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AN AIR INFILTRATION MODEL FOR MODERN SINGLE FAMILY DWELLINGS

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NOTE TO EDITORS

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ABSTRACT

This paper presents a new air infiltration model for single family homes, and more particularly, for homes equipped with central fossil-fuel-fired space heating furnaces. The paper details the development of the model, which was based on the results of tests to obtain the contribution of the existence of a chimney, and furnace operation, to house air infiltration. The initial tests were carried out in a one-room model home (located within a laboratory) which was equipped with a 5-inch and a 7-inch diameter chimneys (20 feet tall), both located outdoors. Most recently, fine-tuning of the model was based on the results of tests with a 1-story and two 2-story homes, located in the Metropolitan Chicago area. The "intensive" testing in these homes provides important information regarding the effect, on air infiltration, of such factors as permeability of electrical outlets, vent-fan operation, house buoyancy, wind direction, structural shielding, etc. The precision and utility of the model was verified by simulation of air infiltration in 23 actual homes. Air infiltration levels, and other important variables, have been monitored in these "extensive" test-homes over a period of nearly 3 years.

An Air Infiltration Model for Modern Single Family Dwellings

Introduction

The ever increasing role of air infiltration in residential building energy consumption is adequately understood, and steps have been taken, and others are underway, to minimize its impact. The importance of air infiltration as a means to control the level of contaminants in the indoor atmosphere has only recently been addressed. The main reason has been the absence of a rigorous, but practical, air infiltration model that can be used to accurately predict the dynamics of air exchange (in a single family residence) that is the result of various interactive forces from within and without the permeable structural envelope. This paper presents an assessment of the state-of-the-art of air infiltration models, all of which are of only limited value, and a summary account of a new approach to modeling of air infiltration for general use. This model and computer program have been used successfully to simulate the air infiltration rates (monitored over a period of 2 years) in over 20 actual homes.

Background

In contrast to the dynamic models available for heat transfer by radiation, conduction and convection through the building envelope, the state-of-the-art for predicting heat transfer by infiltration is relatively primitive, particularly for residential structures. This is surprising in view of the fact that infiltration accounts for a major fraction (25% to 50%) of the total heating and cooling loads in residential buildings. Furthermore, the infiltration-exfiltration characteristics of a house interact with the venting system of the fossil fuel heating system, thus adding to the heat load and decreasing the seasonal utilization efficiency of the furnace.

1. Current ASHRAE Methods

ASHRAE describes two methods[1] for estimating infiltration in residential buildings. The first, and most commonly used, is the air change method, which is based on assuming an air change rate for each room and averaging over the whole house volume. The ratios assumed for each room are dependent on the number of walls with exterior windows and doors and the type of usage each room experiences. Typical air change rates for various types of rooms provided by ASHRAE are presumably based on past experience.

In a somewhat more sophisticated method, known as the crack method, the estimates are based on measured leakage characteristics of the building components (windows, doors, and walls) at selected pressure differentials from 0.1 to 0.5 inch H_2O. It is necessary, therefore, to assume an appropriate pressure differential to which the building components will be exposed.

The leakage characteristics of many of the building components, such as windows and doors, are reasonably well documented, although large variations can occur, depending on design, quality control in manufacture, and, particularly, on the quality of installation. However, the leakage characteristics of many other building components such as sill plates, ceilings, and electrical wall outlets have not been well characterized. Although it is commonly assumed that crackage around windows, doors, and sill plates are the primary sites of infiltration, two recent studies indicate that more than 50% of the permeability of actual homes may be at other sites, including wall outlets, ceiling, exhaust vent, and chimneys.[2,3]

The major limitation of the crack method is the fact that no adequate model exists for estimating the pressure differential to which the various components are actually exposed, particularly in residential structures. The pressure differentials, ΔP, in the range assumed in the ASHRAE data (0.1 to 0.5 inch H_2O), appear to be much too high. Only windward walls could experience pressure differentials in this range with non-windward walls likely to experience pressure differentials less than 0.02 inch H_2O.

2. Achenbach-Coblentz Correlation

Another approach to the prediction of infiltration rates is based on the empirical Achenbach-Coblentz correlation[4] derived by regression analysis of data from two test homes at the University of Illinois[5] and tested against 10 electrically heated homes in Indiana.[4] The correlation takes the form –

$$I = A + B \times WS + C \times \Delta T \qquad (1)$$

where –

I = infiltration rate
WS = wind speed
ΔT = indoor-outdoor temperature differences
A, B, and C = empirical constants characteristic of the particular structure

The constant A presumably represents the contribution of vent fan operation and door openings at zero wind speed and ΔT. The constants B and C are determined by the permeability and other characteristics of the structure, and will vary from house to house. For example, the original Achenbach-Coblentz formula for electric homes was –

$$I = 0.15 + 0.013\ WS + 0.005\ \Delta T \qquad (2)$$

The NBS-LD dynamic simulation model for estimating energy consumption in residential buildings, although otherwise sophisticated, uses the Achenbach-Coblentz formula with the constants arbitrarily increased by two-thirds to "more closely correspond to a typical house" (presumably a fossil fuel heated house)[6]. The constants found in other studies, however, have varied widely as follows:[5,7,8,9]

A = 0.10 - 0.8
B = 0.013 - 0.084
C = 0.005 - 0.016

Laschober and Healy[8], in a later study, found that the wind coefficient B for one house varied from 0.02, with winds normal to the narrowside of the house, to 0.084 on the broadside. They also found that the presence and operation of a gas furnace contributed significantly to the overall infiltration (equivalent to increasing the constant A by 0.083). Thus, the coefficients must be determined empirically for each house, and, as yet, no one has successfully modeled these constants in terms of measurable house structural characteristics. However, there are more important limitations to the method.

The Achenbach-Coblentz approach assumes that the infiltration rates are directly proportional to ΔT and to WS and that these components are additive; these assumptions are not theoretically tenable. First, the relative dependence of infiltration on ΔT and wind speed changes gradually and continuously, from complete dependence on ΔT at zero wind speed to complete dependence on WS at wind pressures sufficient to induce a positive pressure in the house (about 20 mph at ΔT = 75 for a two-story house), depending on height and shape of the house. The equation, therefore, cannot give even reasonable approximations over the whole range of ambient conditions of interest. Second, the model is not set up to reflect the interactions between such parameters as furnace operation (or vent fan operation) and the whole house infiltration so that their effect can be evaluated.

3. The Princeton Studies

The linear regression equation discussed above may be expanded to include other parameters, such as furnace operation and door openings, to improve the quality of correlation, but the results still tend to be highly erratic, as shown recently by Malik[10] in the Princeton studies. This is primarily because the analysis does not take into account the complex interactions between wind speed and indoor-outdoor temperature differences, as well as furnace and exhaust fan operation. This view has been recently corroborated by Sinden[11] (Princeton University) on the basis of a simple analysis of the interactions between wind and house buoyancy forces on the windward and leeward walls of a structure. The analysis shows that wind and temperatures can be simply additive or in certain cases can be subtractive. Most of the time they are complex. Sinden concludes that "the complexity of wind-temperature interaction... is bad news for computer modelers, since it appears unlikely that there exists any simple formula that universally represents natural ventilation in buildings."

Also recently, Harrje[12] has suggested the addition of a cross-product terms, (WS) (ΔT) to reflect the interactions between the two parameters, i.e.

$$I = A + B(WS) + C(\Delta T) + D(WS)\ (\Delta T) \qquad (3)$$

Such a model has recently been evaluated by Malik[10] for infiltration in two townhouses with mixed success. The model was adequate for high wind speeds, having a large component normal to the exposed faces of the townhouses. However, the model appeared to be inadequate for winds at low speeds, regardless of direction, or for high wind speeds having a small normal component to the exposed face. He attributes these differences to the complex interactions between wind and house buoyancy forces. Therefore, this model also does not reflect the effect of these interactions over the whole range of ambient conditions. Furthermore, the constants A, B, and C still depend on the structural characteristics of the house and wind direction and must be determined empirically.

4. The Hittman Approach

The proprietary, Correlated Residential Energy Analysis Program developed by Hittman Associates[6] utilizes the Achenbach-Coblentz infiltration model (as does the NBS-LD program) to predict infiltration loads, but the empirical constants for the latter model were evaluated by a mass flow balance analysis of the original Achenbach-Coblentz data on crackages, wind speed, and direction, and the resulting infiltration rates. Basically, their program used a mass balance equation to estimate the indoor pressure resulting from wind pressures imposed from various directions. The effects of fan and furnace operation were simulated as constant flows. These pressures were then used to estimate the flow rates across each component as well as the overall infiltration rate. The individual component characteristics then could be used to estimate the required Achenbach-Coblentz constants for any house whose structural characteristics are known.

Hittman Associates[13] have recently revised the linear regression equation to a somewhat more acceptable form, as follows:

$$I = OC\ [A + B(\Delta T) + C(WS)^2]^{0.66} \qquad (4)$$

where —

OC = (orifice coefficient) - $\frac{\Sigma OA}{V}$
ΣOA = summation of orifice areas over the whole structure
V = structure volume.

The quantities (ΔT), WS, A, B, and C are as defined in Equation 1.

Orifice areas are estimated by multiplying the appropriate crack lengths by the estimated crack width. Thus, the equation takes the general form of the equivalent orifice method (cracks method):

$$I = k(\Sigma OA)\ (\Delta P)^n \qquad (5)$$

where k is an equivalent orifice constant. In this form, the measurable permeability characteristics of different structures can be used instead of empirical constants. The constants A, B, and C, used to define the relative contributions of wind speed and indoor-outdoor ΔT to the driving force, ΔP, are also determined by structural factors as well as wind direction and must be determined empirically for each house and for each different wind direction. Furthermore, because of the interactions between the different driving forces, the so-called constants B and C undoubtedly vary as the ratio of $WS/(\Delta T)^{1/2}$. Since the model does not take into account these interactive effects, the model cannot be accurate over the whole range of ambient conditions.

5. The NRC (Canada) Method

The mass balance approach has already been used successfully by the National Research Council of Canada in developing a FORTRAN IV infiltration model[14,15] for multi-story commercial buildings, including the effect of stack action, exhaust or pressurization fan action, as well as wind pressures. Infiltration is calculated by writing the mass balance equations for each floor and shaft and solving the resulting nonlinear simultaneous equations. The input parameters include –

- Building leakage characteristics
- Net air supply by air handling system
- Wind pressure coefficients for 16 directions
- Indoor and outdoor temperatures

Infiltration rates are calculated for each specified combination of outdoor temperature, wind speed, and direction and are used as a subroutine for the heating and cooling load calculation program.

Conceptual Approach

The discussion in the previous section makes clear the need for a dynamic infiltration model which can be used, in a practical way, to improve our ability to perform equipment sizing for heating and cooling, to carry out energy analysis of residential buildings, and to understand and control the level of contaminants in the indoor environment. More so, such a model must be based on fundamentals, and must include the interactive effect of multiple forces that affect infiltration (from within and without the building envelope), including people's style of living.

The modeling approach we adopted for this purpose is based on the simultaneous solution of mass balance equations for infiltration and exfiltration and chimney flow equations (for homes equipped with fossil-fueled furnaces), with the basic relationships developed in a laboratory model of a one-room home[16]. These relationships were further embellished by results obtained in three "intensive" test homes which provided the likely effects on infiltration of shielding of the structure by adjacent structures or topography, non-uniform structual permeability, and height discontinuity (for 2 and 3 story structures)[17].

For its use to be practical, the model requires only data readily available for the structure, the heating system, and weather data, and does not require testing. In order to include the aggregate (over a season) effect of the occupants' style of living on infiltration, the components of the preliminary model were tested against data obtained (for a period of 2 years) in 23 actual homes in the Metropolitan Chicago area[18] and other data from the literature[19].

The IGT Model

The basic driving forces for infiltration are the pressure differentials across the various components of the building envelope generated by the following:

- Wind pressure
- House buoyancy forces due to indoor-outdoor temperature differential, ΔT
- Fan exhaust or pressurization
- Chimney buoyancy forces generated by ΔT and by furnace operation

These pressure differentials, ΔP, act upon the various orifices and cracks in the building envelope to produce flow according to classical orifice theory

$$F = \frac{1}{R}\Delta P^n = K\Delta P^n \qquad (6)$$

where –

F = flow rate, CF/min

R = resistance to flow, in. H_2O/CF-min

K = flow coefficient, $= \frac{1}{R} =$ CF/min.-in. H_2O

ΔP = differential pressure across the orifice, in. H_2O

n = power function between 0.5 and 1.0.

The value of the power, n, depends on the relative contribution of kinetic and viscous forces to the energy loss incurred in flow. If the losses are primarily kinetic, n will be close to 0.5 rather than 1.0 which is approached in viscous flow. The literature indicates that flow in the types of orifices found in residential structures will be of the order of 0.5 to 0.65[1].

In reality, the driving force, ΔP, acting on a particular orifice varies widely depending on its location with respect to wind direction and height of the house. The actual pressure drop, ΔP, across a particular orifice is determined by the difference between the dynamic pressure on the outside of the orifice imposed by wind forces, ΔP_w (for which a reasonable model exists), and the resultant indoor-outdoor static pressure difference, ΔP_r:

$$\Delta P = \Delta P_w - \Delta P_r \qquad (7)$$

where ΔP_r is the sum of two indoor-outdoor static pressure difference effects.

One of these pressure differences is ΔP_B, the static pressure difference at a particular height in the house, resulting from the vertical gradient induced by the indoor-outdoor temperature difference only. Its value may be estimated from the indoor-outdoor temperature difference, ΔT, and the height of the orifice above or below the structure's neutral zone. The other is ΔP_x, the static pressure difference induced by the combined effects of wind, chimney buoyancy, and fan forces (at mass balance). The pressure difference, ΔP_x, affects the whole house equally, depending on communication between rooms and between floors.

We can, therefore, define the flow, F, through a particular orifice in terms of the following equation:

$$F = OC\ [\Delta P_w - (\Delta P_B + \Delta P_x)]^n \qquad (8)$$

where OC is the measurable orifice coefficient for the particular orifice. All of the parameters in Equation 8 are calculable or measurable except the flow, F, through the orifice, and ΔP_x. The latter is determined by mass balance between the exfiltration and infiltration through all of the orifices in the house. In order to compute the whole house static pressure difference, ΔP_x, as well as the overall infiltration rate, all of the orifices in the house are characterized in terms of Equation 8 and by setting up an overall mass balance equation for infiltration-exfiltration through all orifices. Such an equation is then solved by the method of successive approximations.

The basic model assumes (for simplicity) that the vertical gradient in permeability is uniform but variable from wall-to-wall. With regard to the usual levels of wind velocities and indoor-outdoor temperature differences characteristic of the four seasons, at least four distinct representations can be envisioned, for the neutral zone position in chimneyless homes, for air infiltration to occur. Figure 1 shows the case when the absolute level of wind, the indoor-outdoor temperature difference, and the relative wall permeabilities are such that, both the windward and leeward neutral zones are within the structure.

Similarly, Figure 2 illustrates the case when the windward wall zone is above the structure and the leeward wall neutral zone is within the structure. Figure 3, on the other hand, shows the reverse case (windward zone within and leeward zone without the structure) and Figure 4 the case when both zones are outside the structure. For homes equipped with a chimney, and with furnace operating, a similar set of representations exist, one of which is shown in Figure 5.

It has been the objective of the modeling effort to provide a tool that allows the determination of the exact locations of the neutral zone in each case (and, therefore, of the rate of air infiltration) by using the basic properties of the structure and weather data. For each case shown in Figures 1 through 5, the mass balance formulations around the structure are obtained by equating infiltration and exfiltration above and below the neutral zone. Each such formulation represents a complex non-linear mass balance equation and the following simplifying assumptions were necessary in order to obtain the required solutions:

- The pattern of crackage is uniform across a wall
- The air flow through a crack is proportional to the 0.50 power of the air pressure differential
- The wind pressure force on the windward walls is positive and does not cause any pressure disturbances on the other walls
- For winds that are not perpendicular to a wall of the house, the wind pressure effect is the cosine of the wind angle (with respect to the walls it acts upon) times the wind speed squared.

Analytically, exfiltration and infiltration across the different zones, as for example those shown in Figure 1, are represented by sets of equations similar to Equation 9 below, for infiltration:

$$\begin{aligned}\text{Infiltration} &= \int_o^Y \Sigma K_x (\overbrace{c\rho_o gh - c\rho_i gh}^{\Delta P})^n\, dh \\ &\quad + \int_o^{Y+Z} K_I (c\rho_o gh - c\rho_i gh)^n\, dh \end{aligned} \qquad (9)$$

and Equation 10 below, for exfiltration:

$$\begin{aligned}\text{Exfiltration} &= \int_o^{H-Y-Z} K_I (c\rho_o gh - c\rho_i gh)^n\, dh \\ &\quad + \int_o^{H-Y} \Sigma K_x (c\rho_o gh - c\rho_i gh)^n\, dh \end{aligned} \qquad (10)$$

where —

H = height of structure
Z = distance between windward and leeward wall neutral pressure zones
Y = distance between house floor and lower neutral pressure zone
h = distance from neutral zone
ρ_o = outdoor air density
ρ_i = indoor air density
g = gravitational constant
c = conversion constant

all in consistent units. Equation 9 also shows that the parenthetic terms in these equations are equal to the ΔP and that in essence Equations 9 and 10 are integral forms of Equation 6 shown earlier.

The distance Z is determined from equation 11, relating the wind speed to the density difference between the inside and outside air,

$$Z = \frac{A\ (WS)^2}{cg(\rho_o - \rho_i)} \tag{11}$$

where —

WS = wind speed
A = conversion constant

In order to describe infiltration and exfiltration across different zones in homes equipped with a chimney, and furnace operation (as for example is shown in Figure 5), in addition to Equations 9 through 11 above, chimney flow and energy flow relations are required. These are summarized in Equations 12 and 13 below:

$$F_c = \frac{K_c}{(T_c)}\ \frac{1}{2}\ [\Delta P_x + 0.26\ Bh\ (\frac{1}{T_o} - \frac{1}{T_c})]^n \tag{12}$$

$$Q = F_c \rho C_p\ (T_c - 530) \tag{13}$$

where —

F_c = chimney flow, CF/min

K_c = flow coefficient of chimney at standard conditions dependent on vent and system geometry, CF/min. - in. H_2O

T_o, T_c = outdoor and chimney gas temperatures, °R

B = barometric pressure, in. H_2O

h = height of chimney, ft

ΔP_x = indoor-outdoor pressure difference, in. H_2O

Q = sensible heat from furnace, Btu/min

ρ = density of flue gas, lb/cu ft (32°F, 1 atm)

C_p = heat capacity of flue gas, Btu/hr - °F (32°F, 1 atm)

Finally, heat transfer (loss) from the chimney is described by Equations 14 and 15 below:

$$T_a = (T_c + T_1)/2 \tag{14}$$

$$F_c\ (T_c - T_1) = (U_a A/\rho C_p)\ (T_a - T_o) \tag{15}$$

where —

T_c = temperature of gases entering chimney, °R
T_1 = temperature of gases leaving chimney, °R
T_a = arithmetic average temperature of gases in the chimney, °R
U_a = overall heat transfer coefficient, Btu/hr-sq ft - °F
A = chimney surface area

A computer program has been developed to facilitate the solution of the mass balance equations mentioned earlier and is also being used to provide a measure of validation of the model.

The data required to perform the mass balance model calculations include the following:

- The height of the house
- The crackage length of the windward wall(s), and of the leeward walls
- The indoor and outdoor temperatures
- The wind speed and direction
- Furnace installation parameters.

The program first computes the magnitude of Z (the difference in the height of the neutral zone) and then compares the magnitude of Y (neutral zone height) for each wall against the structure's height (H), in order to define the appropriate case (as illustrated by Figures 1 through 5) and respective mass balance equation applicable. This program proceeds to set a value for Y for the leeward wall(s) at its lowest limit possible and to increase this value progressively, in small increments, until the mass balance between infiltration and exfiltration is satisfied. The output, then, of the program is the height of the neutral pressure zone on the leeward wall(s) from ground level. Using this value of Y, effective crack length, shielding, and permeability factors for the entire structure, the air infiltration rate is computed as a function of weather.

Model Verification

We have used infiltration data obtained in the 23 IGT field test homes[18], and detailed infiltration data for a well defined home from the literature[19], in order to carry out a preliminary validation of the model discussed above. In the first case, the measured data were used to provide a mechanism that allows the estimation of the equivalent total crackage in a home (over and above those measured for the doors, windows and sill plate). Also, to test various approaches of introducing the effect of shielding of the wind forces by adjacent structures, by ground morphology, etc., and to develop the effect of the non-uniformity of crackage distribution and of the permeability coefficient of the crackages.

In summary, the field measurements in the 23 field test homes show that:

- The average (seasonal) natural ventilation (air infiltration) rate in the test homes, with the furnace burner operating at steady-state, varied from 0.3 to 1.7 air changes per hour, with a mean of 0.67. The minimum infiltration (with the burner on) found was 0.25 air changes per hour, and the maximum was 2.65 air changes per hour. On the other hand, the average (seasonal) natural ventilation (air infiltration) rate of the homes with the chimney closed varied from 0.25 to 1.25, with a mean of 0.55 air changes per hour. The minimum rate, under this condition was found to be 0.12 and the maximum reached 2.41.

- The comparison between the case when the chimney is sealed with the case when the furnace burner is firing at steady state reveals that, on the average, the existence of a chimney and furnace burner operation in a home increases the air infiltration losses by almost 20%.

Use of the model to simulate the measured infiltration data in 19 of the 23 homes (for which crackage and weather data were available) showed that the estimated orifice coefficients varied from about 0.7 to 3.0 cubic feet, per minute, per foot of crackage. The above extreme values (representing a very tight and reasonably tight home, respectively) compare reasonably well with similar data from six (6) homes (located in Toronto) reported by Tamura[3], which varied in the range of 0.6 to 2.7 cubic feet, per minute, per foot of crackage.

Most recently, detailed infiltration data, and enclosure permeability data, were reported[19] for a single story residence (located in Ottawa, Canada), covering three distinct seasons, namely winter, summer and winter-spring periods. The actual infiltration rates measured are shown in Table 1. We have used the IGT model to simulate these data and the results are also shown in Table 1, and illustrated in Figure 6. The infiltration rates computed by the IGT model require that the equivalent total crack length for this house be about 9100 inches and the average permeability factor be 0.9 cubic feet, per minute, per foot of crackage.

The estimated equivalent total crackage is almost three times greater than the actually measured crack length around windows, doors and sill plate reported for this house. However, this is totally consistent with the referenced investigators finding[19] that, in this house, the windows, doors and walls accounted for 35% of the total infiltration rate.

Conclusion

The proposed air infiltration model involves the simultaneous solution of sets of mass-balance equations (Equations 9 and 10), neutral zone height equation (Equation 11), chimney flow and energy equations (Equations 12 and 13), and chimney heat transfer equations (Equations 14 and 15). Given the following simplifying assumptions—

- The pattern of crackage is uniform across a wall

- The air flow through a crack is proportional to the 0.50 power of the air pressure differential

- The wind pressure force on the windward walls is positive and does not cause any pressure disturbances on the other walls

- For winds that are not perpendicular to a wall of the house, the wind pressure effect is the cosine of the wind angle (with respect to the walls it acts upon) times the wind speed squared

the model simulated, with reasonable accuracy, the measured values for a single-story detached home, equipped with an oil-fired central furnace. Work is continuing in order to develop, for most structures, relationships that would provide effective crackage, shielding, and air leakage characteristics (permeability factors) to aid the general use of the model.

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Table I. Comparison of air infiltration model output to measured data in Tamura[19] House No. 1.

Test No.	Measured Infiltration Rates	IGT Model Output
Winter	Air changes per hour	Air changes per ho
1	0.36	--
2	0.41	--
3	0.22	0.21
4	0.23	--
5	0.24	0.22
6	0.25	--
7	0.25	0.28
8	barometric damper sealed	
Spring		
9	0.07	0.06
10	0.10	0.08
11	0.16	0.15
12	0.07	0.04
13	0.17	0.16
14	0.09	0.07
15	0.17	0.11
16	0.08	0.06
17	0.11	0.08
18	0.14	0.14
19	0.06	0.05
20	0.13	0.11
Winter-Spring		
21	0.28	0.30
22	0.22	0.21
23	0.18	0.17
24	0.18	0.20
25	0.25	0.24
26	0.20	0.20
27	0.25	0.25
28	0.18	0.21
29	0.15	0.17
30	0.12	0.15
31	0.12	0.13
32	0.13	0.13

LIST OF FIGURES

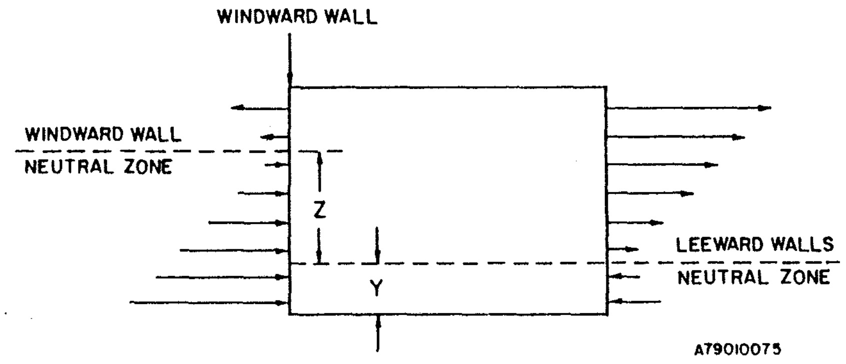

Figure 1. Both windward and leeward wall neutral zones inside the house.

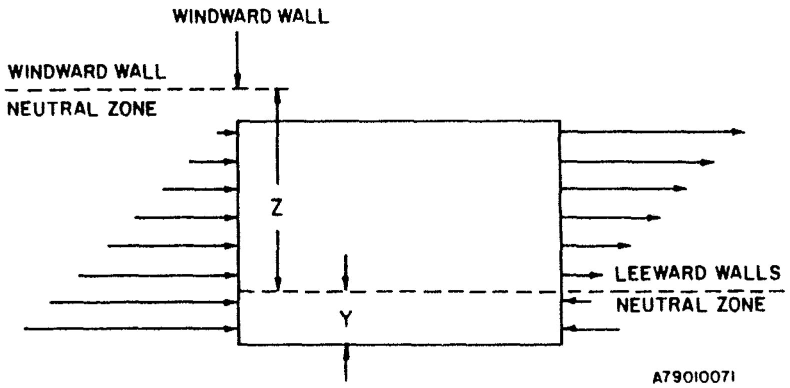

Figure 2. Windward wall neutral zone above house leeward wall neutral zone inside house.

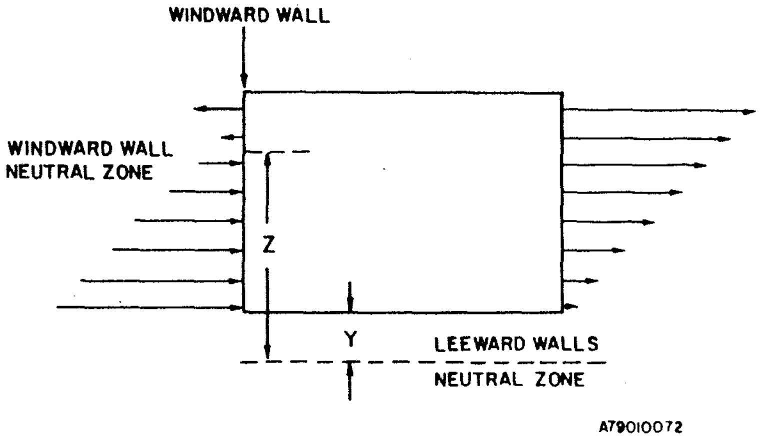

Figure 3. Windward wall neutral zone inside house leeward wall neutral zone below house.

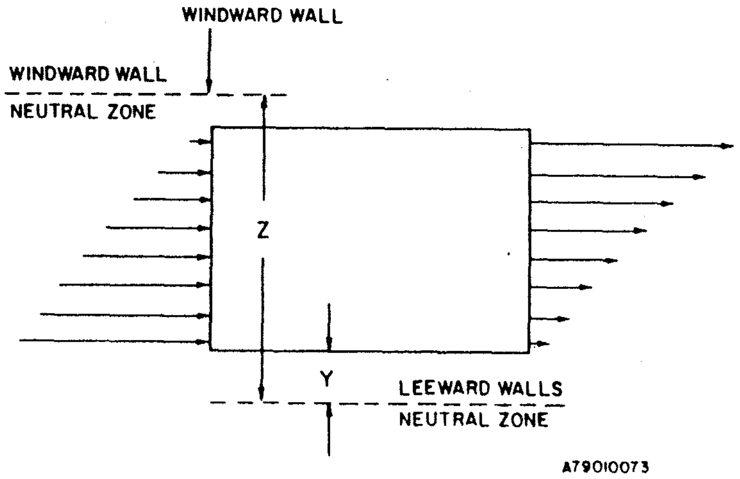

Figure 4. Both windward and leeward neutral zones outside the house.

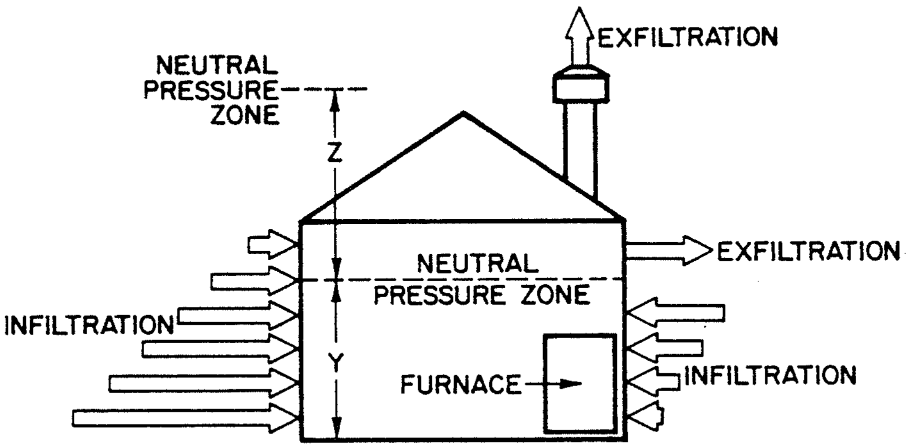

Figure 5. When wind, stack and furnace operation control air infiltration

Figure 6. Comparison of air infiltration model output to measured data in Tamura[13] house No. 1.