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PROGRAMMED COMPUTER MODEL OF AIR INFILTRATION IN SMALL RESIDENTIAL BUILDINGS WITH OIL FURNACE

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ABSTRACT - A computer program for the prediction of the air infiltration load in small residential buildings is described. The model represents an oil-fired furnace, a smoke pipe with barometric damper, a chimney and a non-partitioned building with leakage openings in the building envelope. This envelope includes ceiling, walls, windows and doors, the leakage opening of each being represented by several holes.

The model can be used to predict airflow through wall, window and door leakage openings as well as the chimney, with furnace on or off. The effects of windspeed, wind direction and indoor/outdoor temperature differences are incorporated in the model. The computer program predicts the position of the neutral pressure level of each wall, together with the over-all air exchange rate and infiltration load.

The program is intended for study of the dynamics of air infiltration and for computer experimentation with new design ideas to reduce the energy consumption of small residential type buildings.

RÉSUMÉ - Les auteurs décrivent un programme informatique servant à prédire l'infiltration de l'air dans de petits immeubles résidentiels. Le modèle représente une chaudière à l'huile, un conduit de fumée muni d'un régulateur de tirage barométrique, une cheminée et un bâtiment sans cloisons dont l'enveloppe comporte des ouvertures de fuite. L'enveloppe englobe plafond, murs, fenêtres et portes, les ouvertures de fuite de chacun étant représentées par plusieurs trous.

Le modèle sert à prédire l'écoulement de l'air à travers les ouvertures des murs, des fenêtres, des portes et de la cheminée, avec et sans fonctionnement de la chaudière. Le modèle englobe les effets de la vitesse et de la direction du vent et les écarts de température entre l'intérieur et l'extérieur. Le programme informatique prédit la position du niveau de pression neutre de chaque mur, ainsi que le taux d'échange global de l'air et la charge d'infiltration.

Le programme sert à étudier la dynamique de l'infiltration de l'air et à simuler par ordinateur de nouveaux modèles visant à réduire la consommation d'énergie des petits immeubles résidentiels.

INTRODUCTION

It is known from air leakage and pressure measurements on houses (Tamura and Wilson, 1963; Hunt and Burch, 1975; Bahnfleth, Moseley and Harris, 1957 (a) (b)) that air infiltration may account for a significant fraction of the heating load. With the growing importance of energy conservation, the value of computer simulation of air infiltration for predicting the air exchange rate has become more and more important.

This paper describes a computer model for the study of air infiltration in small residential type buildings. The model consists of a forced-air heating system with oil-fired furnace and a non-partitioned building (Larsen, 1976). The computer program predicts the air exchange rate with furnace on or off for any combination of windspeed, wind direction and indoor/outdoor temperatures. The program comprises a MAIN and the following subroutines (Larsen, 1977).

INFILT	for the simulation of air infiltration/exfiltration through the leakage openings in the building envelope;
FLOWS	for the computation of airflow through the holes representing leakage openings;
PCOEF	for obtaining wind pressure coefficients at the building exterior surfaces;
WIND	for converting windspeed measured at the meteorological site to windspeed at the building site;

PCOEF finds the wind pressure coefficient c_j for any given surface orientation and wind direction and for one of the following eight building dimensions

No.	Height/Width	Length/Width
1	1	1
2	1	2
3	1/2	1
4	1/2	2
5	1/2	4
6	3/2	1
7	3/2	2
8	3/2	4

The pressure coefficient c_j represents an average value over the surface and is obtained by averaging and interpolating the results presented by Chien et al., 1951. The subroutine FLOWS computes G_j for any assumed value of the internal pressure P_1. Similarly, the subroutine CHMNEY returns a value for G_c depending on the operation of the furnace. Finally, in subroutine INFILT an iterative procedure based on the Regula-Falsi method (Rektorys, 1969) is set up to find an approximation to P_1, the root of the non-linear algebraic equation (7).

Once the indoor pressure P_1 at ground level is known, the height of the neutral pressure level at each surface or wall of the building can be determined. The indoor pressure P_i at any given height h is given by

$$P_i = P_1 - r_i g\ h \tag{8}$$

The outdoor pressure P_o at height h is given by

$$P_o = P + c\ r_o \frac{w^2}{2} - r_o g\ h \tag{9}$$

By equating indoor and outdoor pressures, one can obtain an equation that can be solved for height h

$$h = \frac{P_1 - P - c\ r_o \frac{w^2}{2}}{\left(r_i - r_o\right) g} \tag{10}$$

For each wall, h is computed in the MAIN program according to equation (10). Note that a) in the absence of wind effects the neutral level is the same for every wall of a building, and b) when indoor/outdoor air densities are equal (i.e., in the absence of stack effect), h becomes indeterminate (when such a condition arises, the program computes a finite but very large h).

MODEL FOR FLUE-GAS EXHAUST SYSTEM

The flue-gas exhaust system is illustrated in Fig. 1. It consists of a chimney and a horizontal smoke pipe with barometric damper (Larsen, 1976; Colborne and Moffatt, 1959; Moffatt and Colborne, 1959). The mathematical model allows the computation of the gas flow G_c in the chimney, given the pressure P_1 at the ground level inside the house and the gas flow G_f from the furnace. The model does not take heat losses from the smoke pipe and chimney into account. The chimney cross-section is rectangular, the smoke pipe cross-section circular.

Pressure, P_4, at the barometric damper opening just outside the smoke pipe is given in terms of pressure P_1 as

$$P_4 = P_1 - r_i g\ h_2 \tag{11}$$

where h_2 is the distance between the ground level and the axis of the smoke pipe (h_2 is negative if the smoke pipe is located below ground level).

Pressure, P_3, at the chimney opening is the algebraic sum of atmospheric pressure at ground level, wind pressure, and the weight of a column of outdoor air per unit area extending from the chimney top to ground level

$$P_3 = P + c\ r_o \frac{w^2}{2} - r_o g\ h_3 \tag{12}$$

where c is the wind pressure coefficient at the chimney top (a value of -0.5 was used) and h_3 is the distance between ground level and the top of the chimney.

Pressure, P_2, inside the smoke pipe at the barometric damper (on the side nearest the furnace) is given, by Bernoulli's equation, as the algebraic sum of P_3, the weight of a column of air per unit area in the chimney, the pressure loss due to friction at the smoke pipe and chimney walls, and pressure loss due to a change in flue-gas velocity

$$P_2 = P_3 + r_c g\left(h_3 - h_2\right) + DE + r_c \frac{v_c^2}{2} - r_f \frac{v_f^2}{2} \tag{13}$$

where

r_c = density of flue gases in the chimney;

DE = pressure drop due to friction losses in the smoke pipe and chimney;

v_c = velocity of flue gases in the chimney;

r_f = density of flue gases leaving the furnace;

v_f = velocity of flue gases entering the smoke pipe.

The pressure drop DE due to friction losses is given by the following expression

$$N_c = 2(1 - 2M)\, f^2 + (4M - 1)\, f \qquad (18)$$

A complete cycle consists of an on-cycle period and an off-cycle period. Their duration in seconds is given by

$$t_{on} = 3{,}600\, \frac{f}{N_c} \qquad (19)$$

and

$$t_{off} = 3{,}600\, \frac{1}{N_c} - t_{on} \qquad (20)$$

respectively. If the steady-state off-cycle temperature of the flue gases leaving the furnace is θ_{offs} (typically 21°C), the average on-cycle flue gas temperature is T_{on} and the average off-cycle flue gas temperature is T_{off}, then the heat loss during one on-cycle period is given by

$$L_{on} = [G_f C_{pf}\,(T_{on} - \theta_{offs}) + 0.085\ H\ E\ F]\,t_{on} \qquad (21)$$

where C_{pf} is the specific heat of the flue gases (taken as the same as the specific heat of air at temperature T_{on}) and E is the heat of vaporization of water at temperature θ_{offs}. Similarly, the heat loss during one off-cycle period is given by

$$L_{off} = 0.45\ G_f C_p\,(T_{off} - \theta_{offs})\,t_{off} \qquad (22)$$

where C_p is the specific heat of air at temperature T_{off}. Thus the furnace efficiency E_f can be computed from

$$E_f = 1 - \frac{(L_{on} + L_{off})\ N_c}{3{,}600\ F\ HHV\ f} \qquad (23)$$

The average on- and off-cycle temperatures T_{on} and T_{off} needed to find the losses L_{on} and L_{off} can be calculated if one assumes that the flue gas temperature during the on- and off-cycles can be represented by rising or decaying exponential functions of time (t), respectively (Larsen, 1976; Bonne and Johnson, 1974; Bonne, et al 1975). A typical situation is illustrated in Fig. 2. In the general case, the on-cycle flue gas temperature $\theta_{on}(t)$ can be expressed as

$$\theta_{on}\,(t) = (\theta_{ons} - \theta_{offs}) \left(1 - e^{-\frac{t\,+\,a}{\tau_{on}}}\right) + \theta_{offs} \qquad (24)$$

where θ_{ons} is the steady-state on-cycle flue gas temperature (typically 300°C) and τ_{on} is a time constant (typically 100 s). The constant, a, represents the time interval that corresponds to the temperature rise from the steady-state off-cycle flue gas temperature θ_{offs} to the temperature θ_{start} at the beginning of the on-cycle (see Fig. 2). Provided that an estimate of θ_{start} can be found, the constant a may be computed from

$$a = -\,\tau_{on}\,\log_e \left(\frac{\theta_{ons} - \theta_{start}}{\theta_{ons} - \theta_{offs}}\right) \qquad (25)$$

The temperature at the end of the on-cycle period, θ_{stop}, can be obtained by evaluating equation (24) at time $t = t_{on}$.

The temperature fall during an off-cycle period has two distinct parts, each described by a decaying exponential. During the first part of an off-cycle period the air circulation fan is on and the temperature is given by

$$\theta_{off1}\,(t') = \theta_{ons} - \left(\theta_{ons} - \theta_{offs}\right) \left(1 - e^{-\frac{t'\,+\,b}{\tau_{off1}}}\right) \qquad (26)$$

where t' is the time measured from the start of the off-cycle and τ_{off1} is a time constant (typically 150 s). The constant b represents the time interval that corresponds to the temperature drop from the steady-state on-cycle flue gas temperature θ_{ons} to the temperature θ_{stop} at the end of the on-cycle (see Fig.2). It is given by

$$b = -\,\tau_{off1}\,\log_e \left(\frac{\theta_{stop} - \theta_{offs}}{\theta_{ons} - \theta_{offs}}\right) \qquad (27)$$

Assuming that the air circulation fan is controlled by thermostat and that the fan stops when the flue gas temperature falls to θ_{fan} (typically 55°C), the length of time the fan is on (t_{fan}) can be obtained from equations (26) and (27) as

$$t_{fan} = -\,\tau_{off1}\,\log_e \left(\frac{\theta_{fan} - \theta_{offs}}{\theta_{stop} - \theta_{offs}}\right) \qquad (28)$$

During the second part of the off-cycle, when the air circulation fan is turned off, the temperature is given by

$$\theta_{off2}\,(t') = \theta_{fan} - \left(\theta_{fan} - \theta_{offs}\right) \left(1 - e^{-\frac{t'\,-\,t_{fan}}{\tau_{off2}}}\right) \qquad (29)$$

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