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Development and Validation of a Model for Air Infiltration Rates Into Buildings

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ABSTRACT

The objective of this investigation was to develop a computer simulation model to predict hourly mean rates of air infiltration into buildings. The model should account for most of the relevant parameters that influence air infiltration, such as weather, orientation, building proportions, fan operation, etc and should also, internally, calculates the wind pressure coefficients. The agreement between calculation and measurement for all the data sets was felt to be good especially considering the uncertainties in interpreting the data.

INTRODUCTION

The development of computer programs for the modelling of energy flows in buildings is inhibited by a lack of information on the heat exchanges due to air infiltration according to Irving (1). This is rather suprising in view of the fact that infiltration accounts for a major fraction of the total heating and cooling loads in buildings. The traditional methods for calculating infiltration employ large safety margins, and this usually results in over-estimating the plant capacity. It is therefore necessary to improve on these methods, as an over-estimation of plant capacity would lead to unnecessarily high investments and reduced efficiency.

Many computer programs have been developed in order to calculate air infiltration. However most models presently in use are either not within the public domain or are written as research tools, rather than for meeting the needs of dynamic building thermal models. In order to overcome this problem a computer program , called FLOW, has been developed. This code differs from previous calculation methods in that the wind pressure coefficients, and consequently the pressure distribution around the building, are determined internally. In doing so, it accounts for the nature and roughness of the surrounding terrain and the consequent atmospheric boundary layer, the wind speed and direction, the building proportions and for any external shielding. The FLOW program can be run using either a single cell approach, in which the interior of the building is assumed to be at a single uniform pressure, or as a multi-cell model. In the latter case, the interior is subdivided into zones of differing pressure interconnected by leakage paths. The change from single to multi-cell model, or vice-versa, is controlled by simple alteration to the input data.

FLOW PROGRAM'S DEVELOPMENT

Assumptions. The program uses similar basic assumptions to those employed in other infiltration programs. These are:

i) that the building is considered as a series of compartments, each of which has a specified number of air flow paths into and out of it through which infiltration may occur;
ii) that each flow path has a characteristic flow resistance, which may be expressed by an equation relating air flow through it to pressure difference acting across it;
iii) that wind forces and stack effect produce external pressure outside each opening in the building which are time-invariant over the period of time considered in the calculation;
iv) that the internal air temperature in the building is uniform throughout building.

Air leakage characteristics of orificies and cracks
The basic driving forces for air infiltration are the pressure differentials across the various components of the building envelope generated by wind pressure, stack effect and by any mechanical ventilation. These pressure differentials act upon the various orificies and cracks in the building envelope to produce flow according to the classical orifice theory:

$$Q = C\,\Delta P^n \qquad (1)$$

The value of the exponent n depends on the pressure difference, ΔP , across the crack. At very low pressures the flow is dominated by viscous forces and at high pressures, by inertial forces. Therefore, at low pressures n will be close to 1.0 rather than 0.5 which is approached at high pressures. At intermediate pressures the behaviour will be a mixture of these effects. The ASHRAE Handbook (2) indicates that the values of n in the types of orificies usually found in residential structures will be of the order of 0.5 to 0.65.

The values of C greatly vary depending upon the type of crack and may be determined directly from leakage tests made on each leakage path or from published values such as those given in chapter 22 of the ASHRAE Handbook (2).

Infiltration by wind. A wind blowing on a building exerts a pressure which is highest at the centre of the windward wall which is given by:

$$P_s = \rho V^2/2 \qquad (2)$$

where P_s is the velocity pressure in the free air stream, V is the wind speed at a given elevation, and ρ is the air density. The wind speed V, can be deduced from that measured at the nearest weather station, following the procedure described by Melo (3).

The surface pressure generated by the wind action varies in a complex way over building facades, due partly to the wind speed gradient, partly to the presence of neighbouring buildings, and partly due to the aerodynamic characteristics of flow round a bluff body. However, it can be adequately calculated for the present purposes from a pressure coefficient, Cp, defined as:

$$Cp = P_w/P_s \qquad (3)$$

Most of the infiltration models presently in use require the specification of the pressure coefficients for different wind directions as a set of input data. The common procedure is to select these coefficients from existing codes of practice, in spite of the fact that these pressure coefficients are primarily intended for wind load applications and therefore represent the maximum values for each particular building facade. In practice, the pressure distribution is usually non-uniform, and difference between the average and extreme values can be quite large. This can be as much as 50% in the case of windward faces (4).

The inadequacy of the wind pressure coefficients arising from the existing codes of practice for simulating the effects of shelter (5), led to the use of two different techniques based on wind tunnel results. The first technique was developed from Bowen's experimental results (6). It can be used for calculating the wind pressure coefficients when the average height of the adjacent structures, Ha, is in between 16% and 100% of the height of the building itself, Hb. Bowen's results were fed into a computer routine and by using the Lagrange interpolation technique the wind pressure coefficients for any height across any wall and for any wind angle are then calculated. The results thus obtained are related to a minimum degree of shielding of Ha/Hb=1/6, and a correction factor for shielding, F, has then to be applied. If a flow exponent, n, of 0.65 (generally accepted for cracks) is assumed, the air flow correction factor of shielding presented by Shaw (7) reduces to:

$$F = (Cp)_{Ha/Hb}/(Cp)_{1/6} = 1.24\ e^{-1.31Ha/Hb} \qquad (4)$$

The second technique considered was the "harmonic analysis" method. Allen (4), showed that the mean wind pressure coefficients for any symetrical building can be represented by a Fourier series. The series coefficients are dependent on the aspect ratio and on the degree of shielding. It was decided to use this technique only for exposed structures (Ha/Hb<1/6), since very good estimates of the wind pressure coefficients for sheltered buildings (1/6<Ha/Hb≤1) were obtained by using the first technique (3). The Fourier series takes the following harmonic form:

$$Cp(\theta) = a_o + \sum_{m=1}^{7} a_m \cos(m\theta) \qquad (5)$$

were θ is the wind angle of attack. The coefficients , a_m , are given by Allen (4).

Infiltration by stack effect. Air at a given temperature has a pressure thar varies approximately linearly with height, with a slope proportional to be air density. Since the density is inversely proportional to the temperature, it follows that the temperature differences between air inside and outside the building causes pressure differences that drive infiltration. This phenomenom is called the "stack" or "chimney" effect. At some intermediate height a neutral pressure level exists where the internal and external pressures are equal. The stack effect pressure when measured at a height x above or below the neutral level is then given by:

$$P_d = 0.0342\ P_b\ x\ (1/T_o - 1/T_i) \qquad (6)$$

where P_d is the pressure difference due to stack effect, x is the distance to neutral pressure level (positive if above neutral level and negative below), P_b is the atmospheric pressure and T_o and T_i are the absolute temperatures of the outside and inside air, respectively. This equation implies that there is no resistance to air movement inside the building. It is, therefore, necessary to multiply the values arising from equation (6)by the thermal draft coefficient,Ω, wich depends on the air tightness of the exterior walls relative to that of the interior construction (8). With the interior completely open, the value of Ω will approach unity , whereas with each storey completely sealed from others it will approach zero. The values of Ω, as determined experimentally by Tamura and Wilson (9), for a few multi-storey office buildings ranged from 0.63 to 0.88.

Replacing x by (N-λ), as indicated by Shaw and Tamura (10) the following equation is then obtained

$$P_d = 0.0342\ P_b(N-\lambda)\ Hb\ \Omega(1/T_o - 1/T_i) \qquad (7)$$

were N is the ratic of height of level above ground to building height, and λ is the ratio of neutral pressure level to building height.

Calculation of the internal pressures. The internal pressures are calculated assuming that the amount of air entering each limited space, or zone, of a building through cracks is equal to the amount of air escaping from the zone. Thus, the basic mathematical procedure is to obtain a solution to a set of pressure difference equations of the following type:

$$\sum_{i=1}^{m} C_{i,j}(P_i - P_j)^{n_{i,j}} = 0 \qquad (8)$$

where $C_{i,j}$ and $n_{i,j}$ are the flow coefficient and flow exponent applicables to the air flow between the spaces i and j respectively, and m represents the total number of air flow paths of node j. Typically building networks will have a large number of nodes, consequently matrix methods for solving the non-linear set of equations would currently be cumbersome and expensive in terms of computing requirements. The Newton-Raphson iterative technique for multiple equations and unknowns has, therefore, been adopted for the FLOW program. This enables the internal node pressure to be progressively adjusted until the total flow into each node is less than a specified residual value. When the solution to the set of equations is obtained the air flow rate for each path is calculated according to equation (1).

The effects of air-handling systems are taken into account by specifying either the excess amount of supply over exhaust air in each space via equation (8). The solution, in effect, determines the degree of pressurization caused by the mechanical ventilation system, in conjunction with the natural pressures.

FLOW PROGRAM'S VALIDATION

An important part in the development of any air infiltration model is to determine the limits of its accuracy by comparison with field measurements. To assist in this task Liddament and Allen (5) prepared three key data sets so that the full range of applicability of any model being tested can then be assessed. The first data set is based on measurements made in an isolated, detached dwelling in Switzerland, the second in a detached dwelling in Otawa, Canadá and the third in a mid-terrace, three storey dwelling in Runcorn, UK.

Liddament and Allen (5) suggested that the model performance should be considered satisfactory if the computational results fall within ± 25% of the measured air infiltration rate. This 'error criterion' was derived on the basis of possible erros resulting from measurements inaccuracies in both the input data and the air infiltration rate measurements.

The FLOW program was run using all three of the key data sets, and the results for each are presented below in turn.

Swiss test data (Maugwill house). The air leakage distribution was estimated in a similar way to that employed by Liddament and Allen (5), during the tests with the BSRIA model. The component leakage was evenly distribuited along the roof/wall and the gable/roof junction. The assumed flow network is illustrated in Figure 1 and the corresponding leakage characteristics of each flow path are given in Table 1. Figure 2 shows the computation of the single-cell version of the FLOW program against the experimental data. Good agreement between the calculation and measurement was achieved with all but three (actually 83%) of the calculations being within 25% of measurement.

Canadian test data (HUDAC 'upgraded' house. The leakage distribution for the HUDAC house was based on the assumption of uniform distribution of cracks around the building. The assumed flow network and the corresponding leakage characteristics of each flow path are presented by Melo (3). Figure 3 shows that a consistent agreement was also obtained for this test house, with 37 of the 49 values (75%) falling inside the 25% band. The very low summer measurements tended to be underestimated by the model. The measurements of very low infiltration rates are very difficult to make, and this is likely to be the main reason for this disparity.

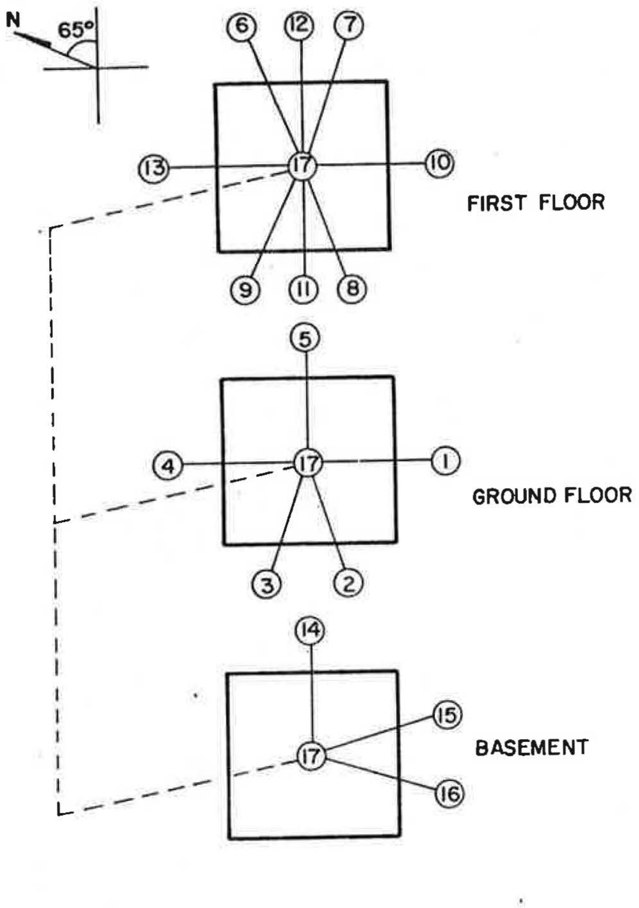

Fig. 1 - Flow network - Maugwill house

Table 1 - Leakage characteristics - Maugwill house

NODE NUMBERS	LEAKAGE SITE	C (m^3/hPa^n)	n
1	Dining room window	0.157	0.67
2	Living room doors	0.296	0.67
3	Studio doors	0.542	0.67
4	Stairwell window	2.4	0.67
5	Kitchen window	0.352	0.67
6	Bathroom window	0.298	0.67
7	Child's bedroom E	0.299	0.67
8	Master bedroom	0.246	0.67
9	Child's bedroom W	0.249	0.67
10	Eaves S	7.31	0.67
11	Gable/roof W	9.47	0,67
12	Gable/roof E	9.47	0.67
13	Eaves N	7.31	0.67
14	WC	0.089	0.67
15	Front door	5.4	0.50
16	Boiler room window	0.216	0.67
17	Internal node	-	-

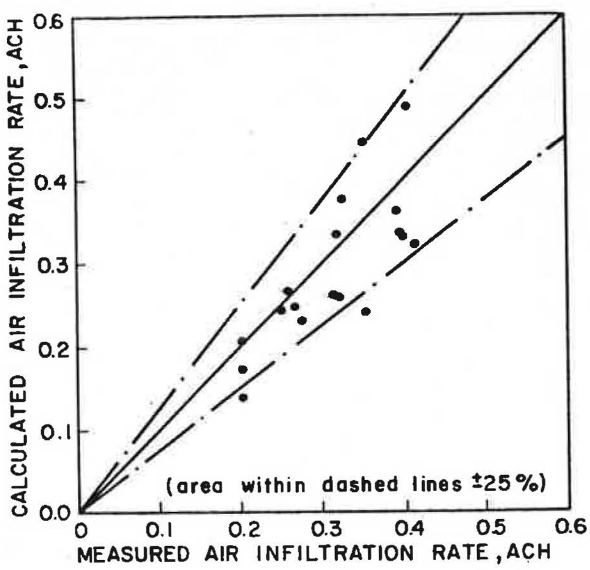

Fig. 2 - Comparison between calculated and measured air infiltration rates - Maugwill house.

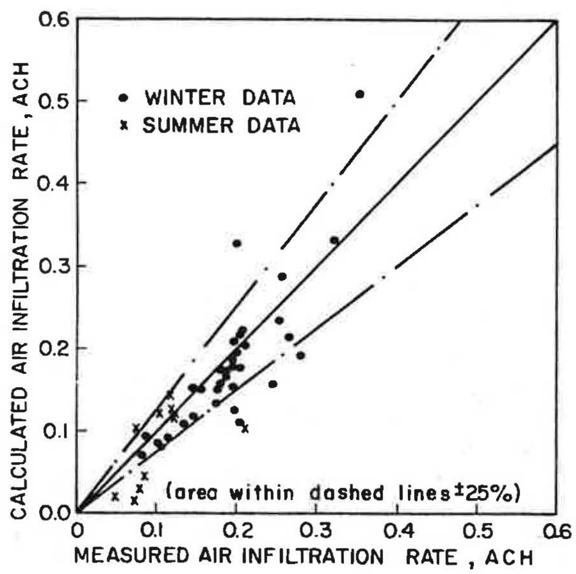

Fig. 3 - Comparison between calculated and measured air infiltration rates - HUDAC 'upgraded' house.

United Kingdom test data (Runcorn house). The leakage distribution for the Runcorn house was considered in a similar way as the Maugwill house. The given leakage characteristics of windows and doors were used directly, while the deficit between component and total building leakage was evenly distributed along the rear and front roof/wall junctions. The assumed flow network and the corresponding leakage characteristics of each flow path are also presented by Melo (3). Figure 4 shows that consistent results were also achieved for this test house, with 11 of the 15 (73%) calculated values being within the specified tolerance bands.

CONCLUSIONS

A method has been presented for computing the air infiltration rates into buildings, taking into account most of the key dependent variables. The air infiltration rates are calculated by assuming the building to be either a single-cell or a multi-cell network system, with specific flow resistances at the cell boundaries.

The main novel feature of the FLOW program is that the wind pressure coefficients are internally calculated, thereby avoiding the common and inadequate practice of selecting these parameters from wind load tables.

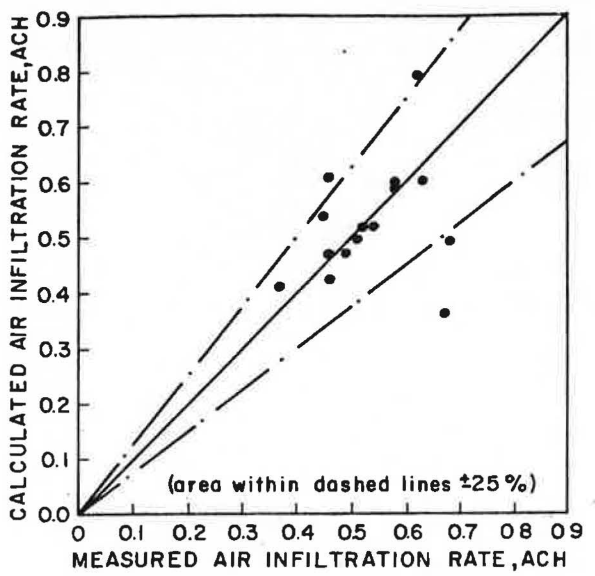

Fig. 4 - Comparison between calculated and measured air infiltration rates - Runcorn house.

REFERENCES

|1| IRVING, S.J., Energy Program Validation:Conclusions of IEA Annex I, Computer-Aided Design, Vol. 14, pp. 33-38, 1982.

|2| ASHRAE, Handbook of Fundamentals, New York, 1985.

|3| MELO, C., Improved Convective Heat Transfer and Air Infiltration Models for Building Thermal Simulation, Ph.D. Thesis, Cranfield Institute of Technology, Bedford, U.K., June 1985.

|4| ALLEN, C., Wind Pressure Data Requirements for Air Infiltration Calculation, Air Infiltration and Ventilation Centre Technical Note AIC-13, Bracknell, U.K., 1984.

|5| LIDDAMENT, M. and ALLEN, C., The Validation and Comparison of Mathematical Models of Air Infiltration, Air Infiltration and Ventilation Centre Technical Note AIC-11, Bracknell, U.K., 1983.

|6| BOWEN, A.J., A Wind Tunnel Investigation Using Simple Building Models to Obtain Mean Surface Wind Pressure Coefficients for Air Infiltration Estimates National Aeronautical Establishment Report LTR LA209, NRCC, Canadá, 1976.

|7| SHAW, C.Y., A Method for Predicting Air Infiltration Rates for a Tall Building Surrounded by Lower Structures of Uniform Height, ASHRAE Transactions, Vol.85, part.I, pp. 72-84, 1979.

|8| TAMURA, G.T. and SHAW, C.Y., Studies on Exterior Wall Tightness and Air Infiltration of Tall Buildings, ASHRAE Transactions, Vol. 82, part I, pp. 122-134, 1976.

|9| TAMURA, G.T. and WILSON, A.G., Pressure Differences Caused by Chimney Effect in Three High Buildings, ASHRAE Transactions, Vol. 73, part II, pp. 1-10, 1967.

|10| SHAW, C.Y. and TAMURA, G.T., The Calculation of Air Infiltration Rates Caused by Wind and Stack Action for Tall Buildings, ASHRAE Transactions, Vol. 83, part II, pp. 145-158, 1977.

SUMÁRIO

O objetivo deste trabalho foi desenvolver um modelo computacional para o cálculo da taxa horária de infiltração de ar em edificações. O modelo leva em consideração a maioria das variáveis que afetam a infiltração de ar, tais como clima, orientação e dimensões da edificação, presença de ventiladores, etc e também calcula internamente os coeficientes de pressão. A concordância entre os resultados calculados e medidos, para todos os conjuntos de dados, foi bastante boa principalmente quando considera-se as incertezas associadas com a interpretação dos dados experimentais.