FLOW - AN ALGORITHM FOR CALCULATING AIR INFILTRATION INTO BUILDING

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1. Introduction

The development of computer programs for the modelling of energy flows in buildings is inhibited by a lack of information on the heat loss due to air infiltration according to Irving (1). This is rather suprising in view of the fact that infiltration accounts for a major fraction (25% to 50%) 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 heating plant capacity. It is therefore necessary to improve on these methods, as an over-estimation of plant capacity would lead to unnecessarily high investiments and reduced efficiency.

Many computer programs have been developed in order to calculate 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.

2. Description of the mathematical model

2.1. 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).

2.2. Infiltration by wind

A wind blowing on a building exerts a pressure wich is highest at the centre of the windward wall (which is taken to be the stagnation point of the flow), and 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 inbetween 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:

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

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:

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

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

2.3. Infiltration by stack effect

Air at a given temperature has a manometric pressure that 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 phenomenam 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:

$$P_d = 0.0342\, P_b\, x(1/T_o - 1/T_i) \tag{6}$$

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, which 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 $(N-\lambda)$, as indicated by Shaw and Tamura (10) the following equation is then obtained

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

where N is the ratio of height of level above ground to building height, and λ is the ratio of neutral pressure level to building height (usually equal to 0.5).

2.4. Combined action of wind and stack effect

The resultant pressure difference on the exterior walls of buildings at any level can be approximated by the algebraic sum of the pressure difference due to wind and the pressure difference due to stack affect.

2.5. 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:

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

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 cumputing 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.

3. Comparisions with field measurement data

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 infiltration rate. Good agreement between the calculation and measurement, for the Swiss house,was achieved. With all but three (actually 83%) of the calculations being within 25% of measurement. Consistent agreement was also obtained for the Canadian house, wich 37 of the 49 values (75%) falling inside the 25% band. The results obtained for the British house were also consistent, with 11 of the 15 (73%) calculated values being within the specified tolerance bands. Due to space limitations only the results for the Swiss and Canadian house are presented in Figure 1, and 2 respectively.

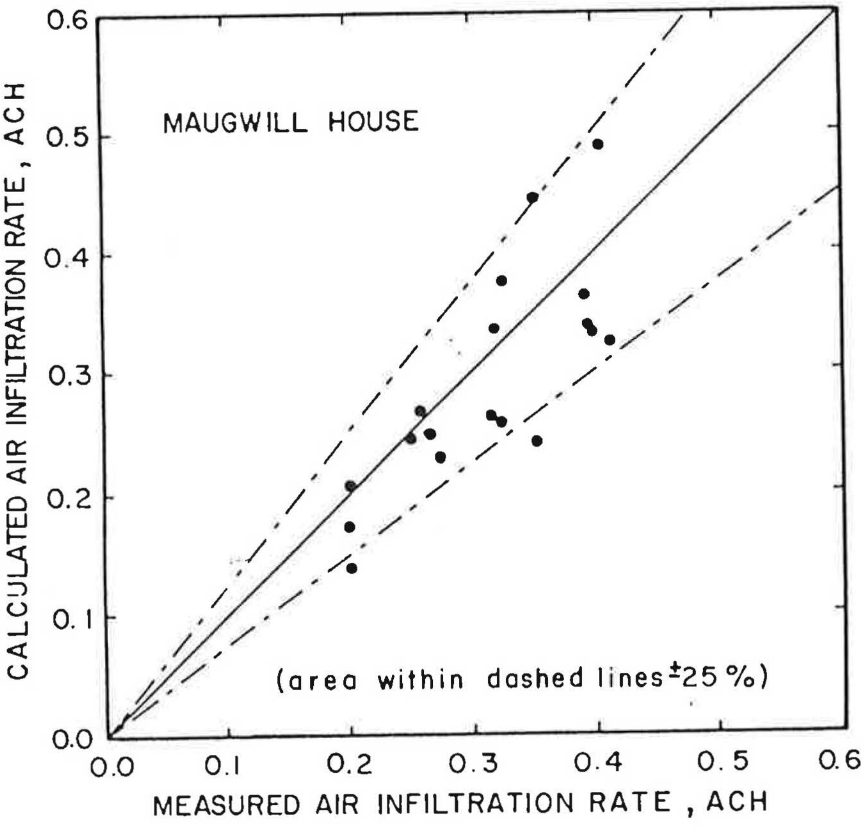

Fig. 1 - Comparison between calculated and measured air infiltration rates - Maugwill house.

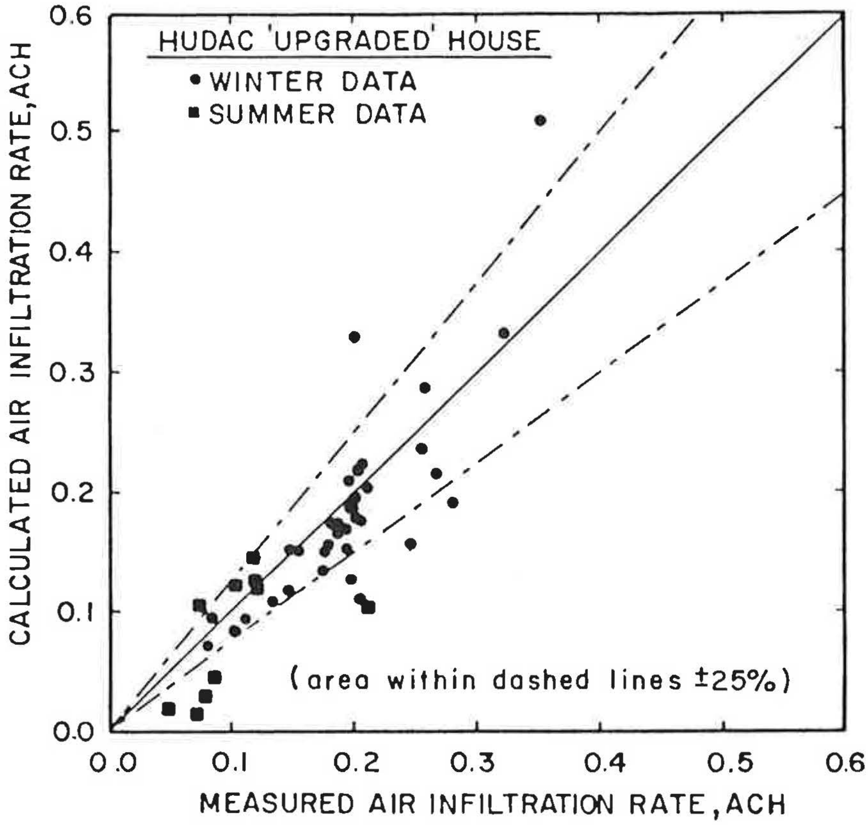

Fig. 2 - Comparison between calculated and measured air infiltration rates - HUDAC 'Upgraded' house

4. 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.

Table 1 shows a comparison between various infiltration models based on the work of Liddament and Allen (5). The only two models that achieve a similar accuracy to that of the FLOW model are the LBL and BRE models. However, they can only be applied to single zone systems. It should also be noted that the LBL model requires whole-house pressurisation test data for the building considered before it can be employed. Consequently, it cannot be used to evaluate infiltration rates at the design stage of a building. The FLOW program is able to utilise component leakage data, such as that given in the ASHRAE handbook (2).

Table 1 - Comparison between various infiltration models - % number of calculations within 25% of measurements.

DATA SET / MODEL	MAUGWILL HOUSE	HUDAC 'UPGRADED' HOUSE (a)	RUNCORN HOUSE
FLOW	83	84	73
BSRIA	94	44	-
NCR (b)	100	40	-
NCR (c)	44	72	80
IMG-TNO	82	-	-
BRITISH GAS (d)	-	84	67
BRITISH GAS (e)	-	71	80
NBRI	88	63 (f)	-
IGT	100	76	67
IBL	100	81	80
BRE	89	70	87
Reeves et al	100	57	14

(a) Winter data only
(b) Codes of practice pressure coefficients
(c) NRC pressure coefficients
(d) Without turbulent correction
(e) With turbulent correction
(f) Winter and sumer data

5. References

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