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Methods for Estimating Air Change Rates and Sizing Mechanical Ventilation Systems for Houses

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Résumé

L'auteur présente ici une méthode simple permettant d'estimer le débit global de renouvellement d'air pour les maisons dotées ou non de ventilation mécanique. La méthode proposée peut servir à évaluer l'effet d'un système de ventilation mécanique sur les débits globaux de renouvellement d'air. Elle peut aussi être intégrée aux programmes informatiques simples utilisés pour estimer les besoins des maisons en chauffage.

L'auteur p[illegible]t au dimension[illegible] des maisons. [illegible]t de ventilation [illegible]l de renouvell[illegible]

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METHODS FOR ESTIMATING AIR CHANGE RATES AND SIZING MECHANICAL VENTILATION SYSTEMS FOR HOUSES

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ABSTRACT

This paper presents a simple method for estimating the total air change rate of a house with or without mechanical ventilation. The proposed method can be used to assess the effect of a mechanical ventilation system on total air change rates. It can also be included in existing simple computer programs for estimating heating requirements for houses.

A calculation procedure is also presented for sizing mechanical ventilation systems for houses. This procedure can be used to estimate the forced ventilation rate required to achieve the desired total air change rate.

INTRODUCTION

The amount of ventilation air introduced into a house has a major influence on its energy consumption, indoor air quality, and moisture problems. In the past, most houses were ventilated by air leakage through the house envelope. However, the demand for energy conservation in recent years has led to the construction of tighter houses where air leakage can no longer be relied on as the sole source of ventilation air. As a result, mechanical ventilation systems are required in these tight houses.

Because of the lack of guidelines for selecting and designing mechanical ventilation systems, an increasing number of tightly constructed and mechanically ventilated houses have shown signs of problems with chimney backdrafting, excessive pollutant accumulation from building materials and furnishings, and elevated humidity levels. Also, occupants sometimes have turned off the mechanical ventilation system to eliminate noise and cold drafts. A series of studies has, therefore, been undertaken on four detached two-story houses to derive the relationship of air change with weather factors and the operation of heating and mechanical ventilation systems. The results have been reported previously (Shaw and Tamura, 1980; Shaw 1981, 1983; Shaw and Brown, 1982).

This paper presents (1) a brief summary of the results, (2) a calculation procedure for estimating total air change rates with or without mechanical ventilation, and (3) a method for selecting a mechanical ventilation system that will provide a specified air change rate without causing a risk of chimney backdrafting.

ESTIMATION OF AIR CHANGE RATES WITHOUT MECHANICAL VENTILATION

In this paper, the term "air infiltration rate", as defined by ASHRAE (1981), means the

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uncontrolled inward air leakage through the envelope of the house caused by weather factors. The "total air change rate" means the total outdoor air supply rate due to the combined action of air infiltration and mechanical ventilation. The "forced ventilation rate" means the nominal airflow rate through a mechanical ventilation system at the indoor design conditions.

Air infiltration rates depend on the size and distribution of leakage openings in the envelope (i.e., air leakage characteristics) and the pressure differences across these openings. As these two parameters cannot be explicitly evaluated, approximations have to be made in developing models for estimating air infiltration rates. In a series of studies (Shaw and Tamura, 1980; Shaw 1981; Shaw and Brown 1982) it was assumed that:

1. the air leakage characteristics of a house could be approximated by two characteristic values, C and n, according to the relationship:

$$q = a_1 C\ (A/V)\ (\Delta P)^n \qquad (1)^*$$

2. the air infiltration rate, I, could be approximated by the equation:

$$I = a_2 C\ (A/V)\ (\overline{\Delta P})^n \qquad (2)$$

The relationships between this pressure difference (and hence the air infiltration rate) and the driving forces have been obtained experimentally (Shaw 1981; Shaw and Brown 1981). They are presented below.

Temperature-Induced Air Infiltration

Figure 1 shows the response of the air inflows of a two-story house to the operation of a chimney and/or an exhaust fan at Δt=28 K. Two different types of chimney were studied: a 127 mm open chimney of a conventional gas furnace and a 80 mm wall mounted exhaust vent of a medium efficiency induced draft gas furnace. The air flow rate through the open chimney was 19 L/s and that through the vent was 10 L/s at Δt=28 K. Instead of the pressure difference across the envelope, the neutral pressure level was used as the abscissa to show its relationship with the air change rate.

The neutral pressure level below the ceiling was determined from the pressure difference measured at several elevations along the exterior walls under calm wind conditions and that above the ceiling was estimated from the pressure difference across the envelope from the equation:

$$h = h' + \Delta P/[(\rho_o - \rho_i)g]$$

where h and h' are the neutral pressure level of the house with and without chimneys or exhaust fans respectively.

When the neutral pressure level was below the ceiling of the top story, the air inflow through the house envelope was measured using the tracer gas decay method. Above the ceiling, it was equal to the air flow rate of the exhaust fan. The air flow rates through the exhaust fan and the chimney were measured using a flowmeter consisting of a pair of total pressure averaging tubes.

As shown in Figure 1, the amount of air inflow increases almost linearly with the neutral pressure level. This linear relationship is expected to be valid until the neutral pressure level reaches the ceiling level of the top story, even though a significant portion of leakage openings is located there. This is because the pressure difference across the ceiling is either negative or zero. Once the neutral pressure level is above the ceiling, the exfiltration through the house envelope ceases and the amount of air inflow (air change rate) is equal to the air exhaust rate of the exhaust devices.

The results indicate that, as the neutral pressure level is raised by a chimney or a fan, the air inflow increases at three different rates. In the linear region where h is at or below the ceiling, the air infiltration rate increases linearly with h. In the transition

* Refer to Nomenclature on page 10 for symbol definition.

region where h is slightly above the ceiling and is, therefore, influenced by both the exhaust fan and stack effect, a sharp increase in airflow occurs due to the increased pressure difference across the ceiling and the air leakage openings. And, in the power law region where the pressure difference depends only on the exhaust fan, the air inflow varies with the n th power of ΔP.

Method I, Based on Overall Flow Coefficients

Figure 2 shows the measured air infiltration rates of a two-story house with and without a 127 mm open chimney (Shaw and Brown 1982). For this particular house, the air infiltration rates have been found to be expressed by the equations:

$$I'_s = 0.32\ C\ (A/V)(\Delta t)^n \qquad \text{No Chimney} \qquad (3)$$

$$I_s = 0.43\ C\ (A/V)(\Delta t)^n \qquad \text{With Chimney} \qquad (3a)$$

In the above equations, the flow coefficient, C, defines the leakage openings in the entire house envelope rather than those experiencing air infiltration only. For the same house, the neutral pressure level is higher with a chimney than without. There are, therefore, more leakage openings experiencing air infiltration with a chimney than without, even though the values of C with and without a chimney are about the same. Because of this, Equations 3 and 3a differ by a constant. This suggests that for generalization, an additional parameter should be included to account for the variation in the leakage openings experiencing air infiltration in the same house as well as in different houses. Since the portion of the house envelope experiencing air infiltration and the pressure difference across it are proportional to the neutral pressure level, Equations 3 and 3a can be modified to:

$$\begin{aligned} I'_s &= a'\ C\ f(h'/H)\ (A/V)\ (\Delta t)^n \qquad \text{No Chimney} \\ I_s &= a\ C\ f(h/H)\ (A/V)\ (\Delta t)^n \qquad \text{With Chimney.} \end{aligned} \qquad (4)$$

From Figure 1:

$$I_s = I'_s\ (h/h')$$

Therefore:

$$f(h/H) = f(h'/H)\ (h/h')\ (a'/a).$$

It can be concluded that the simplest expression for f(h/H) and f(h'/H) would be (h/H) and (h'/H), respectively. Substituting the two variables into Equation (4) and evaluating the two constants a and a' by fitting the measured air infiltration data in Figure 2 to Equation 4, we have

$$\begin{aligned} I'_s &= 0.5\ C\ (h'/H)(A/V)(\Delta t)^n \qquad \text{No Chimney} \\ I_s &= 0.5\ C\ (h/H)(A/V)(\Delta t)^n \qquad \text{With Chimney} \end{aligned} \qquad (4a)$$

where:

- I_s = air infiltration rate caused by stack effect alone, ach,
- C = flow coefficient, $L/(s \cdot m^2 \cdot Pa^n)$,
- H = building height, m,
- n = flow exponent,
- Δt = indoor to outdoor temperature difference, K,
- 0.5 = dimensional constant, $m^3 \cdot s \cdot Pa^n/(L \cdot K^n \cdot h)$.

The values of C, n, h' and h can be evaluated as follows. For existing houses, C and n can be measured directly using the fan pressurization method, and h' and h can be determined by measuring the pressure difference across the exterior wall at several elevations under calm conditions ($W < 3.5$ m/s). For houses under design, C and n can only be estimated from the measurements of similar houses. An examination of the results of 160 standard houses and 40 low-energy houses, mostly with the chimney sealed, indicated that C varied from 0.014 to 0.36 $L/(s \cdot m^2 \cdot Pa^n)$ and n varied from 0.6 to 0.72 (Beach 1979; Dumont, Orr and Figley, 1981). Assuming a constant n of 0.65 (ASHRAE 1981; Tamura 1979), the suggested flow coefficients for houses are listed in Table 1; h' is usually assumed to be one-half the distance between the ground level and the top of the envelope, and h can be estimated using the method given in Appendix A.

Method II, Based on a Reference Air Infiltration Rate

In recent years, advances have been made in tracer gas apparatus and measuring techniques. It is no longer impractical to request such a test, when needed. If the air infiltration rate at one Δt is known, the values for other Δt's can be evaluated from the equation:

$$I_s = I_s^* \; (h/h^*) \; (\Delta t/\Delta t^*)^n \tag{5}$$

where I_s^* and h^* are the air infiltration rate and neutral pressure level corresponding to Δt^*.

Figure 3 shows I_s^* as a function of C at Δt^*=20 K for houses with and without chimneys (Shaw 1981; Shaw and Brown 1982; Manley, Helmeste and Tamura 1984). The linear relationship between I_s^* and C suggests that Equations 4a and 5 will give similar results. Therefore, the two equations are valid for most houses. However, if a house has been retrofitted to improve airtightness, Equation 4a will no longer be valid and Equation 5 should be used. This is because I_s^* not only depends on the size of the leakage openings but also on their location relative to the neutral pressure level; whereas C depends only on the size of the leakage openings. Therefore, if the openings near the neutral pressure level have been sealed, a reduction in C but little or no reduction in I_s^* will result. Thus, Equation 4a will overestimate the effect of retrofit.

Wind-Induced Air Infiltration

To estimate wind-induced air infiltration one has to consider the effects of wind direction and wind shielding in addition to wind speeds. These effects may be approximately accounted for by considering a house to be either exposed to, or shielded from, wind, depending on the wind direction and the surroundings (Shaw 1981). In a developed residential area, houses are normally surrounded by other houses. These houses would likely be shielded from wind, unless they have a windward wall directly facing an open area such as a long roadway or parkland.

Figure 4 shows the measured air infiltration rates as a function of wind speed for both exposed and shielded conditions (Shaw 1981). The empirical relationships between the two have been found to be (Shaw 1981):

$$\begin{aligned} I_w &= 0.4 \; C \; (A/V) \; W^{2n} \qquad \text{Exposed} \\ &= 0.7 \; C \; (A/V) \; W^{n} \qquad \text{Shielded} \end{aligned} \tag{6}$$

where:

I_w = the wind induced air infiltration rate in ac/h,
W = the on site wind speed in m/s, measured at about 20 m above the ground.

Likewise, if a reference air infiltration rate is known, the following equations can be used to calculate the values for other wind speeds:

$$\begin{aligned} I_w &= I_w^* \; (W/W^*)^{2n} \qquad \text{Exposed} \\ &= I_w^* \; (W/W^*)^{n} \qquad \text{Shielded} \end{aligned} \tag{6a}$$

Combined Wind- and Temperature-Induced Air Infiltration

As the pressure differences due to individual effects are additive, the air infiltration rate caused by the combined action of wind and temperature can be approximated by an equation similar to Equation 2:

$$I_{ws} = a_2 \; C(A/V) \; F \; (\overline{\Delta P}_s + \overline{\Delta P}_w)^n \tag{7}$$

where the parameter F has been included to account for the interaction between the pressure differences caused by stack effect and wind. This is necessary because their effects on air infiltration are not always independent (Sinden 1978).

From Equation 2:

$$\overline{\Delta P}_s = \{I_s/[a_2C(A/V)]\}^{1/n}$$
$$\overline{\Delta P}_w = \{I_w/[a_2C(A/V)]\}^{1/n} \tag{8}$$

Substituting Equation 8 into Equation 7 we have:

$$I_{ws} = F\ (I_s^{1/n} + I_w^{1/n})^n \tag{9}$$

Using Equations 4a or 5 and 6 or 6a for estimating I_s and I_w, respectively, and the measured values for I_{ws}, the values of F were calculated for two houses without chimneys and one with chimney (Shaw 1981; ASHRAE 1981). The F factor, as shown in Figure 5, could be expressed by the equation:

$$F = 1 \qquad \text{for} \quad 0 < (I_{sml}/I_{lrg}) < 0.1$$
$$= 0.8\ (I_{sml}/I_{lrg})^{-0.1} \qquad \text{for} \quad 0.1 < (I_{sml}/I_{lrg}) < 1.0 \tag{10}$$

where:

I_{sml} = smaller value of I_s and I_w, ac/h,
I_{lrg} = larger value of I_s and I_w, ac/h.

An expression similar to Equation 9 (without the correction factor, F) has been proposed by Sherman and Grimsrud (1980, ASHRAE 1981). As indicated by Equation 10, the value of F is 1 only if one of the two weather factors is much greater than the other and becomes the dominant driving force.

ESTIMATION OF AIR CHANGE RATES WITH MECHANICAL VENTILATION

Mechanical Ventilation Systems

Figures 6 and 7 show the four mechanical ventilation systems studied (Shaw 1983). They can be classified as either "balanced" systems or exhaust-only systems. A balanced system consists of a supply fan, which draws the outdoor air into the house, and an exhaust fan, which exhausts an equal amount of indoor air to the outdoors. In actual installations, the supply and the exhaust flow rates are rarely equal because no attempt is made to adjust the supply air rate to account for varying outdoor air density. If the two flow rates are equal under summer conditions, the supply airflow can be as much as 20% greater than the exhaust airflow under winter conditions (Figure 6a).

An exhaust-only system consists of an exhaust fan. The air supply flows through the leakage openings in the envelope as a result of the pressure difference created mainly by the mechanical exhaust.

Balanced Systems I and II

Figures 6a and 6b show the effect of ambient temperature and wind speed on total air change rates for the two balanced systems, each with a nominal forced ventilation rate of 0.5 ach (Shaw 1983). As shown, the total air change rate increases somewhat as the ambient temperature decreases (Figure 6a), but is relatively insensitive to wind speed (Figure 6b).

The house ventilation air comes from two sources: air infiltration, I, and mechanical ventilation, Q. Since the operation of a balanced ventilation system appears to have little effect on the house pressure (Figure 6c), the simplest model to combine the two would be,

$$ach_B = I_{ws} + Q \tag{11}$$

Figure 8 shows a comparison between the calculated and measured air change rates. It indicates that Equation 11 consistently overestimates the air change rate by as much as 25%. The reasons for this are not completely known. However, Figure 6c shows that the operation of the balanced system did lower the neutral pressure level slightly, which, in turn, reduced the air infiltration into the house. Therefore, the air infiltration rate with mechanical ventilation was slightly less than that without. An attempt was then made to combine the two flows using an expression similar to Equation 9. As (1) Figure 6a suggests that by applying a temperature correction on Q to account for varying outdoor air density, the dependence of total air change rates on t_o can be reduced, and (2) because the forced ventilation rate should be much greater than the air infiltration rate, F is close to unity, Equation 11 becomes:

$$ach_B = \{I_{ws}^{1/n} + [Q\ (T_i/T_o)]^{1/n}\}^n \qquad (12)$$

where ach_B is the total air change rate caused by the combined action of air infiltration and balanced mechanical ventilation, and Q is the forced ventilation rate at $T_i = T_o$.

Exhaust-Only Systems III and IV

Figures 7a and 7b show the relationship between house air change rates and forced ventilation rates for the two exhaust-only systems (Shaw 1983). The results indicate that the total air change rate was greater than the corresponding forced ventilation rate when Q = 0.25 ac/h but was approximately equal when Q = 0.5 ac/h. This indicates that, as the forced ventilation rate increases, the neutral pressure level moves upward and the area of building envelope experiencing air exfiltration decreases.

As the effect of an exhaust fan on air change rates is similar to that of a chimney, the same linear relationship exists between air change rate and neutral pressure level. An expression of the form of Equation 4a and 9 should, therefore, be valid for the exhaust only system. Furthermore, since the estimated house air change rate should never be smaller than Q, I_s in Equation 9 must be replaced by I_{sQ}, the larger of Q or I_s as defined by Equation 4a or 5. Beyond the linear region, the air change rate must be equal to the forced ventilation rate. Thus,

$$ach_E = F\ (I_{sQ}^{1/n} + I_w^{1/n})^n \qquad \text{for} \quad h < H \qquad (12a)$$

$$= Q \qquad \text{for} \quad h > H \qquad (12b)$$

where ach_E is the total air change rate with exhaust-only systems.

SIZING MECHANICAL VENTILATION SYSTEMS

The forced ventilation rate of a mechanical ventilation system should be determined on the basis of the required ventilation rate and the air infiltration rate. However, in practice, air infiltration is rarely considered because it is difficult to estimate. As a result, the total air change rate under the combination of mechanical ventilation and air infiltration often exceeds the required ventilation rate, causing an unnecessary increase in energy consumption. The energy consequence is not serious under mild weather conditions, because both temperature differences and air infiltration rates are small. This is not the case under winter conditions. For a house with an average air infiltration rate of 0.26 ac/h in winter, Figure 6a shows that the total air change rate with a balanced system can exceed the forced ventilation rate of 0.5 ac/h by as much as 40% if air infiltration is neglected.

On one hand, to satisfy the ventilation requirement, a mechanical ventilation system should always be capable of delivering the design ventilation rate. On the other hand, to conserve energy, it should be operated under a reduced flow during the winter months to take advantage of the increased air infiltration. Because of the frequent opening of windows in non-air-conditioned houses, the need for mechanical ventilation is much less during mild weather conditions than during the winter months. Thus, mechanical ventilation systems could be equipped with a flow controller, such as a two-speed fan, and operated continuously with a reduced capacity suitable for the winter months. A manual switch, an outdoor temperature controller, or an indoor humidistat can be used to increase the flow to the design value, as required. The forced ventilation rate for winter operation can be determined on the basis of the design ventilation rate and the mean air infiltration rate for the winter months. These two parameters are estimated below.

Design Ventilation Rate

For houses, ASHRAE Standard 62 (1981), "Ventilation for Acceptable Indoor Air Quality," calls for a 5 L/s of acceptable outdoor air supply rate for each room, an additional 50 L/s intermittent air supply for kitchens, and a 25 L/s intermittent air supply for each bathroom. For a typical three or four bedroom house, this roughly translates into an outdoor air supply rate of 0.5 ach. Thus, the design air change rate, ach_D, can be based on the ASHRAE Standard: 0.5 ach is a reasonable value for typical houses.

Mean Air Infiltration Rate For Winter Months

The air infiltration rate of a house varies with weather conditions. However, for temperature differences greater than 20 K and wind speeds ranging from 3.5 to 10 m/s (typical winter conditions for many regions of Canada), the average air infiltration rate can be approximately estimated by Equation 2:

$$\bar{I}_{ws} = 4.5\ C\ (A/V) \tag{13}$$

As a better alternative, $\bar{I}_{ws}$ can also be calculated from Equation 9 based on the winter mean indoor-outdoor air temperature difference for I_s (Equation 4a) and the mean winter wind speed for I_w (Equation 6).

Forced Ventilation Rate for Continuous Operation

Balanced Ventilation Systems. Based on air quality considerations, it is advisable to estimate the forced ventilation rate without taking varying outdoor air density into account. This will give a slightly greater forced ventilation rate than with air density correction. Substituting ach_D and $\bar{I}_{ws}$ for ach_B and I_{ws} respectively, Equation 12 becomes:

$$Q = (ach_D^{1/n} - \bar{I}_{ws}^{1/n})^n \tag{14}$$

Exhaust Only Systems. The exhaust flow rate can be estimated from Equation B2 derived in Appendix B:

$$Q = \bar{I}_{ws}\left(\{[(H/h')-1](ach_D/\bar{I}_{ws})\}^n - [(H/h')-(ach_D/\bar{I}_{ws})]^n\right) \tag{15}$$

This equation indicates that Q is indeterminate if $(ach_D/\bar{I}_{ws})$ is greater than (H/h'). This condition occurs when the forced ventilation rate is sufficient to raise the neutral pressure level above the ceiling level of the top story. Under this condition, the design forced ventilation rate is equal to the design air change rate, i.e., $Q = ach_D$.

SELECTING MECHANICAL VENTILATION SYSTEMS

For houses where there might be sources of radon or other contaminants in the building structure, a balanced system is recommended. Otherwise, the choice between a balanced system and an exhaust-only system should be determined on such factors as air leakage characteristics, type of heating systems, and cost. In general, if the operation of an exhaust-only system will not cause chimney backdraft, it should be used instead of a more expensive balanced system.

Figure 9 shows the effect of an exhaust fan on the venting capacity of a 127 mm open chimney in a tightly built two-story house (see also Figure 1). The chimney flow rates were measured with the chimney draft fully established before the exhaust fan was turned on. To detect the spillage of flue gases, the concentration of CO was monitored in the basement near the furnace. As shown, the chimney flow decreased continuously as the airflow rate through the exhaust fan increased. The chimney backflow occurred when the neutral pressure level reached 35 m above the ground level. The corresponding pressure difference across the envelope was 35 Pa and the air exhaust rate was 310 L/s. The presence of CO was detected when the chimney flow had been reduced to about 14 L/s. This suggests that spillage of the flue gas occurs well before the chimney flow is zero.

It should be pointed out that the exhaust fan was turned on after the chimney draft was fully established. If it were operating before the furnace was on, the chimney would fill with cold outdoor air and lose its draft. Under this condition, the chimney would continue to back flow even though the exhaust fan flow drops to a value well below what is needed to initiate the back flow.

For houses with chimneys, the stack effect reinforced by the airflow through the chimney is usually much stronger than the wind effect during the winter months (Shaw and Brown 1982). The backflow will not likely occur as long as the neutral pressure level is below the ceiling level of the top story. The ceiling level, therefore, would be a reasonable choice as the limit for satisfactory chimney startup.

With the limit for satisfactory chimney start-up established, the interaction between an exhaust-only system and a chimney can be determined using an airflow vs. neutral pressure level graph. Such a graph (e.g., Figure 10) can be constructed for any house if I_s^*, h', n, and H are known. Note that I_s^* and h' are the air infiltration rate and the neutral pressure level of the house without chimneys or exhaust fans. For existing houses, these parameters can be measured. For houses under construction, the values of h' and n are normally assumed to be H/2 and 0.65, respectively. The value of I_s^* can be obtained from Figure 3. To construct such a graph, a reference point A representing I_s^* is plotted on a graph with airflow rate as the ordinate and neutral pressure level as the abscissa. The air infiltration line is plotted next by drawing a straight line through A and the origin, and extending it to H. Since at h' air infiltration rate is equal to air exfiltration rate, the exfiltration line should also go through Point A. To find another point on the exfiltration line, a value for h between h' and H is selected, and the air exhaust rate corresponding to h is calculated from the equation below. This equation was obtained from Equation A8 by replacing $\bar{I}_{ws}$ with I_s^* for no wind conditions:

$$Q = I_s^* \left\{[(H/h')(h/h') - (h/h')]^n - [(H/h')-(h/h')]^n\right\} \tag{16}$$

The exfiltration rate corresponding to h (Point B) is then obtained by subtracting Q from the air infiltration rate. The exfiltration line is obtained by connecting a straight line through A and B. And a line representing "infiltration - exfiltration" can also be determined. If the house has a chimney, the neutral pressure level corresponding to the chimney can be calculated from Equation 16. Finally, a horizontal line representing ach_D is plotted on the graph. If the ach_D line intercepts the infiltration line below H, the chimney will start to vent when the furnace starts. On the other hand, if the ach_D line intercepts the infiltration line above H, chimney backdraft can occur.

Two such graphs are shown on Figure 10, one for a tight house and the other an average house. The values of I_s^* were 0.15 and 0.3 ac/h, respectively. The values of h' and n are assumed to be 2.7 m and 0.65, respectively. The results indicate that an exhaust-only system works satisfactorily in an "average" house with an open chimney but it will cause chimney backdraft in a tight house unless an outdoor air supply is provided in the envelope. On the other hand, the operation of an exhaust fan will significantly reduce the amount of inside air leaving the house through the walls and ceiling. If a house has no chimney (e.g., an electrically heated house) an exhaust-only system will also be satisfactory and will reduce the risk of moisture problems in the house envelope.

CHECK AGAINST MEASURED AIR CHANGE RATES

Equation 9 gives the air infiltration rate due to the combined action of stack effect and wind. It has been checked using the measured air infiltration rates of two bungalows with oil furnaces (T1 and T2) (Tamura 1979). Figure 11 compares the estimated and measured air infiltration rates. The results indicate that, except for three points, all the data lie within ±25% of the line of agreement. To determine statistically if there is any systematic difference between the calculated and measured air infiltration rates, the data have been transformed to the form,

RE = (calculated value - measured value) / measured value

Figure 12 shows the relative error, RE, as a function of the measured air infiltration rate. The mean value of RE is 0.037 and the standard deviation is 0.153. A student "t" test (t value is 0.24) indicates that the difference between the mean and the ideal mean of 0 is not statistically significant. In other words, there is no systematic difference between the calculated values given by Equation 9 and the measured air infiltration rates for the two houses.

Simliar comparisons have been made in Figures 13 and 14 for the two balanced systems and the two exhaust-only systems. Figure 13 shows that the agreement between the calculated and measured air change rates is within ±20% of the line of agreement for the balanced system. The agreement for the exhaust only system is ±15% (Figure 14). Again, there is no systematic difference between the calculated and the measured air change rates.

SUMMARY

A simple calculation procedure has been proposed for estimating the air change rate of a house with or without mechanical ventilation. This procedure can be summarized as follows.

1. Prepare input data, C, n, A, V, h', h, H, T_i, T_o, W and Q where C and n can be measured directly or estimated from Table 1; A and V can be measured directly or estimated from the blueprints. h', h, and Q can also be measured or estimated using the method given in Appendices A and B. T_o, T_i, and W can be obtained from meteorological records for the area.

2. Calculate the air infiltration rate due to stack effect alone from the equations:

$$I_s = 0.5\ C\ (A/V)\ (h'/H)\ (\Delta t)^n \quad \text{No Chimney}$$
$$= 0.5\ C\ (A/V)\ (h/H)\ (\Delta t)^n \quad \text{With Chimney} \qquad (4a)$$

or

$$I_s = I_s^*\ (h/h^*)\ (\Delta t/\Delta t^*)^n \quad \text{With or Without Chimney} \qquad (5)$$

3. Calculate the air infiltration rate due to wind alone from the equations:

$$I_w = 0.4\ C\ (A/V)\ W^{2n} \quad \text{Exposed}$$
$$= 0.7\ C\ (A/V)\ W^n \quad \text{Shielded} \qquad (6)$$

or

$$I_w = I_w^*\ (W/W^*)^{2n} \quad \text{Exposed}$$
$$= I_w^*\ (W/W^*)^n \quad \text{Shielded} \qquad (6a)$$

4. Calculate the air infiltration rate due to the combined action of stack effect and wind from the equation:

$$I_{ws} = F\ (I_s^{1/n} + I_w^{1/n})^n$$

where:

$$F = 1 \quad \text{for } 0 < (I_{sml}/I_{lrg}) < 0.1 \qquad (10)$$
$$= 0.8\ (I_{sml}/I_{lrg})^{-0.1} \quad \text{for } 0.1 < (I_{sml}/I_{lrg}) < 1.0$$

5. Calculate the air change rate due to the combined action of air infiltration and mechanical ventilation from the equations:

Balanced System:

$$ach_B = \{I_{ws}^{1/n} + [Q\ (T_i/T_o)]^{1/n}\}^n \qquad (12)$$

Exhaust-Only Systems:

$$ach_E = F\ (\ I_{sQ}^{1/n} + I_w^{1/n})^n \qquad \text{For} \quad h < H \qquad (12a)$$

$$= Q \qquad h > H \qquad (12b)$$

The proposed method has been checked against measured air change rates. The agreement, in general, was within 25% of the measured values.

In addition, the following two equations are proposed for sizing mechanical ventilation systems for houses.

Balanced Systems:

$$Q = (ach_D^{1/n} - \bar{I}_{ws}^{1/n}\ )^n \qquad (14)$$

Exhaust-Only Systems:

$$Q = \bar{I}_{ws}\ (\{[(H/h')-1](ach_D/\bar{I}_{ws})\}^n - [(H/h') - (ach_D/\bar{I}_{ws})]^n) \qquad (15)$$

where:

$$\bar{I}_{ws} = 4.5\ C\ (A/V) \qquad (13)$$

(Note: $\bar{I}_{ws}$ can also be calculated from Equation 9 based on the mean winter indoor-outdoor temperature difference and the mean winter wind speed).

NOMENCLATURE

a_1, a_2, a, a' = dimensional constant
A = area of building envelope, i.e., area of exterior wall above grade and ceiling area of the top floor, m^2
ach = total air change rate with mechanical ventilation, ach
C = flow coefficient, $L/(s\cdot m^2\cdot Pa^n)$
F = correction factor as defined in Equation 10
g = acceleration of gravity, 9.807 m/s
h = neutral pressure level with chimneys or fans, m
H = building height,m
I = air infiltration rate, ach
K = overall flow coefficient, $L/(s\cdot Pa^n)$
M = airflow rate through the chimney and/or forced ventilation rate (see Q), L/s
n = flow exponent
ΔP = uniform equivalent pressure difference across building envelope, Pa
q = air leakage rate measured by fan pressurization method, ach
Q = forced ventilation rate at design indoor conditions, ach
RE = relative error
= (calculated value - measured value)/measured value
Δt = indoor to outdoor temperature difference, K
T = absolute air temperature, K
V = building volume including basement, m^3
W = on-site wind speed, m/s
ρ = air density, kg/m^3

Subscripts

a = above neutral pressure level
b = below neutral pressure level
B = balanced ventilation system
D = design value

D = design value
E = exhaust-only system
i = indoor
lrg = larger value of I_s and I_w
o = outdoor
s = stack effect
sml = smaller value of I_s and I_w
sQ = larger value of I_s and Q
w = wind effect
ws = combined action of wind and stack effect

Superscripts

' = without chimneys or mechanical ventilation
$\bar{}$ = mean
* = reference

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APPENDIX A

ESTIMATION OF NEUTRAL PRESSURE LEVEL FOR HOUSES WITH CHIMNEYS OR EXHAUST DEVICES

If a house has a chimney or an exhaust-only ventilation system, the neutral pressure level, as shown in Figure A1, will shift from h' to h . The vertical distribution of pressure difference across the exterior wall due to stack effect alone will change accordingly. Assuming that for a house with neither chimney nor exhaust fan (1) the air leakage characteristic can be represented by two openings, one located at the grade level and the other at the ceiling level of the top story, and (2) the vertical distribution of pressure difference is known, h can be estimated from the conservation of mass (Shaw and Kim 1984):

$$K_b\ (\Delta P_b)^n \rho_o = K_a\ (\Delta P_a)^n\ \rho_i + M\rho_i \qquad \text{(A1)}$$

Substituting the following relationships (from Figure A1) into Eq. (A1):

$$\Delta P_b = (h/h')\ \Delta P_b' ,$$

$$\Delta P_a = [(H - h)/(H - h')]\ \Delta P_a' = [(H/h') - (h/h')]\Delta P_b'$$

we have:

$$K_b(h/h')^n = \{K_a[(H/h') - (h/h')]^n + M/(\Delta P_b')^n\}(\rho_i/\rho_o) \qquad \text{(A2)}$$

In the above equation, the terms K_a and K_b define the air leakage characteristic of the house without either chimney or exhaust device. They can be estimated from the mass balance equations (Shaw and Kim 1984):

$$K_b\ (\Delta P_b')^n\ \rho_o = K_a\ (\Delta P_a')^n \rho_i \qquad \text{(A3)}$$

and

$$C \cdot A = K_b + K_a \qquad \text{(A4)}$$

where C is the flow coefficient without chimneys or exhaust fan. Since:

$$\Delta P_a' = [(H - h')/h']\Delta P_b'$$

therefore, Equation A3 can be rewritten as:

$$K_b = K_a[(H - h')/h']^n(\rho_i/\rho_o) \qquad \text{(A5)}$$

Substituting Equation A5 into Equation A2, we have:

$$M/[K_a(\Delta P_b')^n] = [(H/h')(h/h')-(h/h')]^n - [(H/h')-(h/h')]^n \qquad \text{(A6)}$$

Equation A6 can be solved for h/h' as follows.

Existing Houses

The values of C, $\Delta P_b'$, h', and n can be measured and K_a can be estimated from Equations A4 and A5. The only unknown on the left-hand side of Equation A6 is M. The value of M for an exhaust device is usually known (see Appendix B). The value of M for a chimney can be estimated using the method given in ASHRAE (1983).

With all the variables on the left-hand side of Equation A6 known, the value of (h/h') can be obtained by graphical methods. Figure A2 shows a typical plot of (h/h') vs. $M/[K_a(\Delta P_b')]^n$ for n = 0.65 and various values of H/h'. Similar plots can be constructed for other values of n.

Houses under Design

For houses under design, the values of n and h' are usually assumed to be 0.65 and H/2 respectively. The following approximations would also apply.

$$K_b \cong K_a$$

and

$$K_a(\Delta P_b')^n \cong K_b(\Delta P_b')^n \cong \bar{I}_{ws} \qquad \text{(A7)}$$

Replacing M with Q (i.e., converting the unit of M from L/s to ach), Equation A6 becomes:

$$Q/\bar{I}_{ws} = [(H/h')(h/h')-(h/h')]^n - [(H/h') - (h/h')]^n$$

(h/h') can also be obtained from Figure A2.

APPENDIX B

FORCED VENTILATION RATE OF AN EXHAUST-ONLY SYSTEM FOR WINTER MONTHS

The design exhaust airflow rate for winter operation can be estimated from Equation A6:

$$M/[K_a(\Delta P_b')^n] = [(H/h')\ (h/h')-(h/h')]^n - [(H/h')-(h/h')]^n \qquad \text{(A6)}$$

To solve for M, one has to know (h/h') and $K_a(\Delta P_b')^n$. These two terms can be estimated as follows.

Consider a house with an average air infiltration rate of $\bar{I}_{ws}$ for the winter months. The neutral pressure level is h'. If an exhaust-only system is installed, the neutral pressure level will rise to h. If the ventilation system is properly sized, the amount of outdoor air entering into the house should be equal to ach_D, the design ventilation rate. As shown in Figure A1, the outdoor air supply rate is approximately proportional to the neutral pressure level. Thus:

$$(h/h') = (ach_D/\bar{I}_{ws})\ , \qquad \text{(B1)}$$

noting that

$$K_a(\Delta P_b')^n \cong \bar{I}_{ws}\ . \qquad \text{(A9)}$$

Substituting Equations B1 and A9 into Equation A6 and replacing M with Q (i.e., converting the unit of M from L/s to ach), we have

$$Q = \bar{I}_{ws}\ \left[\{[(H/h')-1](ach_D/\bar{I}_{ws})\}^n - [(H/h')-(ach_D/\bar{I}_{ws})]^n\right] \qquad \text{(B2)}$$

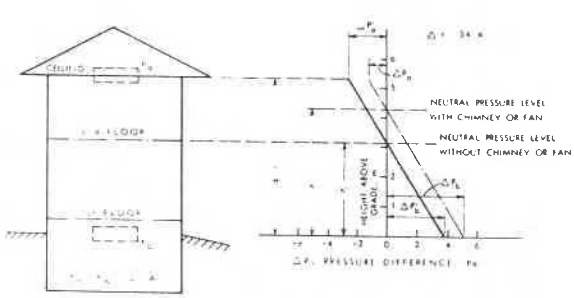

Figure A1. Distribution of leakage openings and pressure difference profile caused by temperature difference

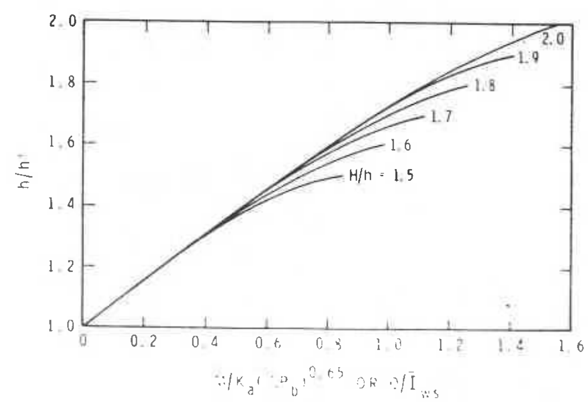

Figure A2. h/h' versus Q / I̅ws

TABLE 1

Suggested Values for Flow Coefficient and Exponent

Construction	Types	Rating	Flow Coefficient C, $L/(s \cdot m^2 \cdot Pa^n)$	Flow exponent, n	Number of houses
Standard	Bungalow	Tight Average Loose	0.07 0.22 0.36	0.65	58
	Split Level*	Tight Average Loose	0.08 0.19 0.3	0.65	49
	Two-storey	Tight Average Loose	0.01 0.19 0.27	0.65	54
Low Energy	Bungalow	Tight Average Loose	0.01 0.08 0.14	0.65	14
	Split Level*	Tight Average Loose	0.02 0.07 0.12	0.65	14
	Two-storey	Tight Average Loose	0.03 0.15 0.27	0.65	15

*Including bi-level and 1½-storey

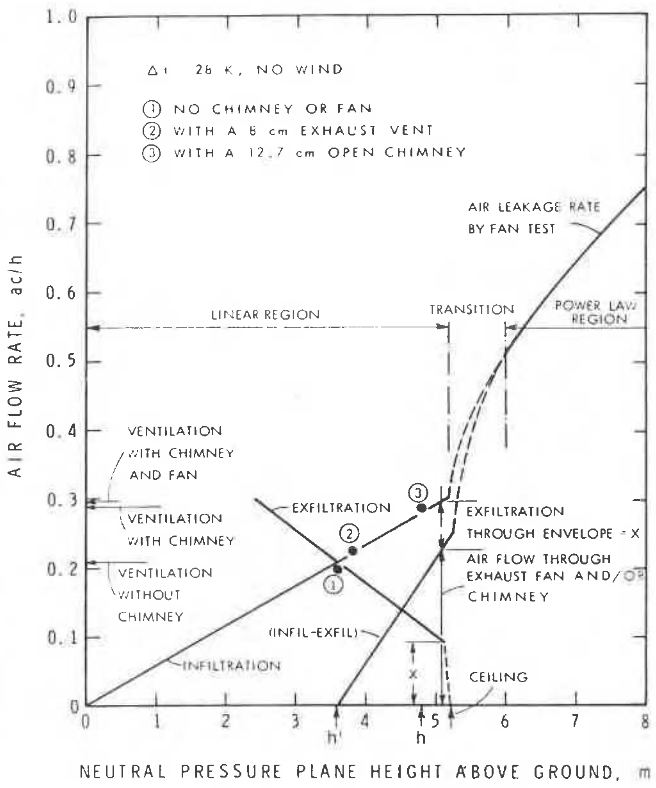

Figure 1. Supply and exhaust airflow rates versus height above ground level for a two-story house

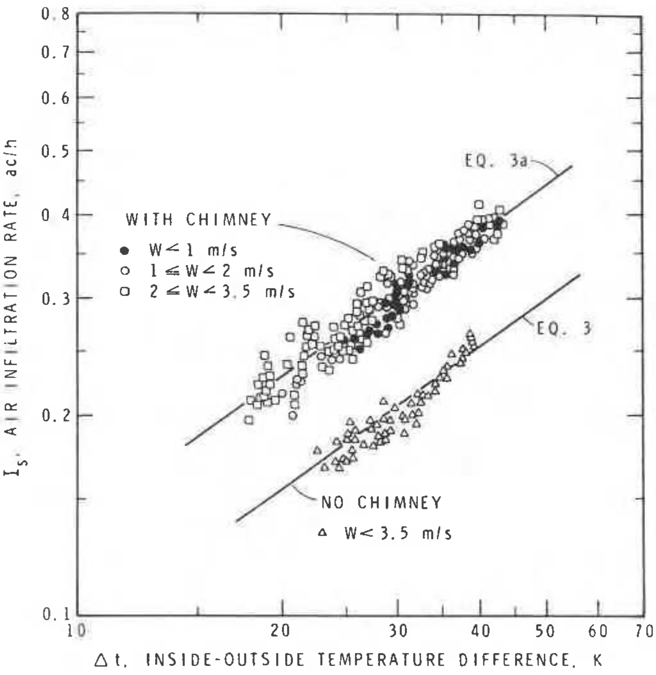

Figure 2. Air infiltration rates with and without chimney as determined by tracer gas decay method

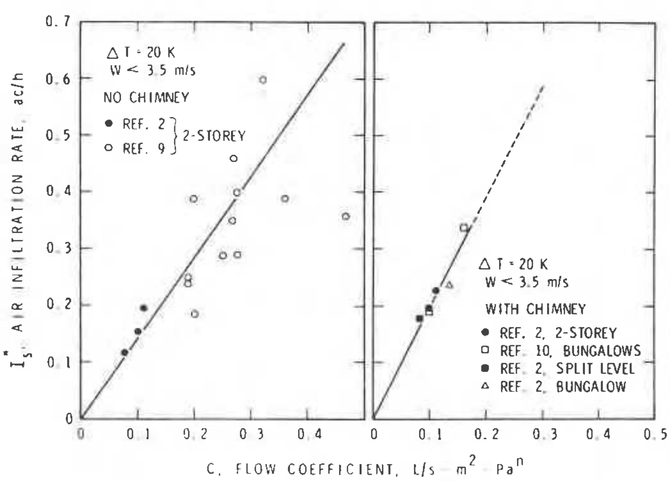

Figure 3. Relationship between flow coefficient and air infiltration rate for ΔT = 20 K

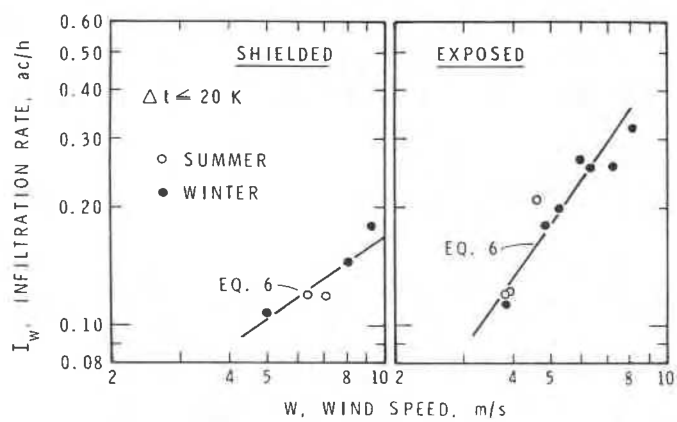

Figure 4. Wind induced air infiltration rates

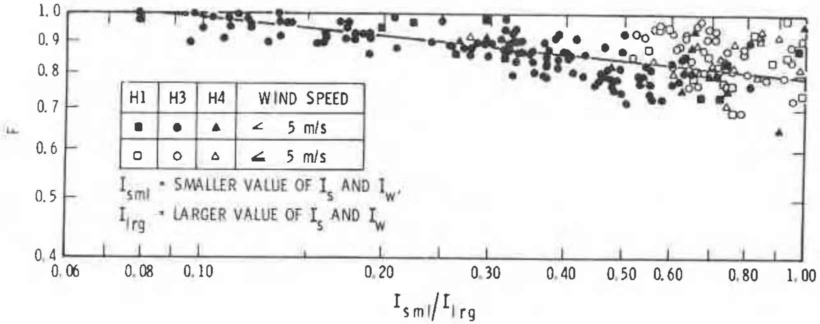

Figure 5. F versus Isml / Ilrg

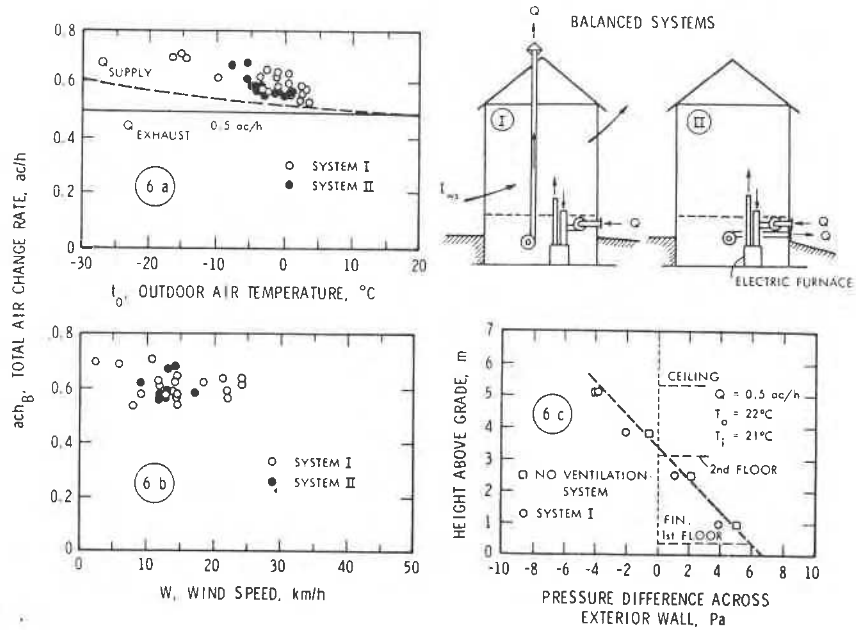

Figure 6. Total air change rate and pressure difference profile of balanced systems

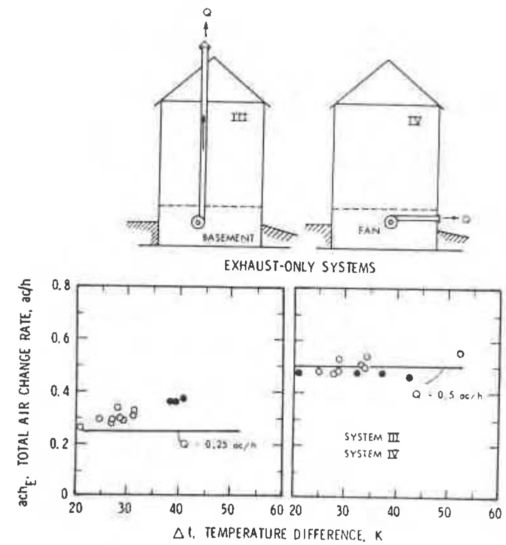

Figure 7. Total air change rate versus temperature difference for exhaust-only systems

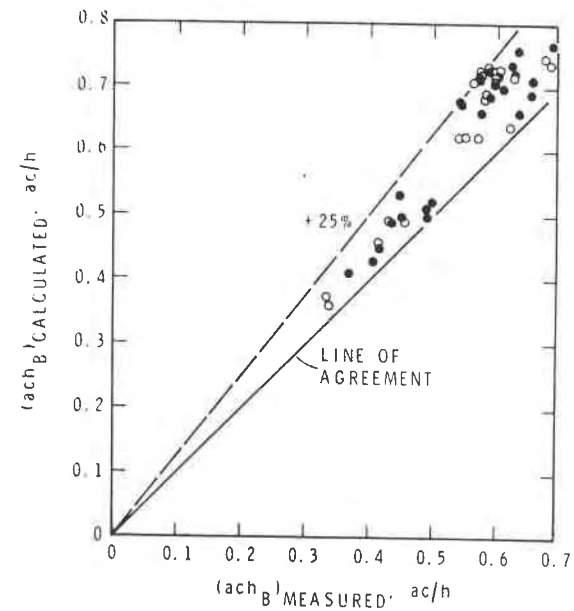

Figure 8. Comparison between the measured air change rate and rate calculated by Eq. (11)

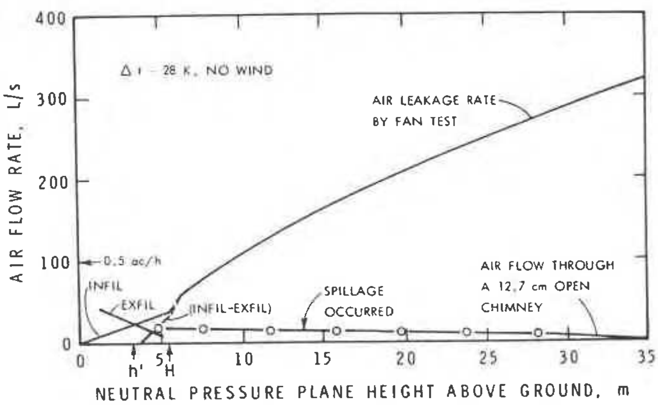

Figure 9. Effect of exhaust fan on the venting performance of an open chimney

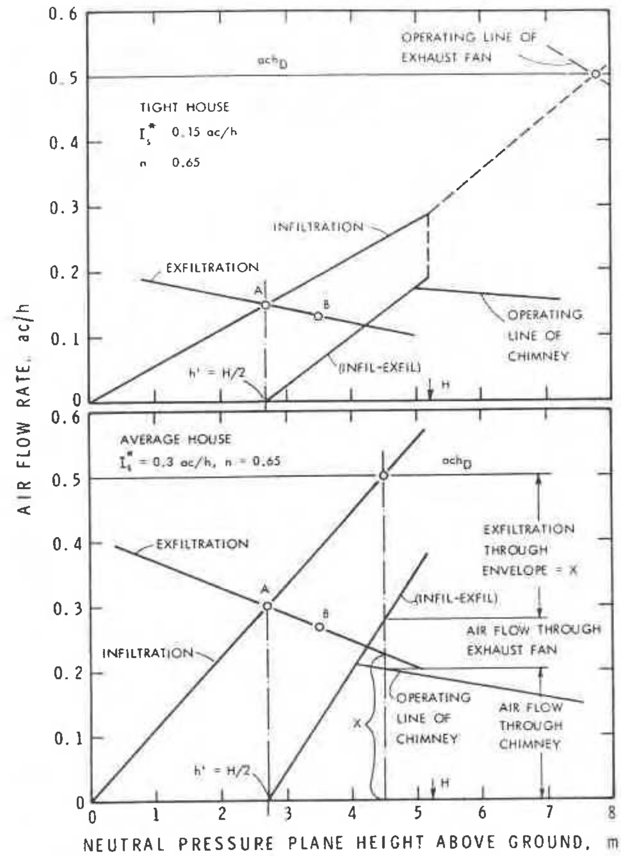

Figure 10. Air flow versus neutral pressure level diagram for selecting ventilation systems

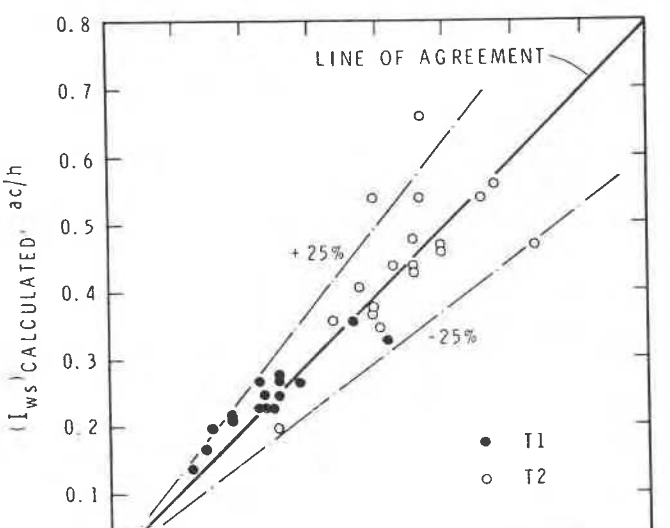

Figure 11. Comparison of calculated and measured air infiltration rates for houses T1 and T2

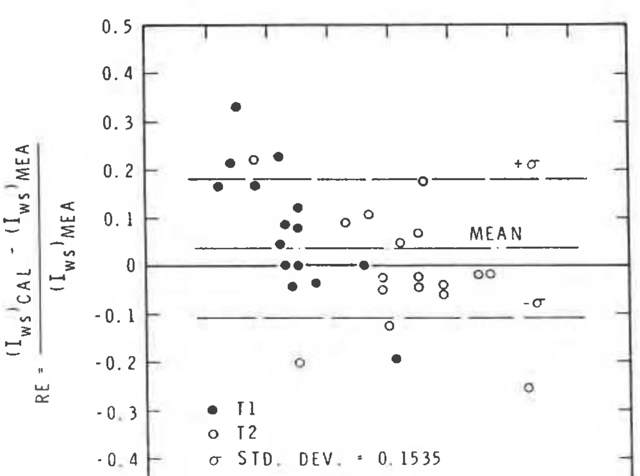

Figure 12. Relative error versus measured air infiltration rates for houses T1 and T2

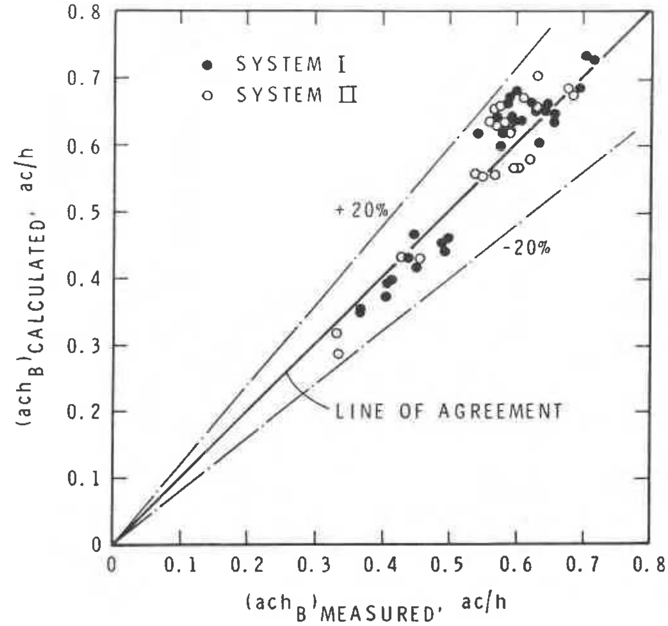

Figure 13. Comparison of calculated and measured air change rates for systems I and II

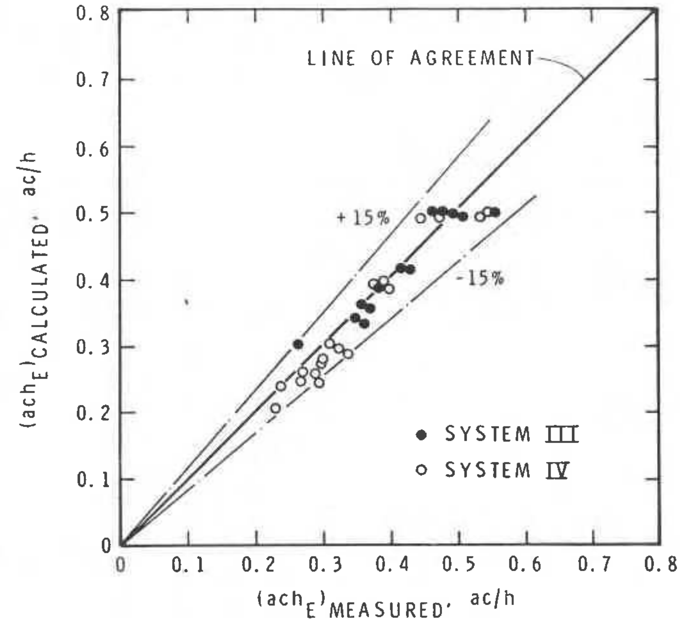

Figure 14. Comparison of calculated and measured air change rates for systems III and IV

Discussion

D. HARRJE, Princeton University, Princeton, NJ: Please explain the differences with the David Wilson paper as to how mechanical and natural ventilation are added. In that paper, it is direct addition: here it takes the form $(A + B)^n$.

SHAW: Because our measurements indicate that the two flows are not directly additive, an expression of the above form has been derived to combine the two flows. The calculated air change rates using this expression which are lower than the sum of the two flows, are in good agreement with the measured values.

D. WILSON, University of Alberta, Edmonton, Canada: The exponent in the wind driven infiltration varies by exactly a factor of two between shielded and unshielded houses. Would you speculate on a physical reason for this experimentally observed difference?

SHAW: The two exponents have been obtained by the curve fitting technique. I don't know why they differ by a factor of two.