas cannot be determined.

Simulation tools can calculate the position of the neutral pressure level by first estimating the pressure distribution, and then making repeated estimates of the pressures using an appropriate iterative scheme. The inverse solver developed in this work turns the problem on its head. The designer defines the exact position of the neutral plane, thereby simplifying the design process to successive applications of equations (1) and (2). This is very easy and fast, and can therefore be applied very easily at the concept stage of design development.

Sizing and Location of Passive Ventilation Openings

The fixing of the required neutral pressure by the designer is a very simple task. In developing the ventilation strategy for the building, the designer will first establish the intended flow path for the air through the building. As detailed above, fresh air will enter at low level in the building, and be exhausted at high level via a stack or atrium. It will be necessary for the neutral pressure level to be above the top level of accommodation in order to ensure fresh air flows through the space rather than air being exhausted from another space as illustrated in Figure 2.

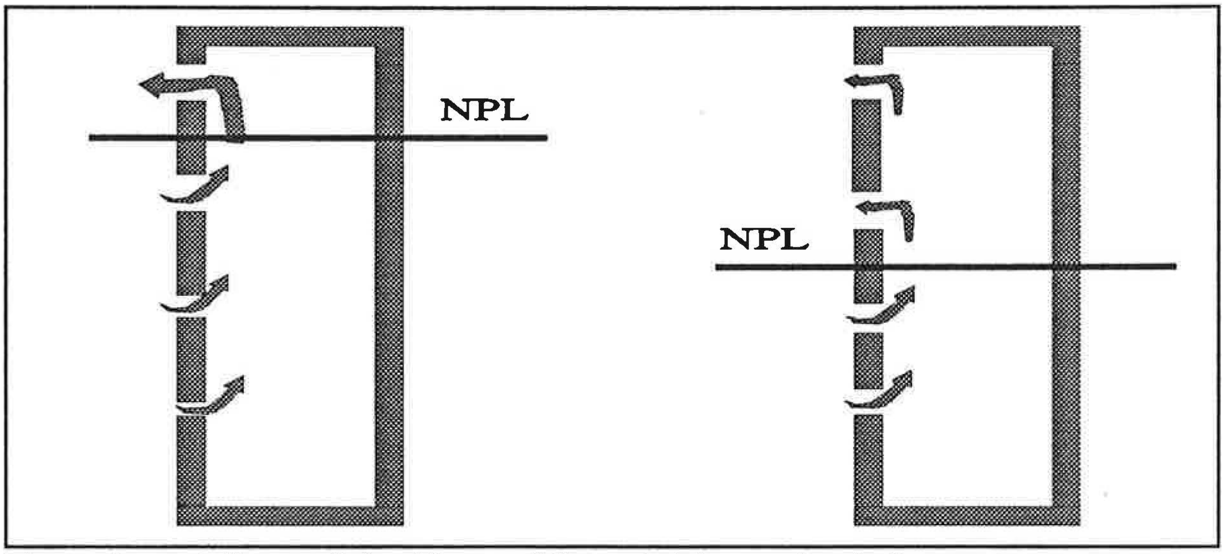


Figure 2 Effect of fixing NPL at different heights on the air flow pattern

This very simple principle sets the lowest possible height for the NPL. In order to achieve flow out of the building, the NPL must be below the exhaust ventilation opening in the shaft or atrium roof. This fixes the maximum height of the NPL. The designer can then explore the effect of adjusting the exact position of the neutral plane on the various opening sizes that would be required. Raising the height of the neutral plane will reduce the required inlet areas, but will increase the required size of the exhaust ventilator. Lowering the NPL within the allowable range will result in a smaller exhaust vent, but increase the required sizes for the inlets. This effect will be more pronounced for the upper floors of the building where the inside–outside pressure differences are smallest.

In order to demonstrate the method, consider the simple stack driven design shown in Figure 3. The story heights are all 3.25m, with the centre of each ventilation opening positioned 1.85m above floor level. Each room has a plan area of 100 m^2. The exhaust vent is positioned at a height of 11.5m, and the NPL is fixed at 10.0m above datum level.

For example, say that separate analysis has demonstrated that in order to control overheating, each floor requires 5 air changes per hour of outside air at the design condition. For a stack driven design, this design condition will be a hot still day. The appropriate condition can be established using data in CIBSE Guide A2 [4]. Temperatures for overheating risk can either be taken from table A2.29, or by using the banded weather data in tables A2.7 and A2.8. In the case described below, an external dry bulb temperature of 25 °C has been taken.

Using the detailed equations developed in appendix 1, it is possible to calculate the pressure distribution, and hence the required opening sizes for the three inlets and the outlet. These sizes have then been input to BREEZE along with the same temperature distribution as shown in Figure 3. BREEZE was then used to calculate the flowrates that would exist with the opening distribution calculated by the inverse solver. The results of this sequence are shown in the following table.

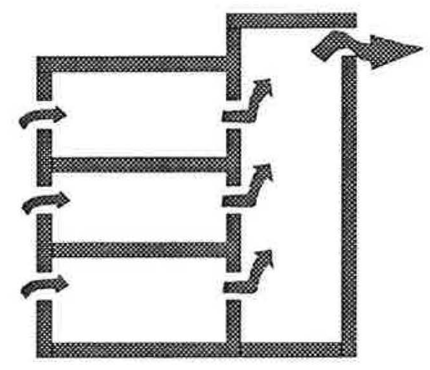


Figure 3 Example of a stack driven design

In this table, as in the others which follow in this report, areas are given to four decimal places. This is not intended to imply a particular degree of precision. It is only given because the flow balance calculation is sensitive to the area of opening, and in order to demonstrate the level of agreement between the inverse solver and BREEZE, such a degree of precision is required in the BREEZE input data.

Opening	Required flow (achr^{-1})	Predicted area (m^2)	BREEZE output (achr^{-1})	Difference in flows (%)
Ground floor	5.0	0.5645	5.015	0.3
First floor	5.0	0.6809	4.998	0.04
Second floor	5.0	1.1193	4.942	1.16
Exhaust vent	N/A	3.2244	N/A	N/A

It can be seen that the differences in flowrate are very small. Certainly for all practical purposes, the results from the two methods are identical. In testing the method, a number of such calculations were carried out. These explored variations in required flowrates (both in magnitude and floor by floor variations), inside and outside temperatures. The inverse solver proved to be robust for all these variations. More details of these parametric variations are provided in the supplementary report to this publication [5].

Sizing and Location of Passive Ventilation Openings

The difference in flows between the design tool and BREEZE seem to be proportional to the size of the opening. This would be consistent with the fact that BREEZE uses an iterative scheme, and reports a solution once all nett zone mass flows are within a given tolerance. The effect of this tolerance will result in a small difference between the BREEZE opening pressure difference and the "exact" solution. This small difference will amplify the difference in reported flowrates for larger openings.

The extension of the method to include other effects are discussed in subsequent sections of this report.

3.2 Wind Driven Ventilation

The assessment of wind driven ventilation is in many respects much simpler than the stack driven case. This is because each flow path from inlet to outlet is independent of all the others, whereas stack driven strategies have multiple inlets but a common outlet. In the absence of any local stack effects, the pressure drop across the flowpath is given by the difference in wind pressure acting on inlet and outlet.

$$\Delta P_w = 0.5 \cdot \rho \cdot v_{ref}^2 . \Delta C_p \quad (3)$$

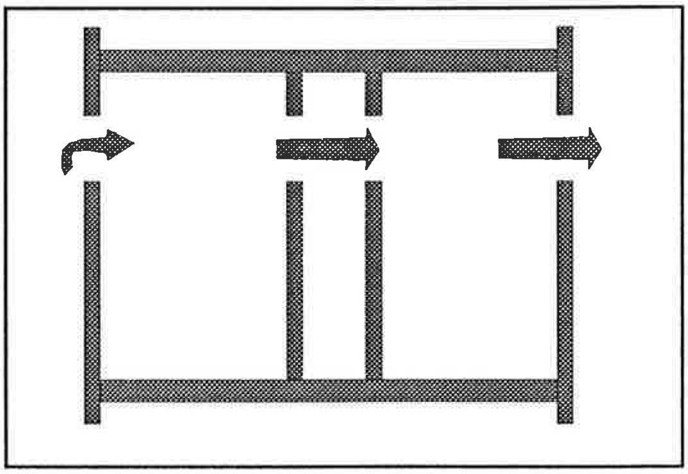


Figure 4 Example of wind driven cross ventilation strategy

where ΔP_w = the wind pressure across the flowpath (Pa)
ρ = density of outside air (kg/m^3)
v_{ref} = the reference wind velocity (m/s) for the building site, usually given at the height of the building.
ΔC_p = the difference in wind pressure coefficient between the inlet and the outlet.

A simple, but very realistic design assumption can enable the wind driven case to be solved explicitly. In most wind driven cross ventilation schemes, the ventilation openings are openable windows or trickle ventilators. These will be identical in form on each facade, and so it can be assumed that the required opening areas will the same on both facade. Rearranging equation 2 gives the pressure drop across an opening. Since both inlet and outlet area will be the same, the area of each opening can be calculated from equation 4.
In order to demonstrate the validity of the method, the inverse solver was applied to the example shown in the figure, and the calculated areas input to BREEZE. For the specific

$$\Delta P_w = 2 \cdot (\frac{Q}{C_d A})^2 \cdot \frac{\rho}{2} \qquad \textbf{(4)}$$

case shown below, the site wind speed was 3m/s, and the windward and leeward pressure coefficients were 0.58 and –0.2 respectively. The BREEZE predicted flows again agree with the required flowrates as shown in the following table.

Opening	Required flow ($achr^{-1}$)	Predicted area (m^2)	BREEZE output ($achr^{-1}$)	Difference in flows (%)
Windward	5.0	0.399	5.0	0.0
Leeward	5.0	0.399	5.0	0.0

In reality stack effects are always likely to be present, and so it is important that these combined effects can be accounted for in the method.

3.3 Combined Wind and Stack Effects

The problem of combining wind and stack effects in simplified calculation methods has been addressed by many different researchers. The problem is created because the calculations are all simulation oriented, predicting flows for defined opening sizes.

Because the flowrate – pressure drop relationship is non–linear, it is not possible to calculate the flow due to wind separately from the stack driven flows and then to summate to give the total flow. The most common approximation is to sum the individual contributions to the flow in quadrature, i.e.

$$Q_{TOT} = \sqrt{Q_w^2 + Q_s^2} \qquad \textbf{(5)}$$

where Q_{TOT} = Total flowrate (m^3/s)
Q_w = Flowrate due to wind pressures alone (m^3/s)
Q_s = Flowrate due to stack pressures alone (m^3/s)

By looking at the problem from the design view of the world rather than the simulation perspective, the non–linearity problem is avoided. Although the individual components of the flowrate are not additive, the pressures that drive the flows are additive. Consequently, the pressure driving the flow along any flowpath from inlet to outlet is given by

$$\Delta P_{TOT} = \Delta P_w + \Delta P_s \qquad \textbf{(6)}$$

where the pressure terms correspond to the flow terms given above. These individual pressure terms can be calculated as described in sections 2.1 and 2.2. The required opening sizes can then be determined by equating the total available driving pressure to the pressure drop from inlet to outlet. As a first approximation (corrections are discussed in section 2.4), it is reasonable to assume that all the resistance is concentrated at the inlet and outlet, and so the following expression can be derived.

$$\Delta P_w + \Delta P_s = (\frac{Q_{inlet}}{C_d A_{inlet}})^2 . \frac{\rho_{inlet}}{2} + (\frac{Q_{outlet}}{C_d A_{outlet}})^2 . \frac{\rho_{outlet}}{2} \qquad (7)$$

where Q_{inlet} = the volume flow through the inlet (m^3/s)
A_{inlet} = the area of the inlet opening (m^2)
ρ_{inlet} = the density of the air flowing through the inlet (kg/m^3)
etc... plus corresponding terms for the outlet.

It should be noted that the Q and ρ terms must be based on the same condition. In other words if the required volume flowrate is expressed as air changes per hour, then this will be evaluated at room conditions of temperature and air density. Consequently, the relevant room density should be used in equation 7.

Consideration of equation 7 indicates 4 unknowns, namely the inlet and outlet flowrates and areas. For the wind driven cross flow strategy, as has been previously discussed, it is valid in the vast majority of cases to assume inlet and outlet areas are equal. Inlet and outlet flows must be equal, and so equation 7 can be easily solved for A_{inlet}.

The case of the stack driven case described in section 2.1 is less simple because the flowpaths interact. The laws of conservation of mass will demonstrate that the outlet mass flow is simply the sum of all the inlet mass flows. This still leaves two unknowns in equation 7, namely the inlet and outlet areas. This problem is resolved by a further application of the principle of additive pressures. The no-wind design tool predicted the sizes needed for all the openings. The wind will effect all the inlets differently because they will be in different areas of the facade, and subject to varying wind pressures. The common outlet is effected in the same way. Consequently it is sensible to carry forward into this combined wind and stack calculation, the originally calculated stack-only outlet area, and re-adjust each of the inlet areas. Consequently, equation 7 can be re-arranged to give the pressure drop available across the inlet as shown below.

$$\Delta P_w + \Delta P_s - (\frac{Q_{outlet}}{C_d A_{outlet}})^2 . \frac{\rho}{2} = (\frac{Q_{inlet}}{C_d A_{inlet}})^2 . \frac{\rho_{inlet}}{2} \qquad (8)$$

By successively applying equation 8 to each of the 3 flowpaths shown in Figure 3, revised values for each of the inlet opening areas can be determined. As before, the approach has been tested by using the method to predict the required opening sizes, and then using BREEZE to predict the flowrates using those sizes as input. The example described in section 2.1 has been re-analysed for the situation when the wind is blowing. A site wind speed of 3 m/s has been taken, with pressure coefficients of +0.58 for each inlet, and −0.2 for the outlet. The following table illustrates the results of this analysis.

Opening	Required flow ($achr^{-1}$)	Predicted area (m^2)	BREEZE output ($achr^{-1}$)	Difference in flows (%)
Ground floor	5.0	0.2517	5.015	0.30
First floor	5.0	0.2599	5.013	0.26
Second floor	5.0	0.2727	5.011	0.22
Exhaust vent	N/A	3.2244	N/A	N/A

To all intents and purposes, the predicted flowrates are the same as the required flowrates, thereby confirming the validity of the approach. The above example is but one illustration of a number of "validation" comparisons that were carried out to prove the inverse solver. All these calculations confirmed the capacity of the design tool to provide the required opening areas.

3.4 The Effect of Internal Resistance

As has been intimated in the preceding discussion, certain simplifying assumptions have been made in the development of the analysis. Perhaps the most important of these is the assumption that all the flow resistance occurs at the inlet and outlet. This may not always be true. Consider an atrium office building. In designs involving an open atrium, there are large openings between the office space and the atrium itself, resulting in a very small resistances to flow. In some situations, the atrium is closed, and special openings are provided between the office space and the atrium to provide the flowpath. In such cases, the resistance at the boundary between the office and the atrium will be significant, and indeed may even exceed that between the outside and the office. Figure 5 shows the true resistance network. The analysis developed thus far has assumed that $A_{atrium} >> A_{facade}$. The analysis still holds true once it is appreciated that what has been calculated in sections 2.1 – 2.3 is the equivalent area of an opening corresponding to the two openings in series. Applying a designer's view of the world, it is relatively simple to fix one of the two values. For example in the case of a closed

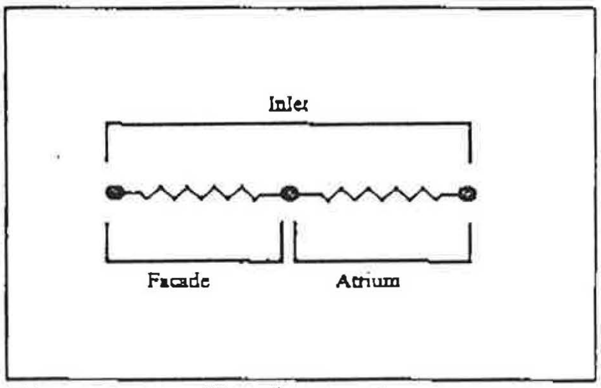


Figure 5 The flow resistance network

atrium, the designer would probably want to specify identical windows across the whole of the facade, and so a fixed value can be selected for the opening area of the window unit. The design tool can then be used to predict the size of the opening between each office space and the atrium. In an open atrium, the large opening from the office onto the atrium is fixed by the general geometry of the building. The window opening needed to balance the flows can then be calculated. In both cases, the unknown opening size can then be calculated from a simple expression which relates the effects of two resistances in series –

$$\frac{1}{A_{inlet}^2} = \frac{1}{A_{facade}^2} + \frac{1}{A_{atrium}^2} \qquad (9)$$

This method has been applied to the generic building described in section 2.3, and using a 3 m/s wind speed in combination with the stack effect, the revised window areas have been determined. These calculated areas have then been input to BREEZE.

In this case, the facade opening areas were fixed, and the atrium areas calculated. The results of this analysis are shown in the following table.

Opening	Required flow ($achr^{-1}$)	Areas (m^2)		BREEZE output ($achr^{-1}$)	Difference in flows (%)
		Facade	Atrium		
Ground floor	5.0	0.3	0.4623	5.010	0.20
First floor	5.0	0.3	0.5201	5.011	0.22
Second floor	5.0	0.3	0.6539	5.012	0.24
Exhaust vent	N/A	3.2244		N/A	N/A

Again, this comparison confirms the validity of the approach.

3.5 Building Envelope Leakage

The analysis has so far assumed that the building envelope is completely airtight – desirable in theory but impossible to achieve in practice. This section of the analysis provides a way to make an allowance for the effects of facade leakage in calculating the required opening sizes. The method involves a further refinement to the flow network as detailed in Figure 6. An additional flow resistance is introduced in parallel with the opening in the facade. It should be recognised that this is a simplification of the overall picture, since in reality there will be other leakage paths (from the occupied space into the stack, from the stack to outside, vertically between one occupied space and those above/below etc). The analysis of these more complex interactions is very much the domain of the simulation tool.

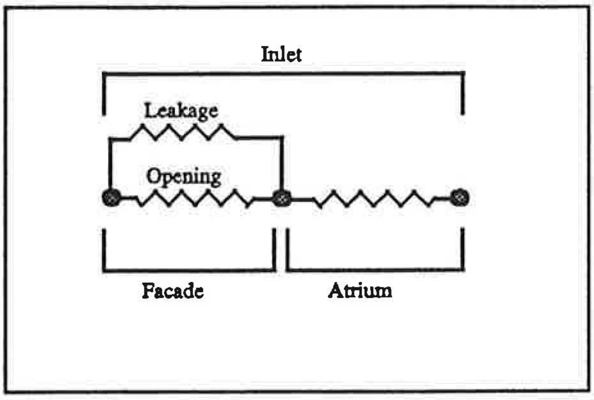


Figure 6 Flow resistance network including infiltration path

Facade leakage is something which cannot be predicted in absolute terms at the design stage. It is a parameter which can only be determined by pressurization measurements. Consequently the leakage is usually expressed at a flowrate per unit area of facade at an applied pressure of 50Pa. Based on previous experimentation, it is possible to give broad indicators on likely leakage rates as a function of the attention to detailing component joints, construction quality etc [6]. These generalised factors can then be used to assess the sensitivity of the design to facade leakage. The pressures which exist under natural ventilation conditions are very much less than the 50Pa at which leakage rates are quoted. Consequently it is necessary to use the flow equation for cracks to generate the leakage flows which would exist at reduced pressures

$$Q_{leak} = Q_{50} \cdot \left(\frac{\Delta P}{50}\right)^n \qquad (10)$$

where Q_{leak} = Infiltration flowrate ($m^3/s.m^2$)
ΔP = Facade pressure drop (Pa)
Q_{50} = Facade leakage at applied pressure of 50 Pa ($m^3/s.m^2$)
n = Flow exponent (usually 0.66 for leakage flows)

This expression can be used to adjust the required opening sizes to account for infiltration. Essentially the approach is to extend the principles outlined in the development of equation 8. Now the pressure drop across the inlet has been divided into two components (the external facade and the boundary between the office space and the stack), it is possible to calculate the pressure drop across the facade alone. This is done by subtracting from the value determined from equation 8, the pressure drop across the inner of the two resistances making up the overall inlet resistance. Equation 10 can then be used to calculate the infiltration flowrate at this pressure drop. The required flow through the facade opening can then be obtained by

$$Q_{facade} = Q_{inlet} - Q_{leak} \cdot A_{leak} \qquad (11)$$

where Q_{facade} = Flow through the facade opening (m^3/s)
A_{leak} = Area of facade subject to the infiltration flow (m^2)

This revised flowrate can then be substituted into the normal orifice flow equation to determine the opening size for the ventilation opening.

The problem is a bit more complicated when the designer wishes to fix the facade opening, and size the inner opening. Because the large opening and the leakage paths have different flow exponents, it is not possible to combine them directly into an equivalent flow resistance. This means that the only way to solve for the room pressure is by iteration. A first approximation to the value can be determined in the same way as described above. Instead of subtracting the leakage flow from the required room flow, the two values are added in this case. This combined flow is then substituted into the orifice flow equation to determine a reduced size for the inner opening. These problems re-enforce the earlier comment that analysing the effect of facade leakage is beginning to stretch the applicability of the design tool to its limits, and serious consideration should be given to the use of a multi-zone simulation tool.

4 APPLICATION OF EQUATIONS IN A DESIGN TOOL

Section 2 of this report has discussed the underlying principles of the design methodology developed under this contract. In order to be useful as a design tool, it is necessary to capture these principles into a usable design tool.

Two such implementations are described below, one manual, the other automated.

4.1 Design Calculation Sheet

The design method has been put into in a manual calculation worksheet. This is attached as Appendix 2, along with a set of notes explaining its use.

4.2 Spreadsheet Implementation

In a similar way to 3.1 above, the procedure has been encapsulated into a standard spreadsheet (the specific implementation is in Quattro Pro, but only "standard" features are used). Figure 7 shows the spreadsheet calculating the parameters for the calculation described in section 2.3.

Based on the material in Section 2, and the more detailed description of the equations in Appendix 1, such a spreadsheet can be generated fairly easily.

4.3 Worked Example

The example building used in section 2 is clearly a simplified form, and was used to indicate the principles involved. As a more realistic demonstration of the use of the tool, a design has been selected which more closely reflects common design practice. The form of this building is shown in Figure 8, and consists of a 3 storey building surrounding a central atrium. The atrium is intended to act as a solar driven stack, drawing air across each side of the building

Analysis title:	**Stratified stack**		**Date: 24/1/95**	
Outside temp (C)	25.0			
Wind speed	3.0	Met/Loc?	loc	
Terrain class	Urban	K value	0.35	
Building height	12.000	a value	0.25	
Site wind speed	3.00			

Stack data

Height of top of element (m)		3.250	6.500	9.750	12.000
Temp of stack element (C)		27.0	28.0	29.0	30.0
Pressure (Pa)		−0.25	−0.62	−1.12	−1.55
Req'd NPL (m)	10.000		Pressure		−1.17

Design condition – zero wind

Openings data	1	2	3
Opening height (m)	1.850	5.100	8.350
Room volume (m3)	322.9	322.9	322.9
Rm Temp (C)	27.0	27.0	27.0
AC/hr	5.0	5.0	5.0
Pressure (Pa)	−0.14	−0.46	−0.91
Vol flow (m3/s)	0.448	0.448	0.448
Mass flow kg/s	0.525	0.525	0.525
No−wind window area (m2)	0.564	0.681	1.118

Sizing of Outlet

Height of outlet (m)	11.500
Mass flow (kg/s)	1.575
Vol flow (m3/s)	1.359
Pressure (Pa)	−1.46
No−wind vent area (m2)	3.2244

Adjustment of window areas for wind			Outlet Cp	−0.20
Opening number	1	2	3	
Opening Cp	0.58	0.58	0.58	
Pw inlet (Pa)	3.077	3.077	3.077	
Pw outlet (Pa)	−1.06	−1.06	−1.061	
Driving pressure (Pa)	5.451	5.130	4.686	
Outlet loss (Pa)	0.286	0.286	0.286	
Inlet delP (Pa)	5.165	4.844	4.400	
With−wind window area (m2)	0.252	0.260	0.273	

Figure 7 Example of spreadsheet implementation

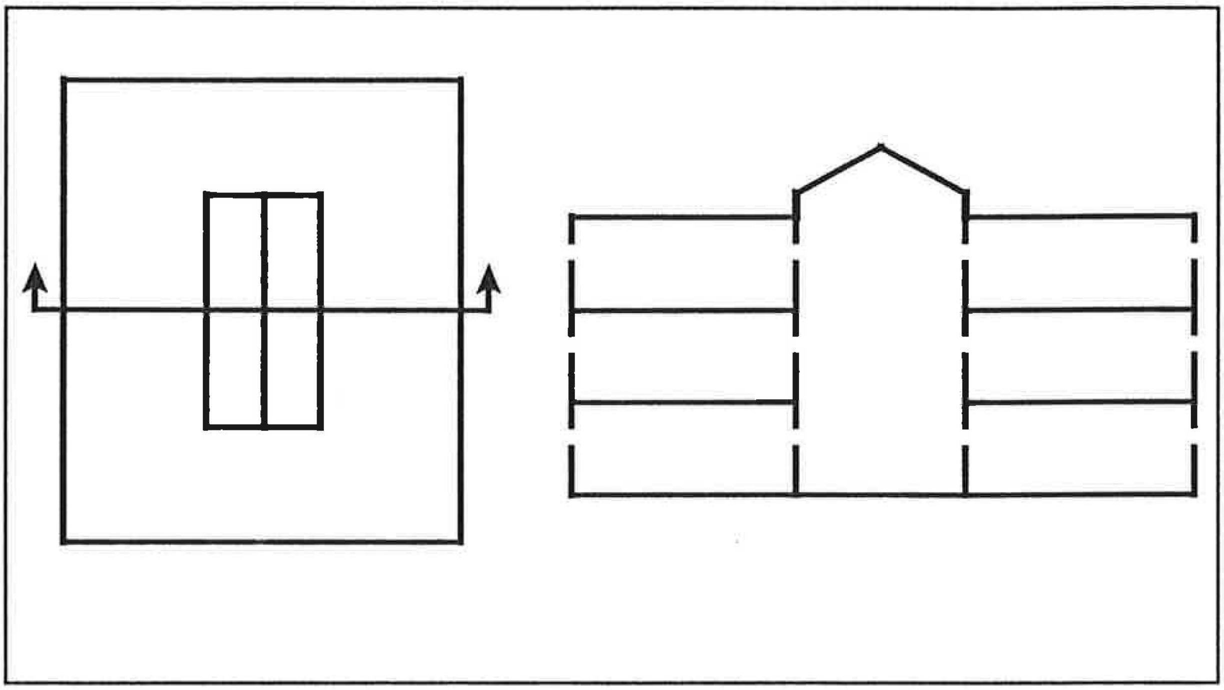


Figure 8 Plan and section of example building

from outside to the atrium, and exhausting at high level.

It has been assumed that there will be temperature stratification in the atrium, and different temperatures have been defined for each notional vertical "slice" of the atrium. Design weather conditions have been assumed of 25°C with a 3 m/s wind speed. Wind pressure coefficients from the BRE dataset [7] have been ascribed to the various facades of the building. For the case shown below, the wind is assumed to be from the North. Separate thermal analysis has indicated that in order to control temperatures to 25°C in the office spaces, 5 air changes per hour of outside air are required. The atrium is assumed to be stratified, with temperatures rising from 25°C on the ground floor to 28°C at the outlet level. All these factors have been input to the design tool, and the required opening areas determined. As before, the results have been input into BREEZE, and the flows calculated. The results are summarised in the following table (note that each floor has been modelled as one open zone in BREEZE).

The robustness of the tool to complex and realistic design tasks is amply demonstrated by this comparison. The very slight differences in results are due to the fact that the design tool does not account for interactions between the various zones on each floor. In an open plan situation implicit in most natural ventilation strategies, (and in the BREEZE model of this building), such interactions are inevitable. However the deviation in results are wholly acceptable in the context of design, especially in the early stages of the design process where this tool is seen as having its major impact.

Opening	Required flow (achr^{-1})	Areas (m^2)		BREEZE output (achr^{-1})	Difference in flows (%)
		Facade	Atrium		
Ground S	5.0	2.8176	60.0	5.0	0.0
Ground W	5.0	1.0302	20.0		
Ground N	5.0	1.0811	60.0		
Ground E	5.0	1.0302	20.0		
First S	5.0	2.9815	60.0	4.985	0.3
First W	5.0	1.0609	20.0		
First N	5.0	1.0897	60.0		
First E	5.0	1.0609	20.0		
Second S	5.0	3.6407	60.0	4.968	0.6
Second W	5.0	1.1623	20.0		
Second N	5.0	1.1145	60.0		
Second E	5.0	1.1623	20.0		
Exhaust vent	N/A	50.1352			

5 EFFECTS OF OCCUPANT INTERACTION

The discussion thus far has considered the effects of building form, ventilation strategy and the prevailing climate on the ventilation flowrates. All aspects of building design must consider the impact of the occupant, and design for natural ventilation is no exception. This influence must go beyond satisfying the user's expectations of thermal comfort. The designer must also consider whether the user can operate the system successfully, and should explore the robustness of the design to occupant abuse.

It is therefore essential that the designer test the robustness of the calculated openable areas by exploring how sensitive the solution is to the calculated openable areas. This section provides examples of such interactions, and uses BREEZE to analyse the robustness of the design strategy.

5.1 Mechanisms for Occupant Interaction

The occupant can interact with the natural ventilation system in a number of ways. Firstly there is the issue of adaptation to changing thermal environments, and the impact that this has on the acceptability of certain temperature thresholds. This is a huge subject in its own right, and the reader is referred to other publications to explore this topic [8].

More relevant to this particular study is the ways in which occupants interact with their window openings to control the ventilation rates in their particular occupied zone. This is a potential problem with natural ventilation design because the use of a particular window will effect the flowrate through another window because of the interaction between elements in the flowpaths.

5.1.1 Stack Driven Strategies

Consider again the simple building described in section 2.1 and illustrated in Figure 3. The pressure distribution driving the flows is influenced by the distribution of the openings. The design tool calculates the area required to achieve a given flowrate on each of the floors at the design condition. If in practice, a floor of the building is not occupied for whatever reason, then the window is unlikely to be opened on that particular floor, and this will influence the air flow distribution if the other windows are set to their design opening value. These effects cannot be explored by the design tool, and must be evaluated by a simulation program, and on a case by case basis.

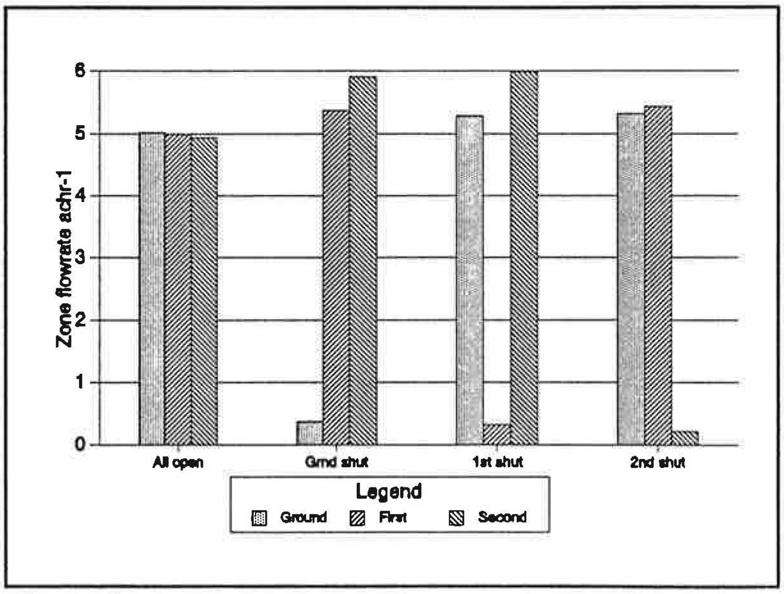


Figure 9 Effect of shutting off floors under design conditions.

In order to give an insight into the ways in which flow distributions are affected, the building has been modelled for the scenarios where each of the floors has been shut off in turn, leaving only a trickle ventilator of area 0.04 m^2. The results in Figure 9 for the no-wind situation indicates that the flows through the open floors increase. This means that the required flow can be re-established by reducing the openings from the design value, and so the occupant can always use his own control to bring conditions back into acceptable limits.

A more difficult problem can arise at external conditions away from the design value. The same building has been analysed for conditions where the outside temperature is the same, but there is a windspeed of 3m/s. The design tool has been used to calculate the reduced opening sizes required to give the same flows under these new conditions. BREEZE was then used to predict what would happen if each floor in turn failed to adjust its opening, and left the window at its fully open position. This operational behaviour will tend to reduce the flowrates on other floors.

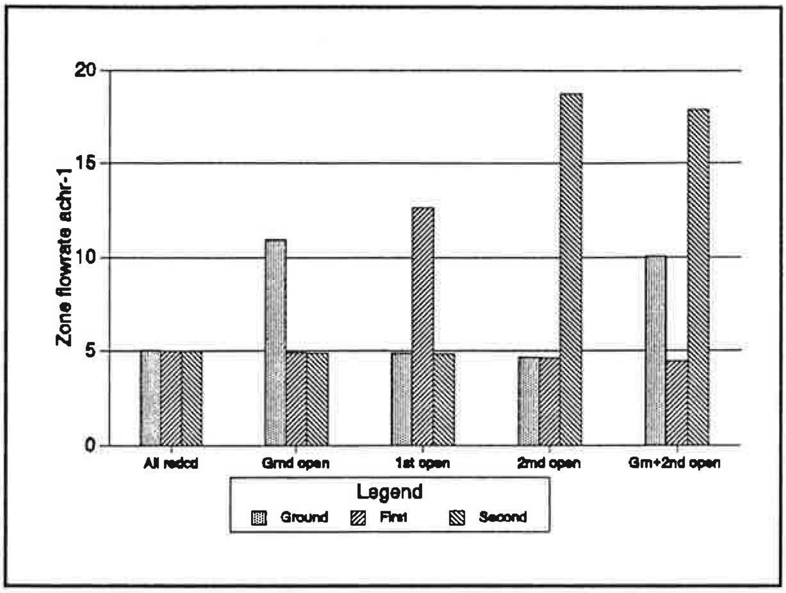


Figure 10 The effect of not adjusting opening areas at increased windspeeds.

The worst effect is seen on the second floor when the ground floor is left fully open. The final set of bars on the histograms shows the effect when the top floor user re-opens his window to the maximum extent. It shows that the user can easily recover his required flowrate.

This simplified analysis has demonstrated that significant interactions can occur, but the user has the capacity to improve the flowrates in the space under his control if a reduction is caused by the misuse of an occupant in another zone. In many cases this capacity to improve can re-establish the required flowrates. ***It must be stressed again that this is a generalisation, and each case <u>must</u> be examined on its own merits.***

5.1.2 Wind Driven Strategies

A similar analysis to the above can be applied to the wind driven cross ventilation strategy described in Section 2.2 (Figure 4). This strategy is perhaps more susceptible to operational abuse because different occupants may interact with openings at either end of the flowpath. At the extreme, if windows on either side of the building are left shut for whatever reason, the cross flow is zero (other than that taking place through leakage paths). In reality, the flowpath will be a series of parallel routes, and so if a proportion of the outlets are closed, then the effect is the same as a proportional closing of all the individual outlets.
This situation has been analysed and the results shown in Figure 11. The graph shows the flowrate through the fully open window in the windward office as a function of the

percentage opening of the leeward window for two windspeed conditions – the design windspeed, and a windspeed increased by a factor of 2.

Because the wind pressure difference increases as the square of the windspeed, the available driving pressure increases very rapidly as the design situation moves away from the relatively still day. This means that for the double windspeed case, the design flow can be achieved even if the leeward windows are only 37% open.

These results should be regarded as illustrative only, and each design must be examined on a case by case basis.

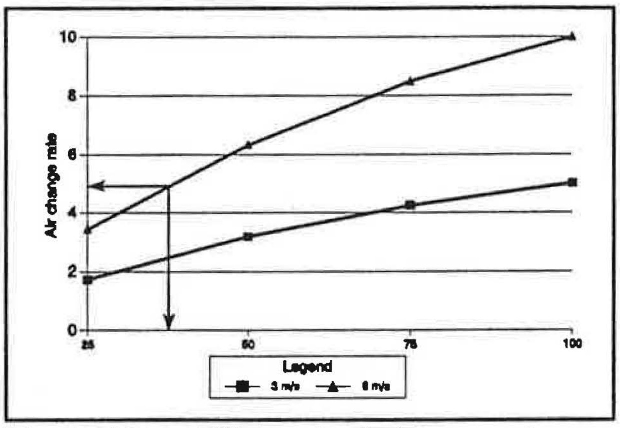


Figure 11 Effect of window opening on cross ventilation rate for different windspeeds.

6 OTHER DESIGN CONSIDERATIONS

Ventilation design must be integrated into the design of the other environmental control systems. Winter heating, control of summertime overheating, lighting and acoustics are all important issues which must be considered in parallel with the sizing and location of the ventilation openings. This document is not a general design guide, and so only very general design guidance is given here, and the user referred to other more comprehensive publications. The CIBSE Applications Manual on Natural Ventilation [9] provides a general overview of the interaction of natural ventilation with other design issues. Some of the broad principles are summarised below.

6.1 Glazing Area

Glazing provides many useful functions. Its primary purpose is to give the occupant a view of the outside. It can capture useful solar gain in winter, but can also admit unwanted gain in summer. It is a means of admitting natural light, but can also generate excessive glare. Conduction losses from glazing are usually significantly greater than through opaque walls (Building Regulations require U–values of 0.45 W/m^2K for walls, double glazing units are typically about 3.0 W/m^2K). Analysis using the LT method [10] suggests that in terms energy performance terms, there is a shallow optimum for glazing areas which lies between 25–40%.

6.2 Overheating Risk

Heat gain in offices arises from two principal sources – solar gain through glazing, and internal gains from lights, equipment and people. Equipment gains and occupancy gains are not really within the control of the designer (except perhaps in the space allocation per person). It is important however that the designer makes a realistic assessment of the heat output from office equipment, since this is a factor which has been grossly over estimated in the past [11]. It is unlikely that the heat gain from office equipment will exceed about 15W/m^2 except in specialist areas with very intense I.T. use.

Lighting systems can be designed for low heat gains during periods of overheating risk. The best way to achieve minimum lighting loads is to ensure the lights are switched off at times of peak solar gain. The gain to the space and the lighting energy consumption can be reduced at all times of the year by selecting high efficiency light sources.

It may be a false economy to reduce design lighting levels, since visual comfort is a very important factor in staff productivity. However it may be appropriate to only provide the design illumination on the task, with a lower background level. Lighting design issues are discussed in detail in the CIBSE Interior Lighting Code [12].

Solar gain through glazing can be controlled by limiting the glazed area and/or by solar protection of the glass. Solar protection can be provided by coatings etc on the glass itself, but this will also reduce daylight transmission. The alternative is to use shading devices which may be fixed or movable. The effectiveness of fixed shading devices such as overhangs in controlling peak solar gains is very orientation dependent. They are ineffective on east and west facades because of the low sun angles at these orientations. They work very effectively on predominantly southerly aspects because they can cut out the summer sun but admit the beneficial winter sun.

Blinds can be external, mid-pane or internal. Their effectiveness is reduced as the blind is moved progressively from external to mid-pane to internal, but maintenance problems are reduced. The control of blinds, especially in relation to the impact on utilisation of daylight is an important design issue.

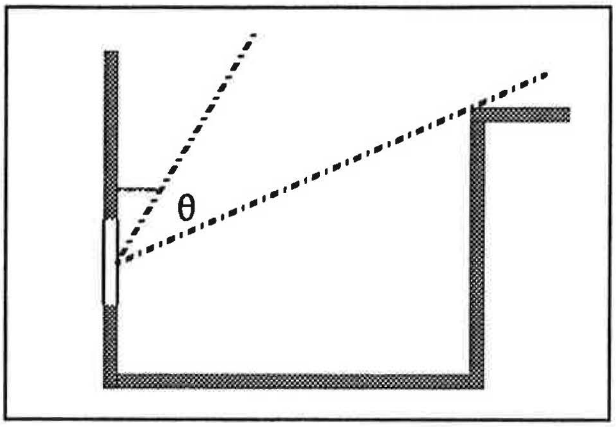
6.3 Daylighting and Glare

Daylighting is an enormous subject in its own right, and so readers are directed to other documents such as CIBSE Window Design Manual [13], and useful commentaries such as Daylight in Buildings [14]. Natural lighting and natural ventilation work in sympathy with each other. The maximum depths for natural ventilation are comparable to the maximum depths for effective daylighting. To achieve good daylight, an average daylight factor of 5% is desirable. This factor can be calculated from the equation given in the CIBSE Applications Manual on Window Design [13]. The depth of space that can be sidelit is a function of the percentage of glazed window wall (seen from the inside) is as follows

where W = net glazed area (m2)

DF = target average daylight factor

$$W = \frac{\overline{DF} \, . \, A \, . \, (1 - R^2)}{T \, . \, \theta} \qquad (12)$$



A	=	total internal area of all surfaces (walls, ceiling, floor)
R	=	area weighted average reflectance of the interior surfaces (including the windows)
T	=	diffuse transmittance of the glazing material (including the effects of dirt)
θ	=	angle subtended in the vertical plane normal to the window, by sky visible from the centre of the window (degrees).

Clearly the daylight levels will reduce towards the back of the room, and so the average daylight factor has to be qualified by avoiding excessive contrast glare between front and back. This can be achieved by ensuring that the depth of the space does not exceed the limiting depth, given by

$$\left(\frac{l}{w} + \frac{l}{h}\right) < \frac{2}{(1 - R_B)} \qquad (13)$$

where l	=	depth of room from window to back wall (m)
w	=	width of the room parallel to the window (m)
h	=	height of the window head above floor level (m)
R_B	=	area weighted average reflectance of the half of the interior furthest from the window.

The shape and position of the window, as well as its area is important. Good daylighting deep into the space is achieved by glazing at high level. Therefore taller narrower windows are better than low wide windows. As well as providing good natural lighting levels, attention needs to be paid to eliminating glare by

a) screening the sun from direct view

b) controlling brightness contrast by choice of surface colour and finishes.

The high level glazing and the reduction in contrast glare can be combined by the use of a light shelf which helps project daylight into the space whilst providing shading (and reduction in daylight levels) close to the window.

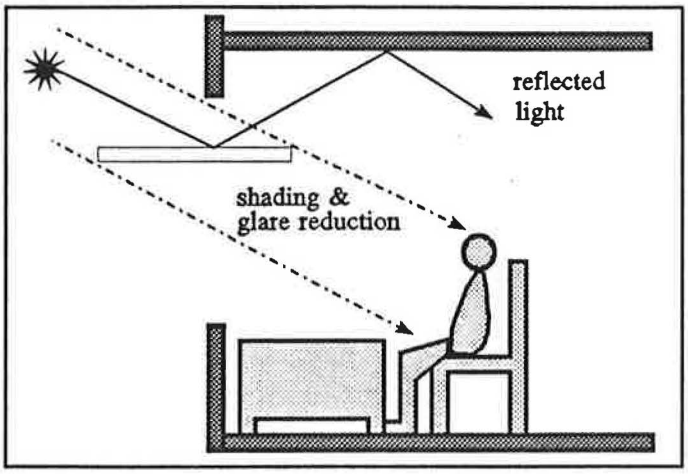


Figure 13 The performance of a light shelf

7 CONCLUSIONS

This report has concentrated on describing the development and proving of a design tool to be used in the scheme design stage. A simplified (but physically rigorous method) has been developed, and its applicability demonstrated by comparison with an existing sophisticated simulation program. The report has gone on to discuss the other issues which must provide a context in which the designer has to work.

8 ACKNOWLEDGEMENTS

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A - DEVELOPMENT OF EQUATIONS

This appendix provides a fuller treatment of the development of the inverse solve discussed in section 2 of the body of the report. It follows the same order of treatment, i.e stack only, wind only, combined driving forces, internal resistances and external leakage. It is assumed that the reader is familiar with the content of section 2 as this appendix expands on, rather than repeats, that material.

A.1 Stack Induced Flows

The stack pressures are generated by variations in hydrostatic pressure between inside and outside. These variations in pressure are themselves the result of temperature and density differences inside and outside the building. The pressure reduces linearly with height in a column of an incompressible fluid at constant temperature (equation 1). The difference in pressure gradients can be determined by application of the Ideal Gas Law

$$\frac{d\Delta P}{dh} = -g \cdot \rho_{stan} \cdot T_{stan} \cdot \left(\frac{1}{T_{out}} - \frac{1}{T_{ins}}\right) \tag{14}$$

where ρ_{stan} = air density at standard conditions (kg/m^3)
T_{stan} = Absolute temperature at which standard density is defined (K)
T_{out} = Outside air temperature (K)
T_{ins} = Temperature of stack (K)

In terms of the calculation of airflow through an opening, the requirement is to determine the pressure difference across the opening between the inside and the outside of the stack. Equation 12 gives the difference in pressure gradients between the inside and outside air columns. In order to establish the difference in pressure, it is necessary to know the distance between the opening and the point at which the two columns of air have the same pressure. This point is the Neutral Pressure Level (NPL). By fixing the NPL, the pressure difference across any opening can be determined by the product of the right hand side of equation 12 and the height difference, Δh (m), between the opening and the NPL. This pressure difference can then be substituted into the orifice flow equation (eqn (2)), to calculate the size of the opening.

$$A = \frac{Q}{C_d \sqrt{\dfrac{2 \cdot \Delta h \cdot g \cdot \rho_{stan} \cdot T_{stan} \cdot \left(\frac{1}{T_{out}} - \frac{1}{T_{ins}}\right)}{\rho_{ins}}}} \tag{15}$$

where Q = the flowrate (m^3/s) through the opening at the condition corresponding

to the room temperature
ρ_{ins} = the air density at the same condition.

Equation 13 is correct when the temperature of the stack is constant throughout its height. This may not always be true, particularly if the design incorporates solar gain features to promote buoyancy (e.g. the solar chimney or atrium). In such cases, it is necessary to subdivide the stack into a number of slices, each at their own defined temperature. Integrating equation 12, and applying it successively to each of these elements enables the change in inside-outside pressure difference across the height of the element to be determined. The changes across each individual element can then be summed to give the change at any point in the stack relative to a reference point of the bottom of the stack.

$$d\Delta P = -g \cdot \rho_{stan} \cdot T_{stan} \cdot [\, dh_a \cdot (\frac{1}{T_{out}} - \frac{1}{T_{ins_a}}) + dh_b \cdot (\frac{1}{T_{out}} - \frac{1}{T_{ins_b}}) + ...etc] \quad (16)$$

where ha = length of bottom, "a"th element of the stack.
with equivalents for the other elements.

This method will generate a profile of changes in inside-outside pressure difference with height. The position of the opening and the NPL are known, and so from the profile, the change in the inside outside pressure difference between the opening and the NPL can be determined. Since by definition, the pressure difference at the NPL is zero, this change in inside-outside pressure difference is in fact the pressure difference across the opening. This pressure difference can then be used in the orifice flow equation to generate the required opening area.

A.2 Wind Driven Ventilation and Combined Effects

The wind drive case is very much simpler than the stack driven case, and all the necessary equations are given in section 2.2. Similarly, the way the effects of wind and stack can be combined is relatively straightforward once the principle of addition of pressures is adopted. The required equations are developed in section 2.3.

A.3 Effect of Internal Resistances

As described in section 2.4, the way that the effect of internal resistances has been handled is to first of all generate an equivalent area for the resistance between the outside environment and the stack itself (or the "central corridor" for a cross ventilation design). In reality, in most designs, this overall resistance will be made up of two components – one opening in the outside facade, and a second opening between the ventilated space and the stack or corridor. It is relatively simple to decompose the overall resistance into two components by recognising that the sum of the resistances of the two openings must equal the overall resistance, and that the flowrate is the same through both resistances. Using the orifice flow equation to generate the pressure drop across each resistance, the following equation can be generated.

$$\left(\frac{Q}{C_d \cdot A_{inlet}}\right)^2 \cdot \frac{\rho}{2} = \left(\frac{Q}{C_d \cdot A_{facade}}\right)^2 \cdot \frac{\rho}{2} + \left(\frac{Q}{C_d \cdot A_{atrium}}\right)^2 \cdot \frac{\rho}{2} \qquad (17)$$

Equation (9) in section 2.4 follows easily from equation 15.

A.4 Building Envelope Leakage

The principles and the equations required are fully described in section 2.5.

B - NATURAL VENTILATION WORK SHEETS

B.1 Stack Dominated Designs

ANALYSIS TITLE					
WEATHER DATA					
Outside temp. °C		Air density kg/m^3 [1]			
Wind speed (m/s)	Local/Met? [2]	Terrain class [3]	Building Ht (m) [4]	Site wind speed (m/s) [5]	
STACK DATA					
Element no.	1	2	3	4	5
Height of top (m)					
Element temp (C)					
Density kg/m^3					
dΔP across element [6]					
Cumulative dΔP Pa [7]					
Req'd NPL (m)		dΔP to NPL (interpolation in above row)			
DESIGN CONDITION - ZERO WIND					
Opening number	1	2	3	4	5
Opening height (m)					
Room volume m^3					
Room temp C					
Density kg/m^3 [5]					
Req'd ac hr^{-1} [8]					
Vol flow m^3/s [9]					
Mass flow kg/s					
dΔP to opening [10]					
Opening ΔP Pa [11]					
Area m^2 [12]					
SIZING OF OUTLET					
Outlet ht (m)	dΔP to outlet [9]	Mass flow kg/s[13]	Vol flow m^3/s [14]	Outlet ΔP Pa [15]	Area m^2 [11]

Continued overleaf

Sizing and Location of Passive Ventilation Openings

ADJUSTMENT FOR WIND EFFECTS					
Outlet Cp		Pw on outlet Pa[16]			
Opening number	1	2	3	4	5
Opening Cp					
Pw on inlet Pa [15]					
ΔP for path Pa [17]					
Inlet ΔP Pa [18]					
Revised area m^2 [12]					
ADJUSTMENT FOR SERIES RESISTANCE					
Type (FE/FI) [19]					
Area of fixed m^2					
Facade area m^2 [20]					
Internal area m^2					
ADJUSTMENT FOR FACADE LEAKAGE					
Background leakage m3/hr.m2 @ 50 Pa					
Facade area m^2 [21]					
Facade ΔP Pa [22]					
Infiltration m^3/s [23]					
External area m^2 [24]					
Internal area m^2 [23]					

Sizing and Location of Passive Ventilation Openings

B.2 Wind Driven Designs

ANALYSIS TITLE				
WEATHER DATA				
Wind speed (m/s)	Local/Met? [1]	Terrain class [2]	Building Ht (m) [3]	Site wind speed (m/s) [4]
ROOM DETAILS				
Opening number	1	2	3	4
Room volume m^3				
Room temp °C				
Room density kg/m^3 [5]				
Req'd ac hr^{-1}				
Vol flow m^3/s [8]				
Inlet Cp				
Outlet Cp				
Height difference m [25] (inlet to outlet)				
Stack pressure Pa [26]				
Path ΔP Pa [27]				
Area of int resistance m^2 [28]				
ΔP per facade opening Pa [29]				
Area of each facade opening m^2 [12]				

B.3 Explanatory Notes

The following notes are intended to be used alongside the work sheets provided on the previous pages of the report. They assume that the user of the worksheets are reasonably familiar with the principles and the general procedures outlined in the body of the report.

1. The density of the air in any element of the stack can be calculated relative to the standard air density using the following expression

$$\rho = \rho_{stand} \cdot \frac{T_{stand}}{T}$$

where ρ = air density (kg/m3)
ρ_{stand} = air density at standard conditions - usually 1.2 kg/m^3
T_{stand} = Temperature of standard condition - usually 273.16 K
T = Temperature at which density is required.

2. Define whether the stated windspeed is measured at the building site or is the meteorological wind speed. If the latter, then the wind speed must be corrected to that prevailing at the building site by the factors in the subsequent boxes.

3. Terrain class affects the profile of the wind boundary layer according to two parameters using the following equation

$$\frac{V}{V_{met}} = K \cdot z^{a}$$

where V = wind speed (m/s) at the required building height of z m
V_{met} = meteorological wind speed at a height of 10 m.

K and a values are a function of terrain class as given in the following table.

Terrain class	K	a
Open flat country	.68	.17
Country with scattered windbreaks	.52	.20
Urban	.35	.25
City	.21	.33

4. This is the reference height of the building on which the pressure coefficient set is based (usually roof level).

5. If the stated wind speed is local, transfer the value to this box. If the stated wind speed is meteorological, use the equation and data in note 2 to calculate the wind speed (V) at the site.

6. Calculate the change in differential pressure across the full height of the stack using the following equation

$$d\Delta P = -g \cdot \rho_{stan} \cdot T_{stan} \cdot [\, h \cdot (\frac{1}{T_{out}} - \frac{1}{T_{ins_a}})] \qquad \textbf{(1)}$$

where h = length of element of the stack in the vertical direction.

7. This is calculated by accumulating the pressure changes for all the elements of the stack below the one being considered – i.e.

$$Cumd\Delta P_n = d\Delta P_n + d\Delta P_(n-1) + d\Delta P_(n-2) +.... \; d\Delta p_1$$

8. The air change rate will be based on prior analysis of air quality or cooling requirements.

9. The volume flowrate can be calculated from the following equation

$$Q = \frac{V \,.\, N}{3600}$$

where Q = Volumetric flow (m^3/s)
V = Room volume (m^3)
N = required air changes per hour (hr^{-1})

10. This value is obtained by height interpolation in the row headed "Cumulative dΔP" under the Stack Data section.

11. This value is the difference between the "dΔP to opening" and the "dΔP to NPL" values.

12. This is calculated using the orifice flow equation

$$A = \frac{Q}{C_d \cdot \sqrt{(\frac{2 \,.\, \Delta P}{\rho})}}$$

where C_d = Discharge coefficient (usually 0.61)
ΔP = the modulus of the pressure drop across the opening
η = density of air flowing through the opening (kg/m^3)

13. This is the sum of the mass flows through all the inlets.

14. This can be calculated from the mass flow and the density of the air at the outlet. The density is calculated as described in note 5, using the temperature of the stack element in which the outlet is located.

15. This is calculated in exactly the same way as the pressure difference for the inlets (see notes 9 and 10).

16. The pressure on the outlet is given by

$$P_w = 0.5 \,.\, \rho \,.V_{wind}^2 \,.C_p$$

where V_{wind} = Site wind speed (sheet 1) (m/s)
C_p = Pressure coefficient (–) at opening
ρ = density of air at outside temperature (kg/m^3)

17. The overall driving pressure across the flowpath is given by

$$\Delta P_{path} = \Delta P_s + P_{w_{inlet}} - P_{w_{outlet}}$$

where ΔP_s = the stack pressure difference (Pa) given by the difference between dΔP to the opening and ΔP to the outlet
P_w = the wind pressures Pa at inlet and outlet

18. The loss across the opening is given by the path pressure drop less the outlet pressure drop (see note 14).

$$\Delta P_{inlet} = \Delta P_{path} - \Delta P_{outlet}$$

19. Indicate whether the user wants to fix the external (FE) or the inside (FI) opening area.

20. Using the overall inlet area as calculated in note 12, and the area of the fixed opening, the required area of the other opening can be calculated–

$$\frac{1}{A_{inlet}^2} = \frac{1}{A_{facade}^2} + \frac{1}{A_{inside}^2}$$

21. This is the area of the fabric of the facade through which the air will infiltrate.

22. This is the pressure drop across the facade, which is the difference between the overall inlet pressure drop and the pressure drop across the inside resistance.

23. The infiltration rate is calculated from

$$Q_{leak} = \frac{A_{fabric}}{3600} \cdot Q_{50} \cdot (\frac{\Delta P}{50})^n \qquad (1)$$

where Q_{leak} = Infiltration flowrate ($m^3/s.m^2$)
A_{fabric} = Area of fabric at the facade
ΔP = Facade pressure drop (Pa)
Q_{50} = Facade leakage at applied pressure of 50 Pa ($m^3/hr.m^2$)
n = Flow exponent (usually 0.66 for leakage flows)

24. The revised areas can now be calculated by substituting a revised flowrate in the orifice flow equation. If the Inside area is fixed (code =FI) then the revised area of the facade opening is given by

$$A_{facade} = \frac{(Q-Q_{leak})}{C_d \cdot \sqrt{(\frac{2 \, . \, \Delta P}{\rho})}}$$

where Q_{leak} = Infiltration flowrate m^3/s
ΔP = pressure drop across the opening

If the facade opening has been fixed by the user (code =FF), then a first approximation to the inside opening is given by

$$A_{inside} = \frac{(Q+Q_{leak})}{C_d \cdot \sqrt{(\frac{2 \, . \, \Delta P}{\rho})}}$$

This method only accounts for facade leakage and ignores leakage in other building elements. Such issues can only be considered by multi-zone ventilation programs.

25. This is to allow for any stack effect acting in combination with the wind pressure.

26. The stack pressure can be calculated from

$$\Delta P_s = g \, . \, h \, . \, \rho_{stan} \cdot T_{stan} \cdot (\frac{1}{T_{out}} - \frac{1}{T_{ins}}) \qquad (1)$$

where ρ_{stan} = air density at standard conditions (kg/m^3)
T_{stan} = Absolute temperature at which standard density is defined (K)
T_{out} = Outside air temperature (K)
T_{ins} = Temperature of room (K)
h = height difference

Sizing and Location of Passive Ventilation Openings

27. The path driving force ΔP_{path} is the sum of the wind and stack pressure differences

$$\Delta P_{path} = 0.5.\rho.V_{wind}^2.(C_{p_{inlet}} - C_{p_{outlet}}) + \Delta P_s$$

28. This should make allowance for any internal resistances like doorways etc. If there are two doorways in series (e.g. the two sides of a central corridor), the effect of the two doors should be combined using the equation in note 20.

29. This is half the available path pressure drop after the pressure drop across the combined internal resistance has been deducted (i.e. the available pressure drop is split equally between the windward and leeward facades).