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A MULTI-ZONE MODEL TO FACILITATE PREDICTING NATURAL VENTILATION THROUGH BUILDINGS

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A multi-zone model to facilitate predicting natural ventilation through buildings.

Abstract.

A mathematical model has been developed which will facilitate the prediction of infiltration rates within multi-zone buildings. The aim was to cater for:

(i) significantly different temperatures in different parts of the building;
(ii) flow paths at any height, including vertical connections between zones; and
(iii) flow paths extending over large vertical distances.

These aims led to to the requirement in the associated computer program that the variation of pressure with height be accounted for independently within each zone of the building.

In order to achieve these aims, the flows between zones were modelled by considering pressure differences and flow resistances. The neutral pressure level approach was found to introduce unnecessary complications. If the pressure in each zone varies with height, and at a rate which depends on the zone temperature, it is necessary to determine the the pressure in each zone at a reference height. The floor level of each zone was chosen as the reference height. The total building pressures are solved simultaneously to give these reference pressures.

Predictions obtained from the developed computer program have been compared with analytical solutions for simple systems as well as experimental data.

Notation.

A	Area (m^2).
C	Flow coefficient ($m.s^{-1}Pa^n$).
c	Flow coefficient ($m^3s^{-1}Pa^n$).
g	Acceleration due to gravity (9.81 m s^{-2}).
H	Total building height (m).
h	height (m).
N	Ratio of the calculation height to the total building height.
n	Flow exponent which characterises the flow regime for openings in the building structure. e.g. large openings - n = 0.5, cracks around doors - n = 0.66.
p	Air pressure (Pa).
Q	Air flow rate (m^3s^{-1}).
T	Temperature (°C or K).
λ	Ratio of the height of the neutral pressure level to the building height.
ρ	density (kg m^{-3}).
Ω	Thermal draught coefficient to account for the vertical resistance to flow between the floors of a building.

Subscripts

b	Barometric.
e	Exterior.
f	at floor level.
i	Interior.
h	At a specific height.
o	At a datum position.
st	Due to stack effect.
x	Height up an opening above the floor level.

1. Introduction.

1.1 Aim of the project.

This was to develop a computer model which would permit infiltration rates in buildings to be predicted accurately. Air infiltration arising from wind and stack effects often need to be estimated, as well as the effects of mechanical ventilation.

1.2 Need for air exchange in buildings.

Adequate rates of air change in buildings are needed for several reasons. Ventilation is required to maintain the quality of air in a building by replacing indoor air with fresh outside air. This supply of fresh air is is essential for the support of human metabolism, and to dilute and remove internal air pollutions.

Buildings which are designed to use passive solar heating or cooling may rely on ventilation and air movement as the mechanism for heat transfer. If the system is truly passive, then natural physical processes are used as the sole driving force. In hot conditions, a supply of fresh air can also help to increase heat loss from the body and thus aid in preventing discomfort.

However, excessive ventilation is often responsible for significant energy losses from buildings, and can cause cold and draughty conditions. An optimal level of ventilation should therefore be aimed at during the design of a building. Particular requirements must be met if air movement is used for heating or cooling as well as ventilation [1].

Awareness of infiltration as a major factor in the overall conditioning load of a building has led to tighter construction and integrity of the building enclosure. Consequently, infiltration rates, and their related ventilation rates of heat loss have been reduced. However, this has sometimes created other problems with regard to indoor air quality [2].

It is therefore important to be aware of the air flow pattern in a building when estimating indoor air quality, calculating space conditioning rates of energy consumption, or investigating the potential for using passive solar heating and cooling techniques.

1.3 Causes of air infiltration.

The air flow through a building is caused by natural air infiltration and by the use of mechanical ventilation systems. Natural infiltration occurs because of pressure differences across the openings in the building fabric. These arise due to wind, and thermal buoyancy effects (i.e. *the stack effect*). The wind pressure distribution around a building depends upon the building shape, the velocity and direction of the wind, and the nature of the surrounding terrain. The stack effect is caused by differences in air density resulting from the difference in temperature in the building. The rate of infiltration is a function of the pressure differences and the distribution and dimensions of openings within the building structure.

Natural air infiltration is a haphazard process which gives widely varying rates of ventilation and little control of the pattern of air movement within buildings. However it plays a dominant role in the ventilation of many types of building.

Ventilation needs may also be satisfied by the use of mechanical systems. These allow greater control over the air distribution but they do incur penalties both in terms of capital and running costs. Consequently it may be more cost effective to provide the required ventilation solely through natural means.

Where mechanical ventilation systems are used, the interaction of these systems with the natural air infiltration must be considered in order to achieve optimal performance.

2. Modelling air infiltration.

2.1 Previous work.

In spite of its importance, the analysis of inter-zonal airflows has lagged behind the modelling of other building features [3]. This is largely due to the complexity of the problem. Also the dearth of reliable measured data concerning infiltration characteristics of building components has hindered development. Nevertheless, various infiltration models have been developed over the last two decades. These tend to fall into two groups: single-zone models and multi-zone models [4]. A zone is defined as a fully mixed volume with a constant concentration level of the enclosed gas mixture. Single-zone models may be used where the condition within a building approximates to this limit, for example in small buildings with no internal partitions or at least open internal doors. Unfortunately the limits of single-zone models are often violated by attempting to use such models for multi-zone applications.

Where there are internal partitions in a building or there is an inhomogeneous air concentration in the space, a multi-zone model is required for more accurate predictions to be achieved. This allows the user to divide the building into a number of zones, each at a different pressure, and these are connected by flow paths. A review by Feustel [2] shows that although several models have been developed, there has been little dissemination of the results.

There is a requirement for air infiltration and inter-zonal air movement calculations to be included within thermal building simulation models, in order that predicted air infiltration rates can easily and accurately be assessed during the early stages of a building design.

2.2 The FLOW program.

One computer program called FLOW, developed by Melo and Hammond [5] at Cranfield Institute of Technology, was an attempt to model infiltration arising from wind, stack effect and mechanical ventilation in single and multi-zone applications. The wind pressure coefficients were determined internally, using different empirical correlations for exposed and sheltered sites. However, the treatment of of the stack pressure and internal resistances was relatively crude. Nevertheless FLOW was considered to be a good base from which to develop a more sophisticated model of these parameters.

2.3 Limitations of FLOW.

When FLOW is run in the single-zone mode, the interior is assumed to be at a uniform temperature with a corresponding pressure profile. A number of flow paths may be specified connecting the inside of the building to the outside. The multi-zone model allows the building to be divided into zones, each of which has a different pressure. The following limitations occur with the multi-zone model in FLOW:

- (i) The height of each zone must be an integer of the height of a single floor.
- (ii) All paths connecting zones must be at the mid-height of a zone.
- (iii) A single temperature must be specified to cover all zones in the building.
- (iv) Zones may not be connected vertically. The resistance to flows between floors is accounted for by the use of a thermal draught coefficient.
- (v) A consequence of (ii) is that the pressure on each floor of a zone is effectively assumed to be constant, as the stack pressure is always calculated at the mid height of the floor.
- (vi) A further consequence of (ii) is that all openings which constitute flow paths are assumed to have a bottom and top height which is neglible when compared with the the variation in pressure differences with height. In practice, for tall openings, the pressure difference and hence the air flow can vary with height.

As a result of these factors, FLOW was limited in application to the following cases:

- (i) Buildings having a uniform temperature and no partitions.
- (ii Buildings which have a uniform internal temperature, and zones which are separated by variable resistances in the horizontal plane together with a constant resistance to flow between floors throughout the building.

2.4 <u>Changes required to improve FLOW.</u>

In order to model inter-zonal air movements in buildings which do not approximate to the conditions just stated, the following improvements were needed:

(i) It should be possible to specify a different temperature for each zone in the building This would allow the modelling of buildings which have significantly different temperatures in adjacent zones.

(ii) Flow paths should be allowed at any height, including connections which join zones vertically.

(iii) Modelling flow paths which cover large vertical heights should be allowed.

(iv) The three previous requirements lead to a fourth condition; i.e. that the variation of pressure with height in each zone should be accounted for. The reason for this is illustrated in figure 1.

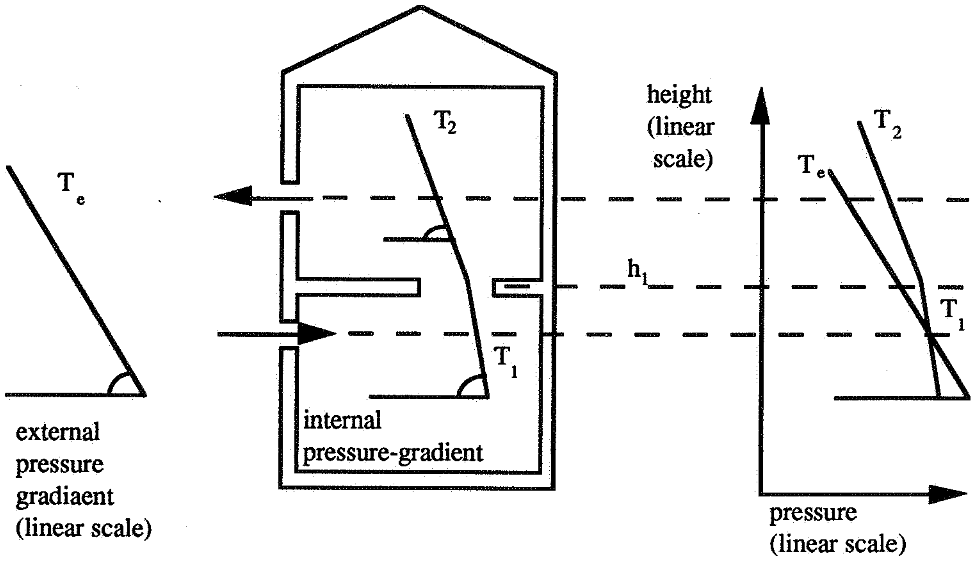

Figure 1: Stack-pressure induced air movements for vertically placed zones at different temperatures.

The figure shows the pressure profiles for a hypothetical case in which flow occurs between two adjacent columns, one of which is split into two zones at different temperatures. The flow between the zones depends on the pressure at the height of each path, which in turn depends upon the temperature in each zone.

2.5 <u>Implications of the required changes.</u>

If the different zones of the building are to have different temperatures, then the pressure profile in a column of the building may vary with height as illustrated in figure 1. For the example shown the pressure profile in the lower zone is given by:

$$p_h = p_1 - 273\,\rho_0\, g \frac{h}{T_1} \qquad ...(1)$$

where p_1 is the floor-level pressure for the lower floor zone. The pressure profile in the upper zone is given by:

$$p_h = p_2 - 273\,\rho_0\, g \frac{h}{T_2} \qquad ...(2)$$

where p_2 is the pressure at the base of the upper floor zone. Combining equations (1) and (2) gives the pressure profile in the upper zone as:

$$p_h = p_1 - 273\,\rho_0\, g \left[\frac{h_1}{T_2} + \frac{(h - h_1)}{T_2} \right] \qquad ...(3)$$

The stack pressure difference between the inside and outside in the upper zone thus varies with height, and is also a function of the pressure in the lower zone.

If a building has more than one column of zones, each with a different temperature profile, then the stack pressure difference between each column will be a function of the pressure and temperature profile in each adjacent column. The pressure profiles for a building with two distinct air columns may be as shown in figure 2.

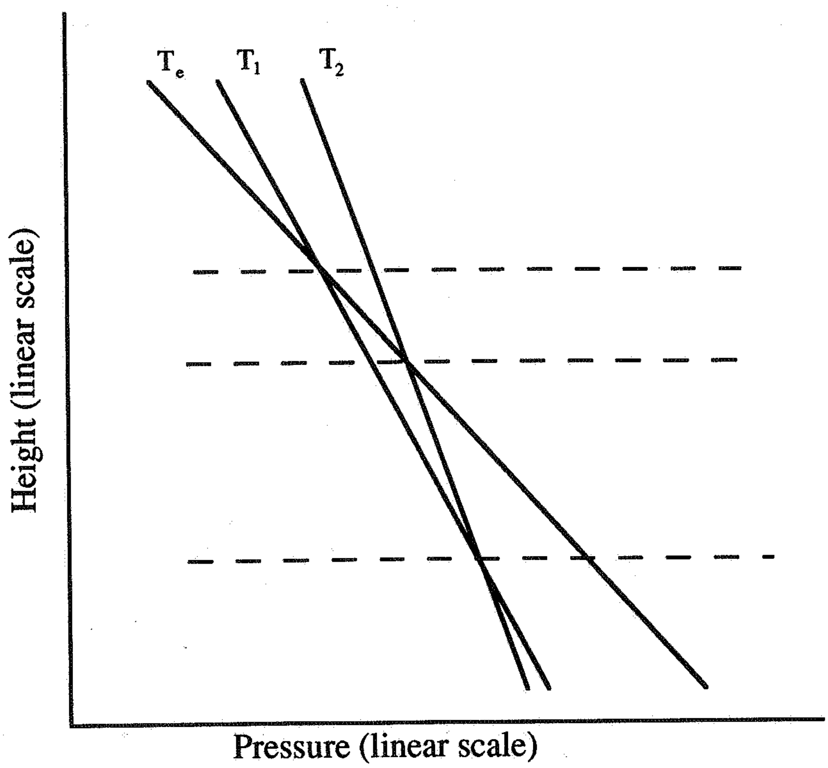

Figure 2: Pressure gradients in a building with separate columns of air at temperatures T_1 and T_2

The problem complexity is increased when resistances are considered in the horizontal plane between zones. At each point where there is a resistance, a discontinuity occurs in the plot of pressure against height, as illustrated in figure 3. FLOW dealt with vertical resistances by using the thermal draught coefficient, which is effectively used to alter the slope of the internal pressure profile. This adjusts the overall stack pressure difference. If variable resistances are to be modelled more accurately, it is necessary to be able to specify each resistance separately.

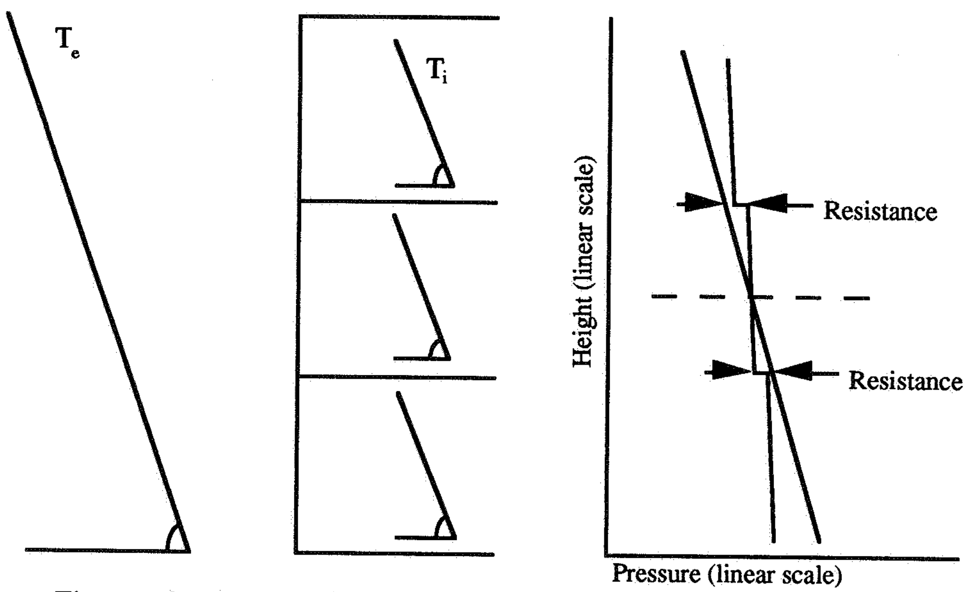

Figure 3: Stack-effect pressure distribution with resistances between floors.

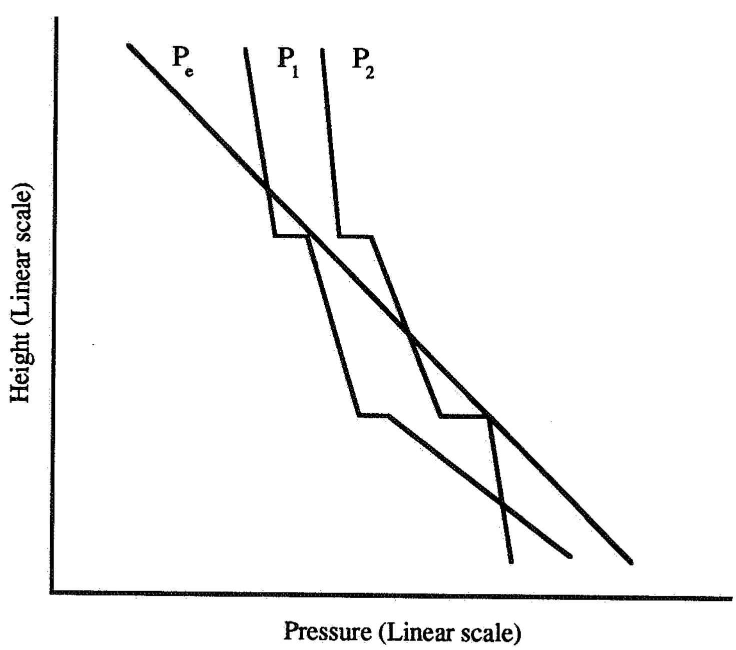

Figure 4: Possible pressure distribution in a building with two separated columns of air, each having zones at different temperatures and separated by varying resistances.

A model should be able to deal with all of the situations previously described, for any building configuration. A possible profile for a building with two air columns, and varying temperatures and resistances, is shown in figure 4.

2.6 Description of the FLOW model.

In FLOW a mass balance of the air entering and leaving each zone is determined. The solution to a problem is found by determining the pressure in each zone at which the set of pressure difference equations for each zone is satisfied, i.e:

$$\sum_{i=1}^{m} Q_{i,j} = 0 \qquad \ldots(4)$$

where m represents the total number of air flow paths connecting to zone i and $Q_{i,j}$ is the flow between zones i and j, and is given by:

$$Q_{i,j} = c_{i,j} (p_i - p_j)^{n_{i,j}} \qquad \ldots(5)$$

where $c_{i,j}$ and $n_{i,j}$ are the flow coefficient and the flow exponent for the flow between zones i and j.

Strictly speaking, this is a volume flow balance rather than a mass balance, as the air density is not included. This introduces an error for flow across the building's external walls, if the internal and external temperatures are different. However, for a flow between internal zones there is no additional error as the zone temperatures are all assumed to be identical.

The effect of mechanical ventilation is accounted for by adding, or subtracting, the net amount of air supplied to, or removed from, each zone to equation (4). Thus the pressurisation caused by the mechanical ventilation system is added to the natural pressure effects.

An iterative technique is needed to solve the sets of non-linear equations. For the single-zone model, the Newton-Raphson method is used. A Taylor expansion is used for multi-zone models and the resulting set of linear equations is solved by Gaussian elimination. Iteration continues until equation (4) is satisfied to within a specified error limit for each zone.

In order to determine the stack pressure differences up the height of the building, an initial estimate is used for the height of the neutral pressure. The user enters this value as one of the input parameters. A previously modified version of FLOW called XFLOW, attempts to improve the estimate of the neutral pressure when an initial solution has been reached for the flows.

3. Strategies for improving FLOW.

In order to improve FLOW so that it meets the criteria suggested in section 2.4, it is necessary to make its operation more flexible.

3.1 Use of the neutral pressure level.

FLOW determined the stack pressure differences on each wall of the building by using the concept of the neutral pressure level. The stack pressure differences were calculated using the expression:

$$p_{st} = 0.0342\ p_b(N-\lambda)H\ \Omega\left[\frac{1}{T_e} + \frac{1}{T_i}\right] \quad ...(5)$$

where N is the ratio of the height at which the pressure p is calculated to the total building height; λ is the ratio of the height of the neutral pressure level to the building height; and Ω is the thermal draught coefficient.

The concept of the neutral pressure level could be extended to be used to find the pressure differences between each adjacent column of air in a building. If there are varying resistances between floors, then there may be more than one neutral pressure level for two adjacent air columns. In the limit, where each floor of a building is sealed from the others, there is a neutral pressure level on each floor, as illustrated in figure 5.

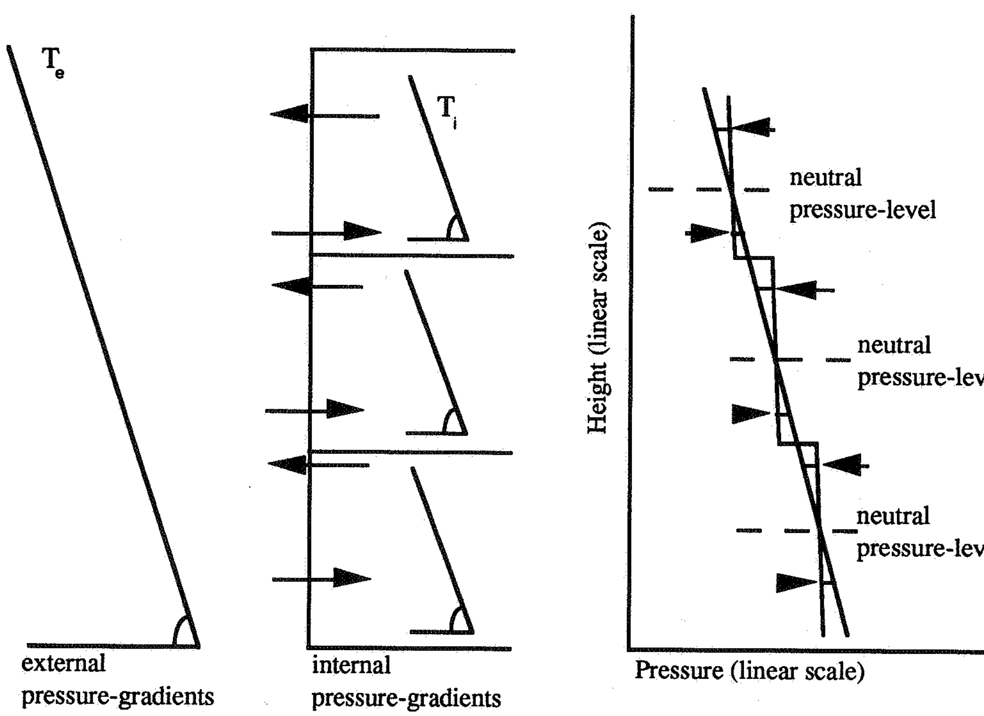

Figure 5: Stack pressure distribution in a multi-storey building with isolated floors.

Because of these complexities, the continued development of FLOW using the concept of the neutral pressure level did not appear to be profitable.

3.2 Consideration of resistances between zones.

Instead of making use of the neutral pressure, it is possible to model the flow between zones by considering pressure differences which act as a driving potential difference across resistances to the flow. An illustrative example is shown in figure 6.

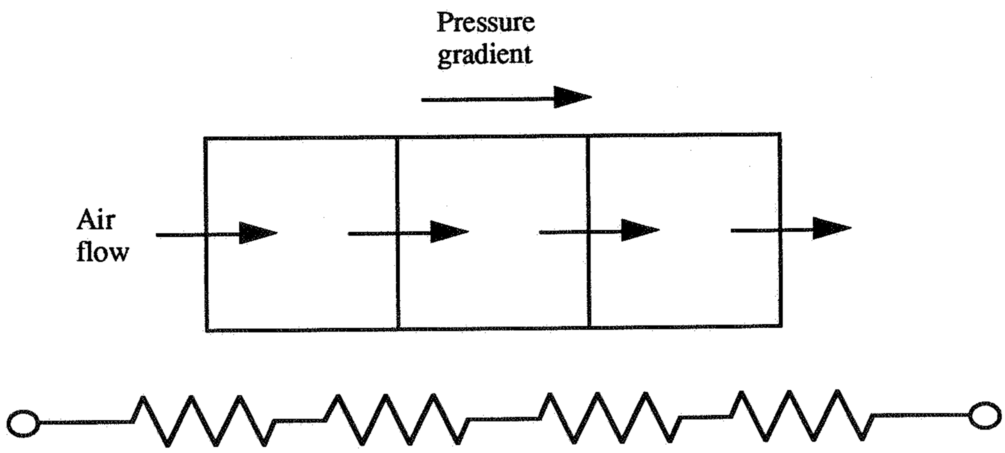

Figure 6: Use of resistances and driving forces to model flow

The pressure in each zone varies with height, and varies at a rate which depends on the zone temperature. Thus if a path joins two zones, which are at different temperatures, the driving force depends upon the height of the path. It is therefore necessary to find the pressure in each zone at a reference height and take account of the variation of pressure with height. The best choice for each reference height was considered to be the floor level of each zone. Some possible pressure profiles for several connected zones are illustrated in figure 7.

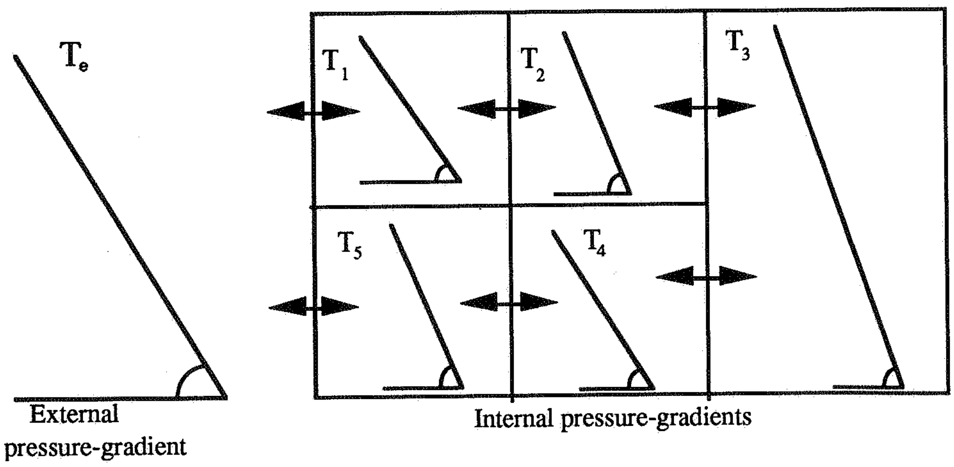

Figure 7: Qualitative indications of representative pressure gradients in some of the various zones.

In order to find the pressure in each zone, a solution must be found which satisfies the boundary conditions (i.e. known outside pressures) and the mass balance for flow into and out of each zone. This can be achieved by estimating the floor level pressure in each zone and taking account of the pressure variations with height, and then using an iterative technique to solve the set of equations. Using this method means that there is no need to determine any neutral pressure levels.

In view of the apparent simplicity of this method, it was adopted to improve the FLOW model.

3.3 Description of the new model.

The new infiltration model was called VARYFLOW. No changes were made to the existing code which calculated the wind pressure coefficients.

The stack pressure effect for each path is calculated using the resistance method described in the previous section (3.2). A flow path may be at any height, so the wind pressure effects are also determined as a function of height, rather than at the mid-height of each floor only. Paths may connect zones vertically as well as horizontally, so there is no need to specify a thermal draught coefficient.

In order to obtain a starting estimate for the floor level pressure in each zone, the following procedure was adopted.

(i) Order the zones by the number of flow paths connecting each one, starting with that containing the lowest number of paths.

(ii) Select the zones which are connected to the outside.

(iii) Estimate the pressure in each of the selected zones, working through the zones in the order determined by step (i). The pressure is estimated to be an average of the pressure in connecting zones (if already estimated) and the outside pressure for paths to the exterior. Each pressure is adjusted for height.

(iv) Find all zones which are connected to the zones whose pressure has now been estimated

(v) Return to step (iii) until the pressures have been estimated in all zones.

Figure 8 shows an example of the order in which zone pressures would be estimated for a 3 by 3 network of zones.

In order to obtain the best estimate for the floor level pressure, p_f, in a zone, a best fit straight line needs to be applied to the pressures in the connected surrounding zones (see figure 9). In the figure, p_i and h_i are the estimated pressures and path heights for the surrounding zones connected to the zone in question.

A mass balance is performed for each zone to obtain a set of equations which may be solved. In performing the mass balance, the density of the air flowing between zones is assumed to be the average density of the air on either side of the path. The set of equations is then solved using Gaussian elimination, as described in section 2.6 .

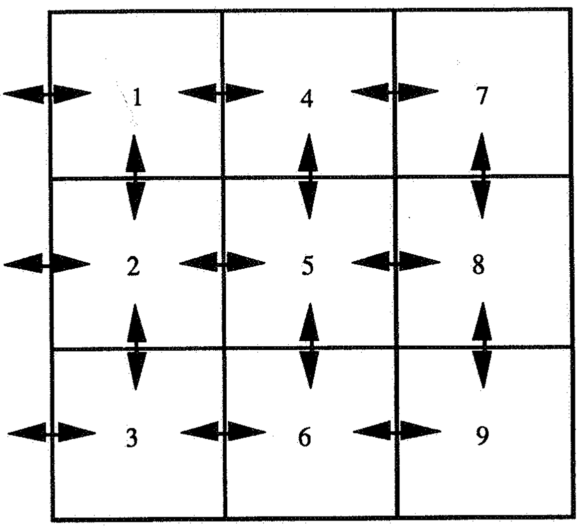

Figure 8: Order of the estimation of pressure in a number of connected zones.

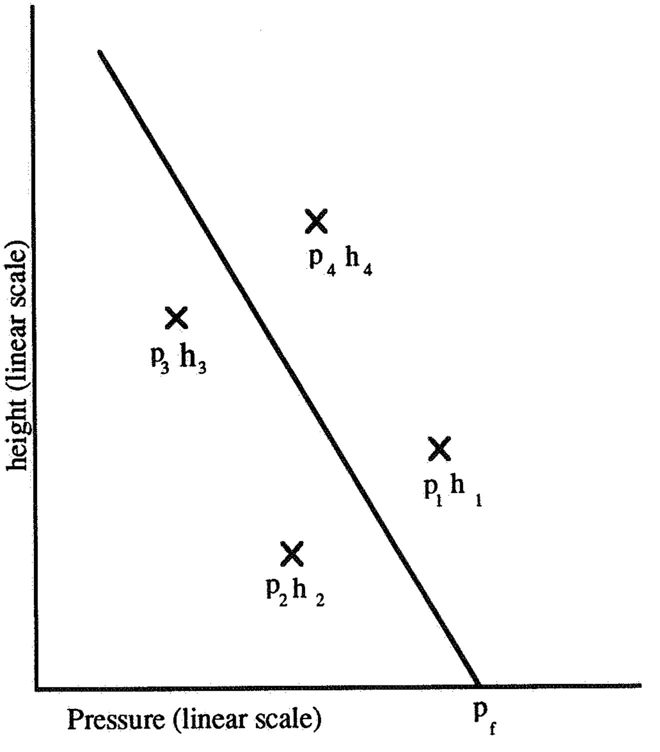

Figure 9: Estimation of p_f from pressures in surrounding zones

The volumetric air flow rate into and out of each zone through each path is reported, using the air density in the zone. Thus the flow rate on either side of a path will be different if the two zones are at different temperatures.

3.4 Large openings.

One further requirement of the new model is that it should be able to predict accurately the flow through large openings. To do this, it was necessary to integrate the flow up the height of the opening in steps such that:

$$Q_x = CA_x(\Delta p_x)^n \qquad ...(6)$$

where subscript x indicates the value is taken at height x. Note that, in this case, the value of the flow coefficient C is different from that used in equation 5 as it does not include the area of the opening.

When entering the data for each flow path, the user may specify those that should be treated as large openings by entering its height and width separately from the value of the flow coefficient, instead of including the path area within the flow coefficient value.

The initial estimate of the flow via each large opening is calculated at the path mid-height. The flow through each path is then calculated in height steps of 0.1m from the bottom to the top, using the pressure difference at each step to get the flow across that particular sub-area. The flows in each direction are summed and reported separately.

The time taken by the program to reach a solution is increased when large openings are used, but the number of iterations taken to reach a solution does not appear to be altered.

3.5 Assumptions made in developing the model.

These were as follows:

(i) Wind pressure coefficients may be used as previously described. the wind speed can be adjusted for height using a power law equation with the magnitudes of the coefficients dictated by the terrain.

(ii) The air in each zone is assumed to be well mixed, and at a single zone temperature.

(iii) Resistance to flow between zones can be modelled using the generalised equation $Q = c.(\Delta p)^n$ where c is the flow coefficient , n is the flow exponent and Δp is the pressure difference across the opening.

(iv) The pressure arising from wind and stack effects may be added together to determine the resulting flow. Air flows arising from mechanical ventilation may be added to the result.

(v) The effect of moisture content on air density may be ignored.

(vi) The density of air passing through a flow path may be taken to be the average of the density on either side of the path.

(vii) The variation of pressure with height is assumed to be linear. In fact, it falls exponentially, but near to the ground the difference is neglible.

3.6 Description of the model code.

The computer program is described below using a pseudo-code representation, in which a formalised language is used to describe the program operation.

3.6.1 Pseudo-code representation of VARYFLOW.

```
Read input data
Validate data and order zones by the number of connections
Write data to output.

DO for each set of weather data.

   IF wind required THEN
        Calculate wind angle
     IF exposed site THEN
        Calculate c values for an exposed site
     ELSE
        Calculate the c values for a sheltered site
     ENDIF
   ENDIF

   DO while the pressure is not estimated in all zones.
        Estimate pressures in zones next to known pressures.
        Find zones now next to known pressures
   ENDDO

        Solve the set of flow equations
        Calculate the air flow into each zone
        Determine the infiltration rates

ENDDO
```

To solve the set of equations.

```
DO   While the sum of flows into each zone is not zero
     Calculate the sum of the flow into each zone due to pressures
     (including mechanical ventilation).
     Calculate derivatives with respect to each zone pressure.
      IF single zone THEN
         Solve the equation using the Newton-Raphson method
      ELSE
         Solve the equation by Gaussian elimination.
      ENDIF
         Calculate improved estimates for zone pressures
ENDDO
```

4. Testing and validation of the model.

4.1 Model testing.

The aim of the first phase of the model testing was to discover whether the model could converge to a result for any given problem which lies within the program's data limits, and to ascertain whether the resulting solution makes physical sense.

The model was initially used to simulate the behaviour of a 2-storey building , shown in figure 10, with no wind effects present. The predicted air flow rate for all paths was 16.2 m^3h^{-1}. This solution was achieved in 3 iterations and agreed with the expected behaviour.

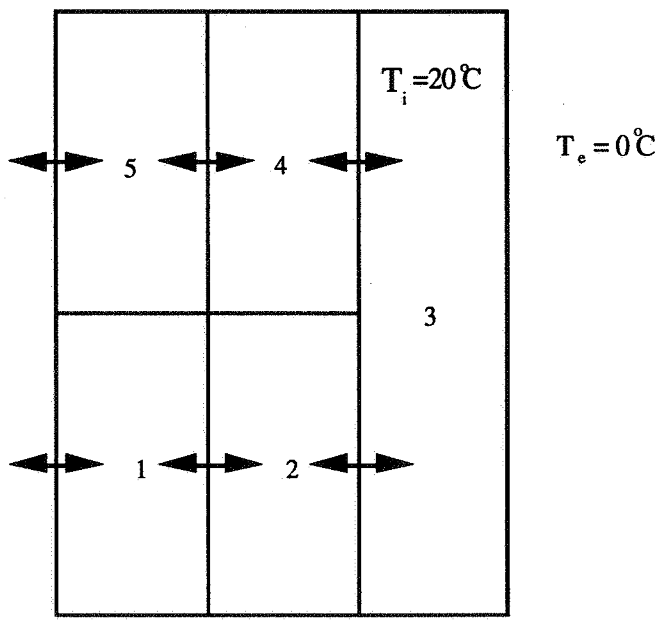

Figure 10: Designation of the zones in the building model to test VARYFLOW

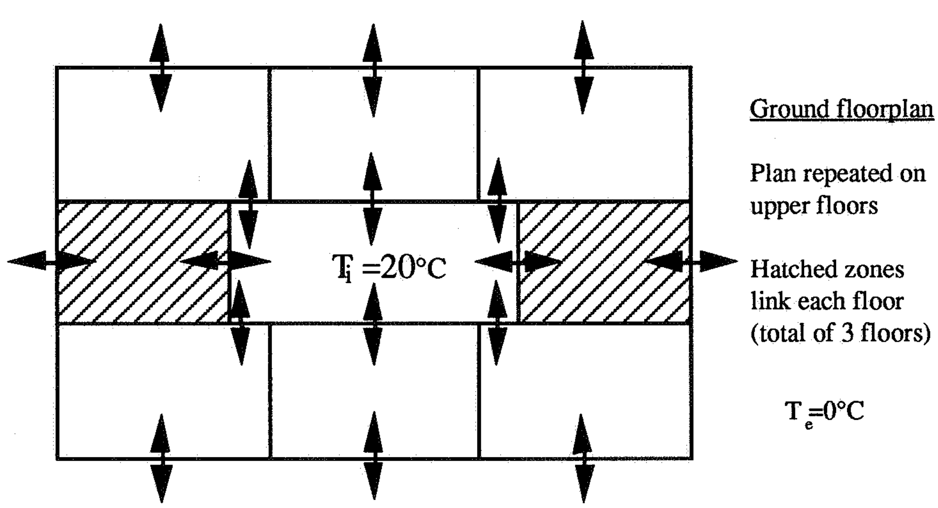

Figure 11: Plan of 48 path building to test VARYFLOW: representative air currents are indicated by the arrows

VARYFLOW was used subsequently to develop models for any configuration of building. It was tested for a variety of problems, one of the most complex being shown by figure 11. Convergence to a solution occurred in 6 iterations. Again, the results agreed with values expected for the problem as formulated by the building model.

4.2 Model validation.

Having produced a model, it is important to determine whether it may be used to obtain accurate predictions of real behaviour. The validation tests performed on the model were in two groups.

First it was necessary to ensure that the program produced results which could be checked by simple calculation. This was achieved by verifying that the results produced by the program were the same as those calculated analytically for simple situations.

The second part of the validation procedure was to compare the predictions of the model with measurements obtained from real buildings. The results of these validation tests are only as reliable as the measured data used for comparison purposes, but they do provide useful information on the model's performance.

4.3 Analytical verification.

For this level of testing, the results produced by the program are compared with analytical solutions for some simple problems, as recommended by Furbringer et al [6]. Each type of infiltration mechanism was tested in order to ensure that the individual parts of the code were examined [7].

The program was tested on a single zone building in which, one flow path was set up on the windward side and another on the leeward side. The model results are compared with those for the analytical solution in Tables 1 and 2.

FLOW MECHANISM	Flow rate, m^3h^{-1}	
	Analytical solution	VARYFLOW solution
Infiltration due to wind	92.4	92.3
Infiltration due to stack effect	2.6	2.6

Table 1. Comparison of infiltration rates for the analytical and VARYFLOW solutions.

FLOW MECHANISM	Over-pressure above atmospheric, Pa	
	Analytical solution	VARYFLOW solution
Mechanical ventilation	411	412

Table 2. Comparison of the calculated over-pressure resulting from mechanical ventilation for the analytical and VARYFLOW solutions.

4.4 Empirical validation.

It is necessary to know the potential accuracy achievable with the model when applied to real situations. In order to determine this, the model was tested using measured infiltration data from real buildings.

4.5 Runcorn House.

Melo [8] tested the original FLOW program against a set of infiltration data which were collected for a house in Runcorn, England. The data available include the flow coefficient and exponent leakage paths between the inside and outside of the building. However, no information was available regarding restrictions to flow between zones within the building. When the measurements were made, all the internal doors were open, so it was assumed that there were no internal resistances to the flows.
The data could thus be used to test the model assuming that the interior of the building could be modelled as a single zone. The temperature was assumed to be constant throughout the building. The house was subject to a high degree of shielding from the wind, so the wind pressure coefficients were calculated using the algorithm for sheltered sites.

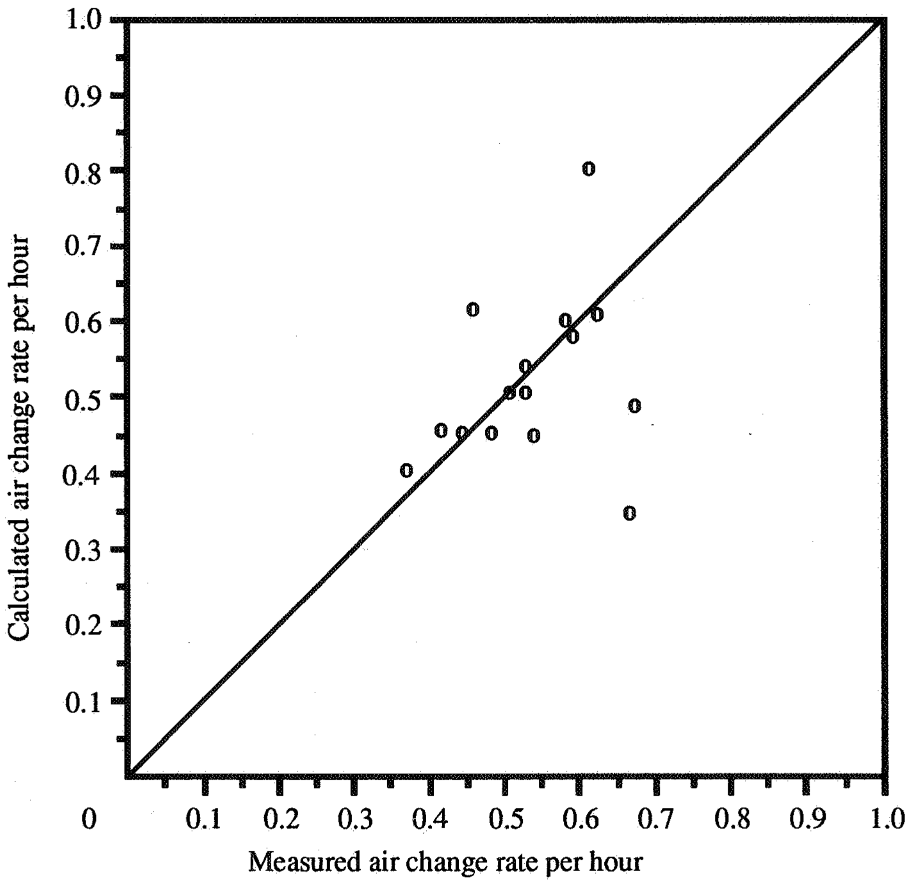

Figure 12: Comparison of the measured and predicted air infiltration rates for Runcorn considered house.

The calculated air infiltration rates are shown in comparison with the measured values in figure 12. Reasonable corroboration ensues, with 11 of the 15 values falling within plus or minus 25% of the perfect correlation line.

4.6 British Gas measurements.

The performance of the model, when used to predict ventilation in a building with zones at different temperatures, was also assessed, using data collected by British Gas [9]. The data available consist of measured air change rates in the rooms of a house, together with measurements of the temperature in each room and the outside weather conditions.

The flow paths and resistance values for each room were not available. However, it was assumed that a flow path existed for each window and door. Values for the flow resistances were estimated using data given by Liddament [4]. During the tests, the toilet and bathroom doors were open, so that these rooms were treated as as being part of the landing. For comparison of the results, the hall was also modelled as being in the same zone.

The values of the measured and predicted air change rates for each room are given in Tables 3 and 4 . The results do not show a high degree of correlation. However, there were probably some considerable errors in the estimates made for the flow coefficients. In particular, there is probably a specific cause for the discrepancy between the predicted and actual values for the flows into the kitchen and bedroom 2 for the predicted values to be so much lower than those measured. The kitchen is downstairs on the leeward side of the building, so it would not be expected to have a high air change rate without good reason.

Data set 1

Wind speed 1.33 ms^{-1}, direction 238^{o}

Outside air temperature = $22.460^{o}C$

Room	Temperature (^{o}C)	Measured air change rate (ac/h)	Calculated air change rate (ac/h)
Lounge	24.63	0.26	0.27
Dining	27.47	0.15	0.13
Bed 1	23.82	0.10	0.23
Bed 2	24.59	0.94	0.34
Bed 3	24.89	0.32	0.26
Bed 4	24.62	0.05	0.28
Kitchen	23.78	1.63	0.34
Hall/bath/toilet	23.52	0.88	0.75
AVERAGE		0.53	0.35

Table 3. Comparison of the British Gas measured air change rates with predicted values for "Data set 1".

Data set 2

Wind speed = 2.0 ms^{-1}, direction 276°

Outside air temperature = 22.47°C

Room	Temperature (°C)	Measured air change rate (ac/h)	Calculated air change rate (ac/h)
Lounge	25.32	0.36	0.58
Dining	27.84	0.17	0.36
Bed 1	24.31	0.21	0.51
Bed 2	25.11	1.24	0.76
Bed 3	25.79	0.48	0.59
Bed 4	24.72	0.09	0.39
Kitchen	23.87	1.79	1.39
Hall/Bath/Toilet	23.50	0.98	1.66
AVERAGE		0.64	0.83

Table 4: Comparison of the British Gas measured air change rates with predicted values for "Data set 2".

5. Conclusions.

The VARYFLOW model allowed a sophisticated and flexible approach to the modelling of infiltration in buildings. In particular, the modelling of stack effect pressures allowed the use of different temperatures in each zone. Also, the more flexible approach to the modelling of flow resistances between zones and particularly between floors now allows the modelling of buildings which do not have a uniform resistance to vertical flow throughout the building.

Simple analytical tests suggest the physical modelling is correct. Comparison of the model's predictions against experimental data have shown that predicted flow rates are in approximate agreement with data.

When the problems involved in obtaining accurate flow measurements are considered, together with the difficulty in making good estimates for the flow resistances of openings within building structures, the predicted and measured results were in remarkably good agreement.

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