THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

5th AIC Conference, October 1-4 1984, Reno, Nevada, USA

PAPER 11

PERFORMANCE OF PASSIVE VENTILATION SYSTEMS IN A TWO-STOREY HOUSE

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ABSTRACT

Air change rates were measured in one two-storey detached house with five basic types of passive ventilation systems: an intake vent in the basement wall; an outdoor air supply ducted to the existing forced air heating system; an exhaust stack extending from the basement to the roof; and two combinations of the supply systems and the exhaust stack. An expression was developed for estimating house air change rate from house airtightness, neutral pressure level and indoor-outdoor air temperature difference. Good agreement was obtained for the test house between the predicted and the measured air change rates. The effects of furnace fan operation, air distribution system, and size and location of vent openings on house air change rates are also discussed.

1. INTRODUCTION

The air leakage characteristic of a house has a major effect on energy consumption, indoor air quality and moisture problems. To investigate the effect of weather, airtightness, and heating and ventilation systems on the air change and air pressure distribution of a house, several studies were undertaken on four detached two-storey houses. These studies were part of the Mark XI Energy Research Project co-sponsored by the Division of Building Research and the Housing and Urban Development Association of Canada (HUDAC).[1] The air change rates and the airtightness values measured for the four houses, and a discussion on the relationship between house air change rate and airtightness, wind and stack action, and the operation of a natural-draft gas furnace, have already been reported.[2, 3, 4] The results of a study on mechanical ventilation systems have also been reported.[5] This paper presents the results of a study on passive ventilation systems.

Interest in passive ventilation techniques has been increasing as more airtight houses are constructed and more moisture problem are reported. Passive ventilation usually takes the form of an air inlet in the exterior wall or an exhaust stack, or a combination of the two. Since the amount of outdoor air supplied by these means varies with outdoor weather conditions, passive ventilation has never been considered as a satisfactory means of providing ventilation air in tight houses. However, for houses in which air leakage provides most of the ventilation, a well-designed passive ventilation system can be a practical means of supplying the additional outdoor air required for controlling indoor humidity and improving indoor air quality.

The main objective of this study was to check expressions developed for predicting the air change rate of houses with passive ventilation systems.

2. EFFECT OF VENT OPENINGS ON HOUSE AIR CHANGE AND PRESSURE

In a previous study, the air change rates of one of the four houses (H3) were measured to determine the effect of venting through a chimney on the house air leakage characteristic.[4] The results are summarized in Fig. 1.

Figure 1a shows the temperature-induced air flow and pressure difference patterns for this house with the chimney capped. Because the air inside the house is warmer, and hence less dense than that outside, it tends to rise and leak out through the upper parts of the house; colder outdoor air leaks in through the lower parts of the house to replace it. The pressure difference across the exterior wall decreases linearly from a positive value at the grade level to a negative value at the ceiling level. Near mid-height, there is a level where the pressure difference is zero. This is called the neutral pressure level.

When a vent, such as a chimney or an exhaust stack, is installed in the house, the air change rate increases due to the air flow through the vent (Fig. 1b). The air flow through the vent depends upon the temperature difference between inside and outside, and the size and location of the vent. As a result, the pressure difference across the exterior wall is redistributed so that a mass flow balance is maintained.

The air change rate caused by stack action alone depends on the airtightness of the envelope and the indoor-to-outdoor air temperature difference. Figure 1c shows the air change rates for the house with and without a chimney. Without a chimney, the measured air change rates for wind speeds lower than 12 km/h agreed closely with the values predicted by Eq. 1 (derived previously for the other two chimneyless houses, H1 and H4, included in the Mark XI project).[3]

$$I = 0.32\ (A/V)\ C(\Delta t)^n \qquad (1)$$

where:

- I = house air change rate, ac/h,
- A = area of building envelope (area of exterior wall above grade and ceiling area of top floor) m^2,
- V = volume of building including basement, m^3,
- C = flow coefficient, $L/(s \cdot m^2 \cdot Pa^n)$,
- n = flow exponent,
- Δt = indoor-to-outdoor temperature difference, K,
- 0.32 = dimensional constant, $m^3 \cdot s \cdot Pa^n/(L \cdot K^n \cdot h)$.

With a chimney, the measured air change rates could be expressed by an equation similar to Eq. 1:

$$I = B(A/V)\ C_v(\Delta t)^{n_v} \tag{2}$$

where:

C_v = flow coefficient with vent, $L/(s \cdot m^2 \cdot Pa^n)$,
n_v = flow exponent with vent,
B = 0.43, a dimensional constant, $m^3 \cdot s \cdot Pa^{n_v}/(L \cdot K^{n_v} \cdot h)$.

As the ratio of the constants in Eqs. 1 and 2 was approximately equal to the ratio of the two neutral pressure levels, a general expression for the two equations was:[4]

$$I = 0.32\ (A/V)\ r\ C_v(\Delta t)^{n_v} \tag{3}$$

and

$$r = 1 + \left| (h_v - h) \right| /h$$

where:

C_v = flow coefficient with vent, $L/(s \cdot m^2 \cdot Pa^{n_v})$,
n_v = flow exponent with vent,
h_v = neutral pressure level with vent, m,
h = neutral pressure level without vent, m.

If both an intake vent and an exhaust vent are installed, the changes in neutral pressure level caused by the vents tend to cancel each other. When there are multiple vents, the expression for r is:

$$r = 1 + \sum^{J} \left| (h_{v,j} - h) \right| /h$$

where J is the number of vents and $h_{v,j}$ is the neutral pressure level corresponding to the j th vent if it were the only one.

Equation 3 requires values of the flow coefficient (C) and exponent (n) and the neutral pressure level of the house with ventilation system. These values can be measured directly or estimated using the methods described in Appendix A.

Although Eq. 3 was derived for stack action alone, it applies equally well where there is the combined effect of stack action and wind (Fig. 1d). The air change rates were measured in a test house and compared with the values predicted by Eq. 3 to check the validity of this equation.

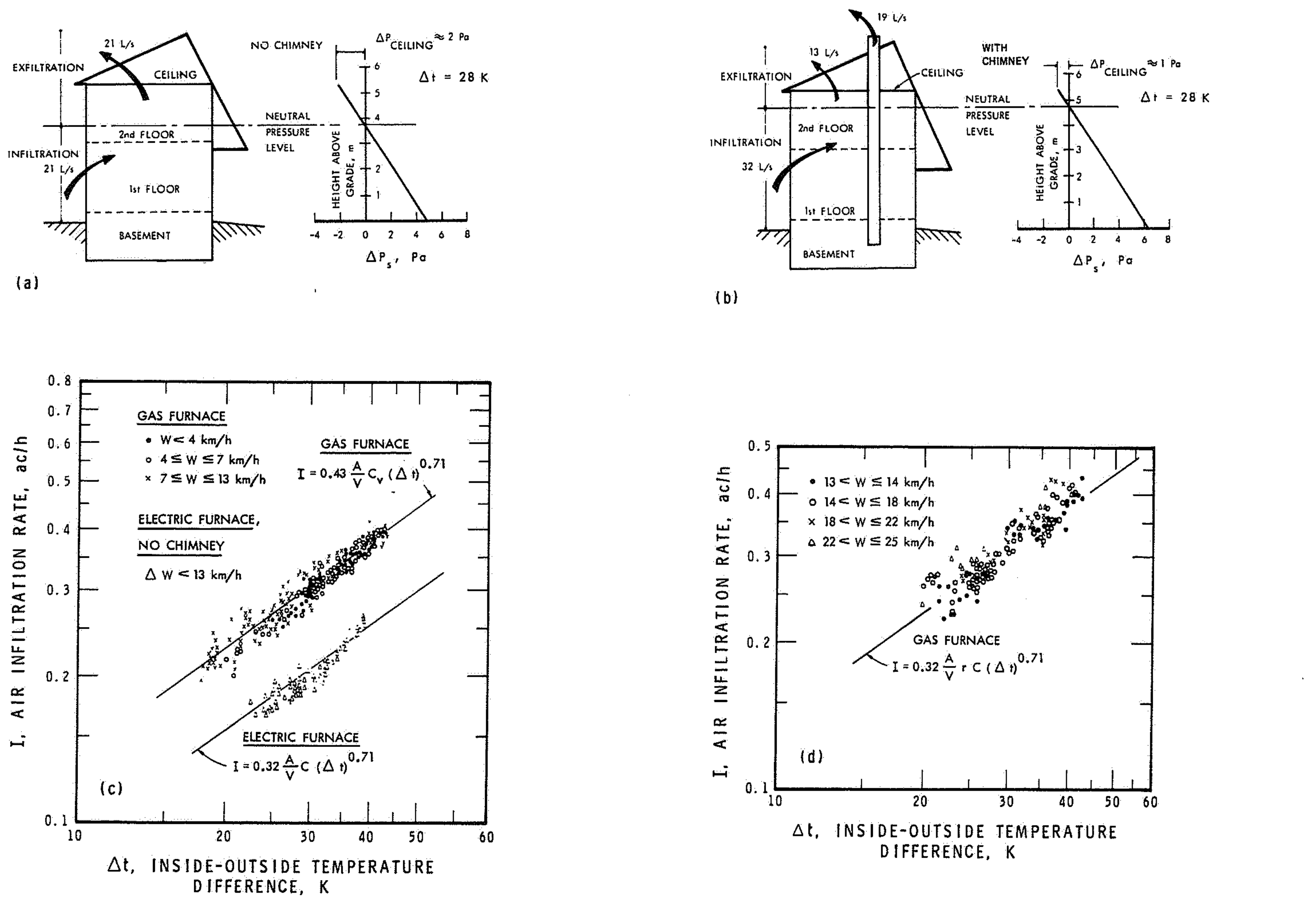

Figure 1. Temperature-induced air flow and pressure patterns, and air infiltration rates (from Reference 4)

3. TEST HOUSE AND PASSIVE VENTILATION SYSTEMS

3.1 Test House

The test house (H4) is a two-storey detached house with a full basement, located in a developed residential area in the city of Gloucester, Ontario. The house has a forced-air heating system with an electric furnace. It also has a 12.7 cm diameter chimney, which was capped when the electric furnace was in use. The volume of the house, including basement, is 386 m^3 and the area of the house envelope, including the area of the second floor ceiling is 227.7 m^2. The second-storey ceiling is 5.4 m above grade level.

3.2 Vent Openings

Each of the two basement windows in the south wall was replaced by a plywood panel with a 10 cm diameter pipe installed at the centre (Fig. 2). One of the pipes could be connected to the return air duct of the heating system. The existing 12.7 cm diameter chimney was used to simulate an exhaust stack. Provision was made for indoor air to exhaust through the stack from either the basement or the second storey.

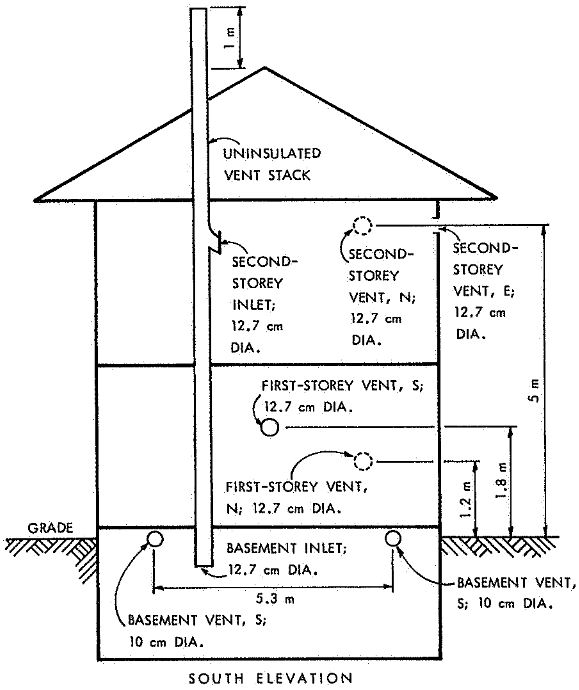

Figure 2. Test house with location of vent openings

Plywood panels with a 12.7 cm diameter circular opening were installed in the opening of one south window and one north window on the first storey, and one north window and one east window on the second storey. These openings could be closed by merely closing the casement windows.

The vent openings and exhaust stack were combined to simulate the five basic passive ventilation configurations shown in Fig. 3a, and the six additional configurations shown in Fig. 3b. The five basic configurations were:

(I) 10-cm diameter opening in south basement wall delivering air to the basement at grade level;
(II) 10-cm diameter pipe supplying outdoor air to the return duct of the forced-air heating system; intake opening at grade level;
(III) 12.7-cm diameter exhaust stack extending from basement to above the roof;
(IV) combination of I and III;
(V) combination of II and III.

Six more configurations were tested to demonstrate the ventilation capability of the different passive ventilation techniques in houses with and without an air distribution system. They were also intended to show how well the ventilation air (outdoor air) mixed with indoor air, and how the location of the vent openings

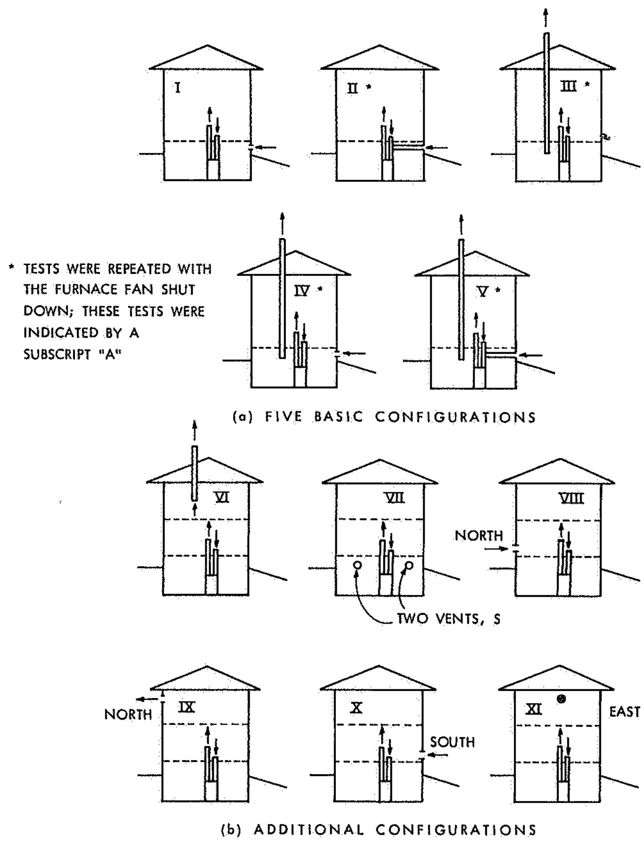

Figure 3. Test ventilation configurations

affected the ventilation rate. The six additional configurations were:

(VI) 12.7-cm diameter exhaust stack extending from second storey to above the roof;
(VII) two 10-cm diameter openings about 5.3 m apart in the basement wall, at grade level;
(VIII) 12.7-cm diameter opening in first storey north window, 1.2 m above grade;
(IX) 12.7-cm diameter opening in second storey north window, 5 m above grade;
(X) 12.7-cm diameter opening in first storey south window, 1.8 m above grade;
(XI) 12.7-cm diameter opening in second storey east window, 5 m above grade.

All of these configurations were tested with the air circulating fan of the forced-air heating system operating continuously. Configurations II to V were also tested with the fan off.

4. TESTS AND MEASUREMENTS

For each weather condition, the various configurations were tested, one after another and the following parameters were measured:

(1) indoor and outdoor air temperatures, measured and recorded on a computer-based data logging system;
(2) local wind speed and direction, measured 10 m south of the house and 18 m above grade, and recorded on the same data logging system;
(3) air change rate(s), (whole house, or living space and basement separately); and
(4) air flow rates through vent openings and exhaust stack.

Air pressure differences across the house envelope were only measured under calm conditions (wind speed less than 8 km/h) and only for some configurations (no vents, and configurations I to V and IX). Fan pressurization tests to determine the airtightness of the house, with and without vent openings, were performed once in early summer under calm conditions and only for select configurations (no vents, and configurations I, II, II_a, III, IV, V, VII, IX and X).

4.1 Air Change Rate

Air change rate was measured using the tracer gas decay method with N_2O (nitrous oxide) as the tracer gas.[6] The door to the basement was kept closed during the measurement. For each measurement, the tracer gas was injected into, and air samples were collected from, the forced air heating system with separate injection and sampling tubes. The furnace fan was operated continuously to mix the tracer gas with the indoor air.

For those special tests with the furnace fan off, the fan was only shut down after the tracer gas was thoroughly mixed (about 30 min. after an injection). During the tracer gas sampling period, mixing was handled by several portable fans located throughout the house. For these tests with furnace fan off, air samples were taken directly from the basement and from the main living area.

The N_2O concentrations were measured on site with an infrared analyzer. The analyzer was calibrated periodically using certified calibration gas.

4.2 Air Flow Rate

The air flow through the vent opening and the stack was measured using either a pair of total pressure averaging tubes or an orifice plate, with a diaphragm-type pressure transducer (static error band of 5% full scale).

4.3 Vertical Pressure Difference Profile

Values of indoor-outdoor pressure difference across the house envelope were measured under calm conditions at four locations along the north wall with a diaphragm-type pressure transducer (static error band of 5% full scale). Pressure probes were installed at the sill and head of a first floor window, and at the sill and head level of a second floor window directly above the first. The probes were located 1.1, 2.6, 3.9 and 5.2 m above grade, respectively.

5. RESULTS AND DISCUSSION

The results of the fan pressurization tests conducted in early summer, with tightness expressed in terms of C and n, are given in Table 1. Also given in Table 1 are the height of neutral pressure levels and the pressure differences at grade level measured under calm conditions with an indoor-to-outdoor temperature difference of 34 K.

The air change rates of the house and the air flow rates through the vents were measured during the 1982-83 heating season under a variety of weather conditions; air temperature difference ranged from 10 to 40 K, and wind speed varied up to 30 km/h. The results for the five basic configurations are shown in Figs. 5 to 9, and are discussed in the following sections.

To determine the effectiveness of these ventilation techniques, the measured air change rates were compared with those measured for the house without passive ventilation (measured in a previous study[3]). For a wind speed lower than 12 km/h, the air change rate increased with inside-outside temperature difference as defined by Eq. 1 (Fig. 4). For higher wind speeds, the air change rate exceeded the values that would apply for the same Δt with low wind speed. However, for temperature differences greater than 20 K and wind speed ranging from 12 to 40 km/h, typical winter conditions for this region of Canada, the air change rate was approximately constant at 0.2 ac/h. Thus, 0.2 ac/h was chosen as the seasonal average air change rate for the test house without passive ventilation.

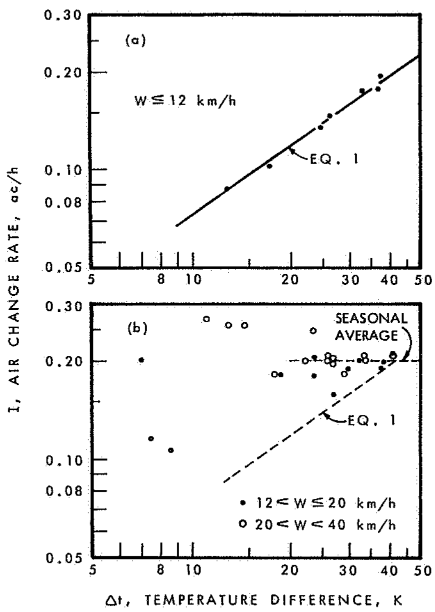

Figure 4. Air change rate without passive ventilation (Reference 3)

5.1 The Five Basic Configurations

Figures 5 to 9 indicate that the house air change rate increased with the indoor-to-outdoor air temperature difference but was relatively insensitive to wind for all systems. However, at a constant Δt, the influence of wind on house air change could be

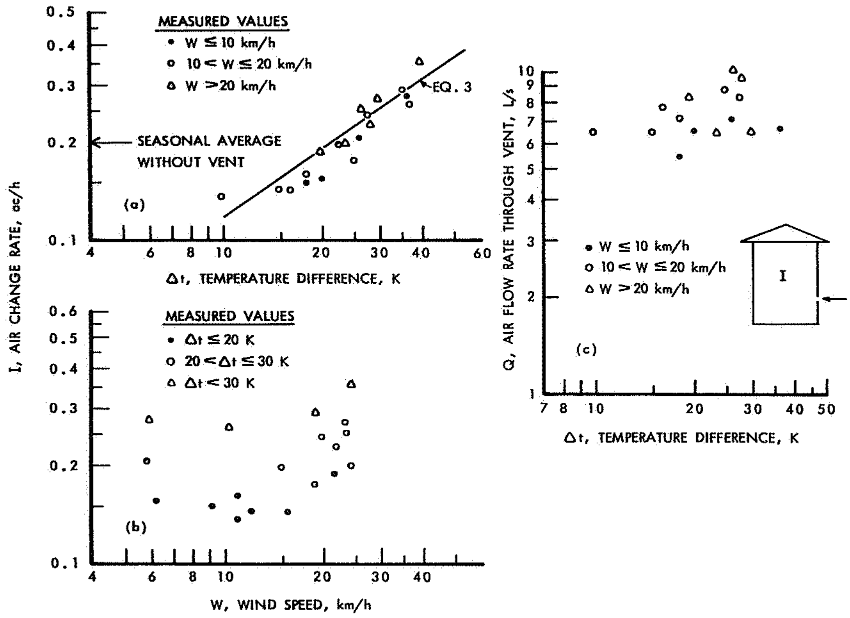

Figure 5. House air change rate and air flow rate through intake vent - configuration I

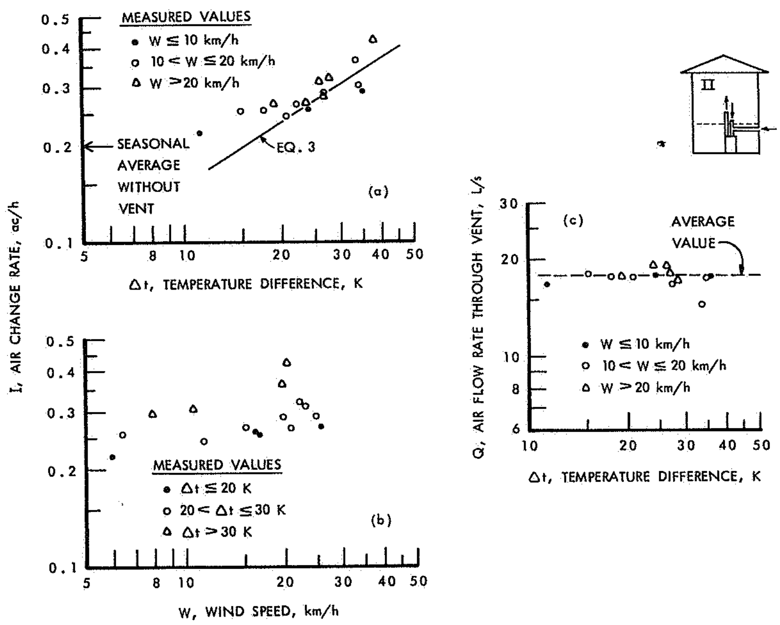

Figure 6. House air change rate and air flow rate through intake vent - configuration II

detected (5a to 9a). Likewise, for a constant wind speed, the scatter in the air change data was mainly caused by stack action (5b to 9b).

The measured air change rates for the five configurations are compared with those predicted by Eq. 3 in Figs. 5a to 9a. In general, the calculated air change rates were within 20% of the measured values.

A comparison between Eqs. 2 and 3 indicates that the ratio B/0.32 should be equal to r, if the values of n are about the same. Since the value of B can be estimated independently by fitting the measured air change rates to Eq. 2, another check on the accuracy of Eq. 3 was made by comparing the ratio B/0.32 with r. The results, listed in Table 1, indicate that the maximum difference between B/0.32 and r is about 10% of r for the five configurations.

5.1.1 Configuration I -- One basement intake vent

This configuration is similar to a house with a preponderance of leakage openings in the lower half of the house envelope, such as a window vent. The ventilation system became effective (i.e., air change rate exceeded that of the house with no vent, 0.2 ac/h) when the temperature difference was greater than 20 K, as shown in Fig. 5a. This figure also shows that Eq. 3 overpredicts the air change rate by about 6% in comparison with the best fit to the measured data.

Figure 5c shows that the air flow through the vent opening also increased with temperature difference. The air flow rate through the vent was also influenced by both wind speed and direction.

5.1.2 Configuration II -- Basement supply to forced-air heating system

This configuration is similar to configuration I, except that the venting action is now augmented by the operation of the furnace fan. The house air change rate exceeded that of the house with no vent (0.2 ac/h) for a temperature difference as small as 10 K (Fig. 6a). This suggests that the furnace fan is effective in increasing the supply of outdoor air to the house. This suggestion is reinforced since the air flow through the supply vent remained nearly constant at a value of about 18 L/s or 0.17 ac/h regardless of temperature difference (Fig. 6c); that is, the supply of outdoor air was controlled by the furnace fan rather than by stack action. As the outdoor supply air rate was constant, the house air change rate should always exceed 0.17 ac/h. The temperature difference corresponding to 0.17 ac/h is 12.5 K (Fig. 6a), suggesting that Eq. 3 should be used only when Δt is greater than 12.5 K. Figure 6a also indicates that Eq. 3 underpredicts the air change rate by about 10% in comparison with the best fit to the measured values.

5.1.3 Configuration III -- Basement exhaust stack

This configuration is similar to a house with a preponderance of leakage openings in the upper half of the house envelope. As Fig. 7a indicates, the house air change rate was greater than 0.2 ac/h when the temperature difference was greater than 20 K. Compared with the previous two systems, this system is more effective than configuration I (probably due to a larger size vent) but is less effective than configuration II, especially under mild weather conditions. Figure 7a also indicates that Eq. 3 coincides with the best fit to the measured data.

The air exhaust rate through the stack was more strongly influenced by stack action than in the two previous configurations (Fig. 7c). Under mild weather conditions, the exhaust rates were also influenced by wind. The wind influence, however, diminished as the temperature difference increased.

5.1.4 Configuration IV -- Combination of I and III

This configuration can be found in houses with a forced-air heating system when the outdoor air supply is disconnected from the heating duct. As shown in Fig. 8a, this system supplied more ventilation air to the house than any of the foregoing systems, and Eq. 3 overpredicts the air change rate by about 7% in comparison with the best fit to the measured data.

Data presented in Fig. 8c show that the air supply and exhaust flows through the intake vent and the exhaust stack were influenced strongly by stack action. Also the air flow through the exhaust stack was almost identical to that of configuration III, and the air flow through the intake vent was about the same as that of configuration I. This suggests that the house pressure, and hence the air flows through the intake vent and exhaust stack, were unaffected by the presence of the other vent.

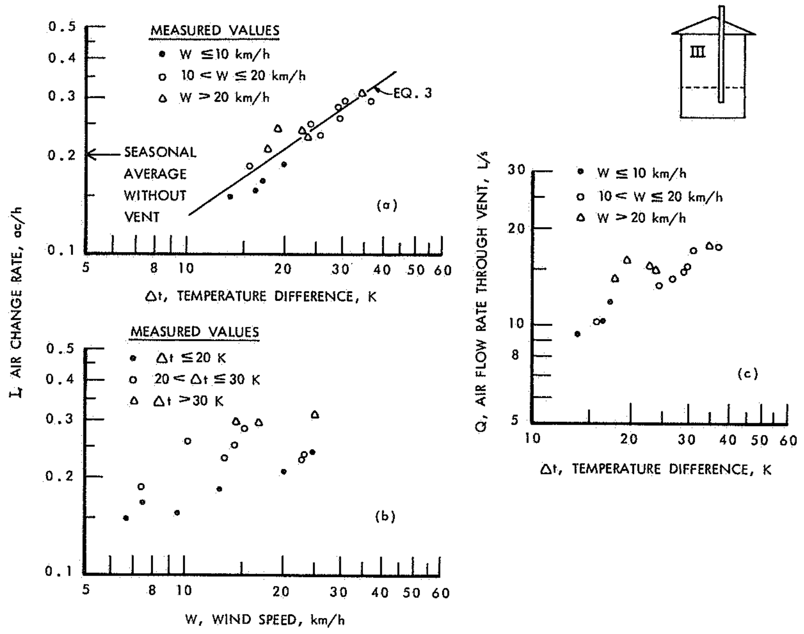

Figure 7. House air change rate and air flow rate through exhaust vent - configuration III

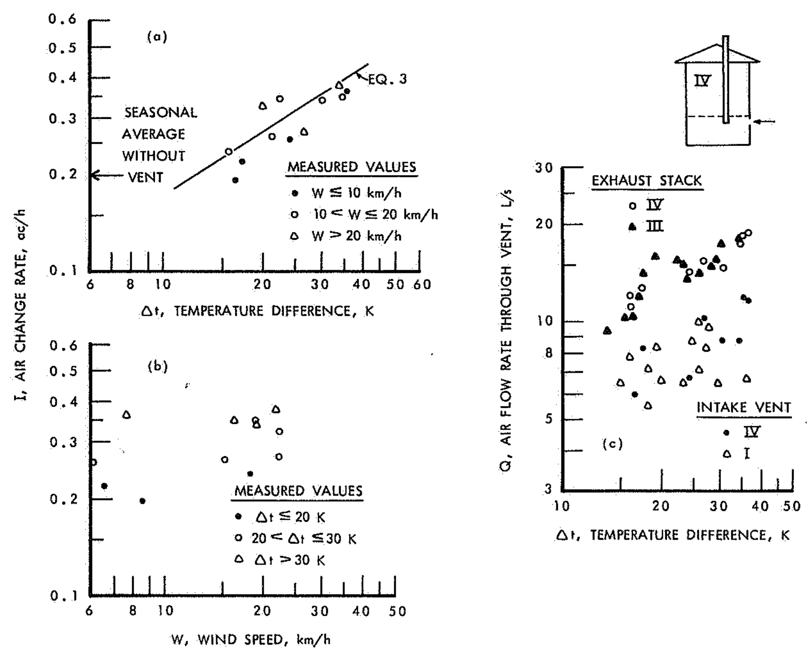

Figure 8. House air change rate and air flow rate through vents - configuration IV

5.1.5 Configuration V -- Combination of II and III

This configuraton can be found in houses with a forced-air heating system having an outdoor air supply connected to its return duct. The temperature difference corresponding to 0.17 ac/h, the outdoor air supply rate, is 10 K (Fig. 9a). As this was the minimum air change rate for this house, Eq. 3 is applicable for Δt greater than 10 K. The air change rates predicted by Eq. 3 are almost identical to those given by the best fit to the measured data.

As was the case with configuration IV, the air flows through the intake vent and exhaust stack were unaffected by the presence of the other vent (Fig. 9c).

Figure 10 shows the temperature-induced air flow and pressure differential patterns for the house with and without a passive ventilation system. The air change rates and the air flow rate through the vents were obtained from Figs. 4 to 9 for Δt = 34 K. Configuration V induced the highest air change rate at 0.42 ac/h, followed by configurations IV, II, III and I at 0.35, 0.33, 0.3 and 0.26 ac/h, respectively. The air leakage rate through the house enclosure for configuration V is greater than that for the house without vents, even though their neutral pressure levels are identical. This discrepancy may be caused by errors associated with neutral pressure level measurement and a possible change in the air leakage characteristic of the house enclosure.

The neutral pressure levels of configurations III, IV, and V, all with an exhaust stack, were higher than that of the house with no passive ventilation, as Fig. 10 shows. Further, the neutral pressure levels of configurations I and II, all without an exhaust stack, were lower than that of the house without passive ventilation. Thus it is not desirable to install a passive ventilation system similar to configurations I and II in houses. Such a system can lower the neutral pressure level of the house, which in turn, increases the amount of humid air leaking out through the upper walls and ceiling. Thus, it increases the potential for developing moisture problem.

6. EFFECT OF FURNACE FAN AND AIR DISTRIBUTION SYSTEM

Configurations II, III, IV, and V were retested with the furnace fan shut down to determine the effect of the furnace fan and air distribution system on ventilation efficiency and capacity. In this series of tests, tracer gas concentrations were measured in the basement and in the first storey living area. The door to the basement was kept closed, but the registers and grilles of the air distribution system remained unsealed.

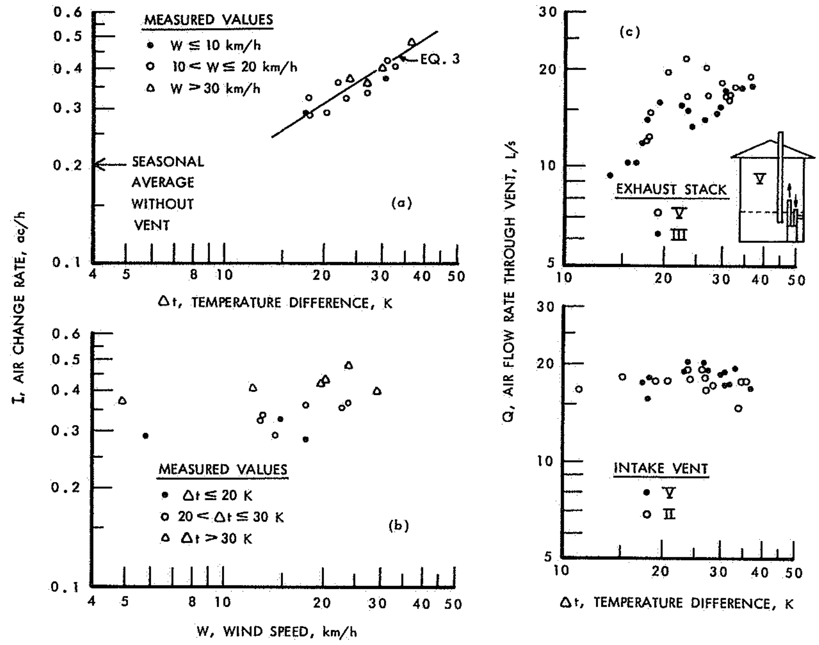

Figure 9. House air change rate and air flow rate through vents - configuration V

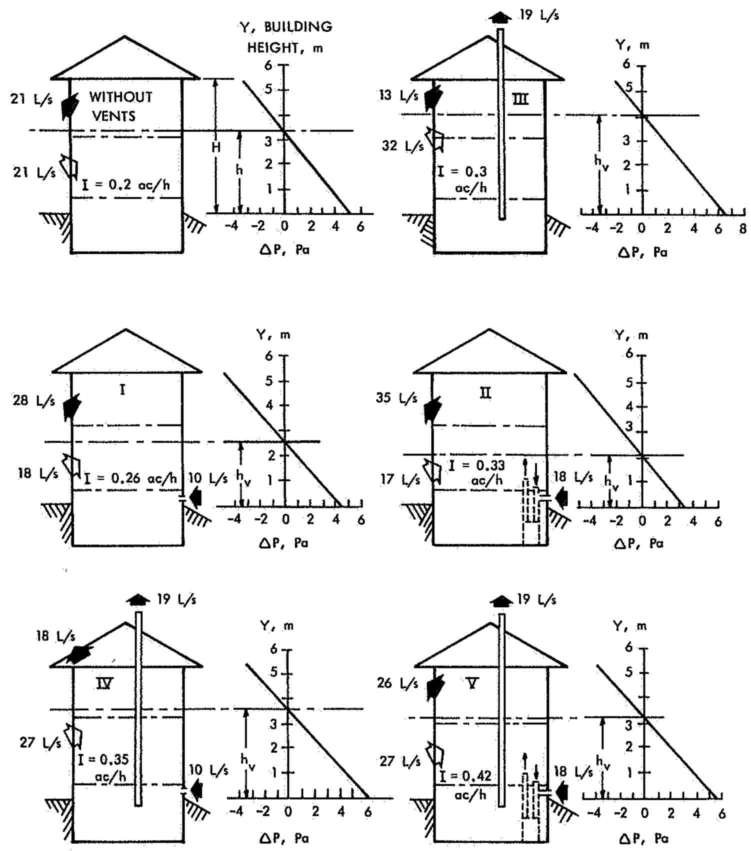

Figure 10. Temperature-induced air flow and pressure patterns for Δt = 34 K

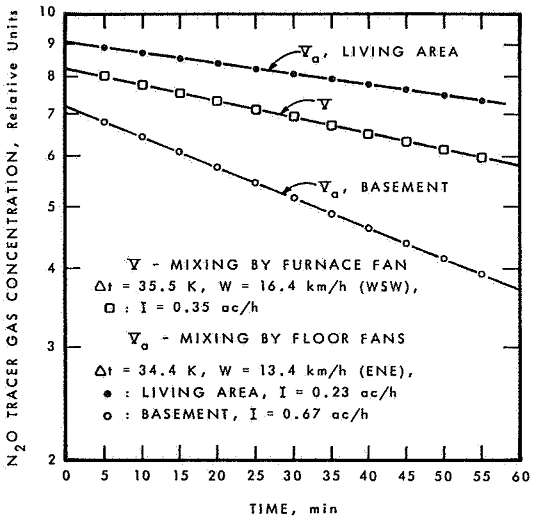

Figure 11. Sample plots of N_2O concentration versus time for air samples collected from return air duct, basement and main living area

Figure 11 shows three sample plots of N_2O concentration versus time; one for configuration V (with furnace fan on) and two for configuration V_a (furnace fan off), obtained under similar weather conditions. The results indicate a straight line relationship between the logarithm of tracer gas concentration and time for all three cases. This suggests that adequate tracer gas mixing was achieved in the test spaces. With the furnace fan off, the tracer gas decay rate for the basement is much greater than that for the first storey living area; that is, the local air change rate was greater in the basement than in the living area. The effect of furnace fan operation on local air change is shown in Figs. 12 and 13 for the four configurations.

Configurations II_a and V_a, shown in Fig. 12, have the outdoor air supply ducted to the heating system, as in houses with gas-heated, forced-air heating systems. Configuration II_a represents the off-cycle condition with high or medium efficiency gas furnaces. Configuration V_a represents the off-cycle condition with a natural-draught gas furnace. The air change rates measured in the basement and in the living space with configuration II_a (Fig. 12a) were almost identical, indicating reasonable mixing of air in the house even with the furnace fan off. This is because the air distribution duct of the heating system permits air entering through the vent opening to reach the living area. The air change rate with the furnace fan off was up to 15% lower than that with the furnace fan operating continuously. This is reflected in Fig. 12c; the air flow through the outdoor air duct with the furnace fan off was nearly constant at 6 L/s and about one-third of the flow with the fan on.

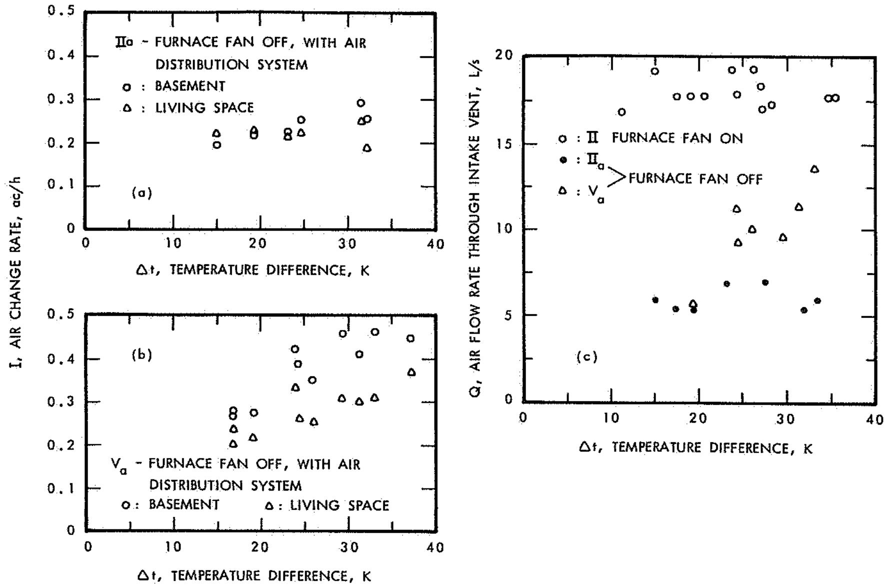

Figure 12. Effect of furnace fan on air flow rate through intake vent and house air change rate

With an exhaust stack in the basement (configuration V_a - Fig. 12b), the air change rate in the basement was consistently higher than that measured in the living space above. This suggests that much of the air leaking into the basement escaped directly through the exhaust stack. The air change rate in the living space, (the effective ventilation rate) with the fan off was about 25% lower than that with the fan on. This is also shown in Fig. 12c; the supply air flow with fan off, although strongly affected by stack action, remained lower than the flow with the fan on.

In Fig. 13, configurations III_a and IV_a, with the vents disconnected from the air distribution system, had a substantially higher air change rate in the basement than in the living space. The difference in air change rate was greater with configuration IV_a (Fig. 13b). With both intake vent and exhaust stack located in the basement, outdoor air entering through the vent opening in the basement bypassed the living area and went directly out through the exhaust stack. Consequently, outdoor air entering through the vent was not ventilating the living space. Moreover, the air infiltration through the basement wall was also bypassing the living space.

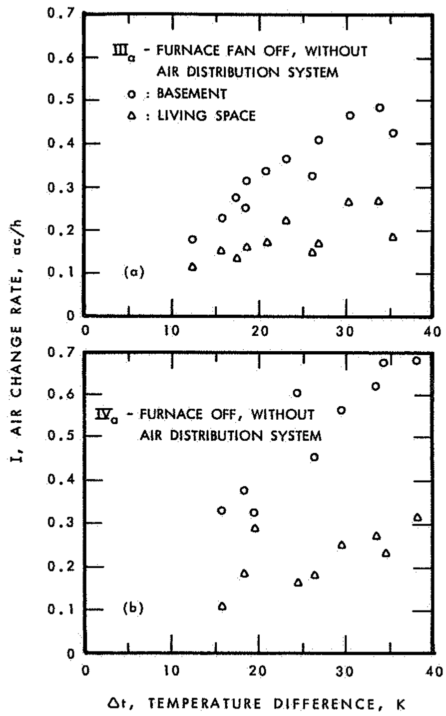

Figure 13. Effect of air distribution system on house air change rate

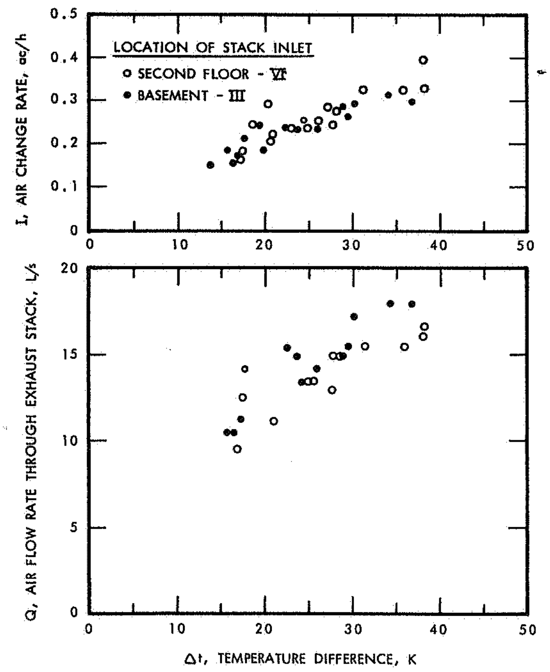

Figure 14. Effect of location of stack intake on house air change rate and venting capacity

7. EFFECT OF EXHAUST STACK CONFIGURATION

Figure 14 compares the house air change rate and the exhaust stack flow of configurations III and VI, which differed only in the location of the inlet to the exhaust stack. Both the house air change rate and the exhaust stack flow remained relatively unchanged regardless of whether the indoor air exhausted from the basement or from the second storey. The location of stack inlet has very little effect on the venting performance of an exhaust stack when the furnace fan is on. However, when the furnace fan is off, or when there is no air distribution system, the preferred location of the inlet to the exhaust stack is in the living space. This location will ensure that outdoor air entering the basement, either through the wall or through a ventilation inlet, will pass through the living space.

8. EFFECT OF VENT OPENING LOCATION

House air change rates were measured with a 12.7 cm diameter vent installed at various locations in the house enclosure (configurations I, and VIII to XI). The vent was located near the sill of a first storey window, or near the head of a second storey window (Fig. 15).

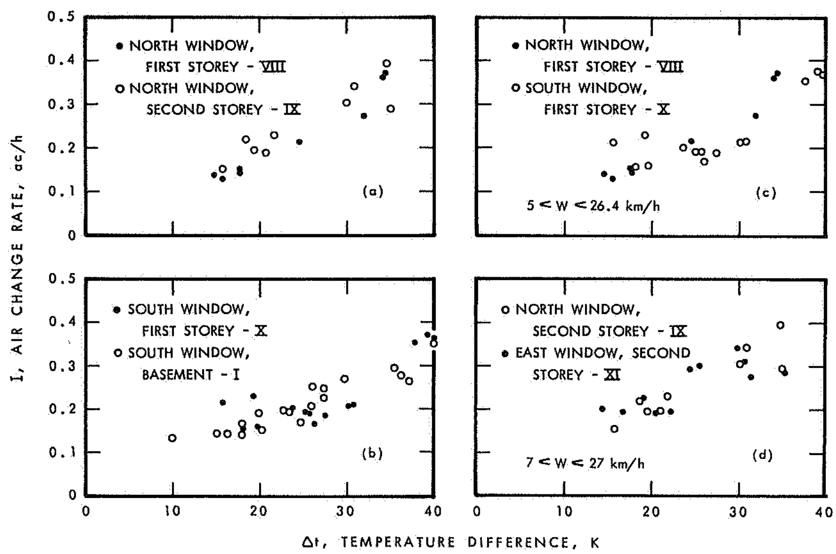

Figure 15. Effect of vent location on house air change for wind speeds up to 25 km/h

The house air change rate was not strongly affected by an elevational change of the vent opening, nor by whether the vent opening was acting as an intake vent (VIII) or as an exhaust vent (IX) (Fig. 15a). There was no apparent difference (Fig. 15b) in house air change rate between a basement vent location (I) and a first-storey location (X), even though the area of the basement vent was 38% less than that of the first storey vent. The directional orientation of the vent opening had no noticeable effect (Figs. 15c,d) on house air change for wind speeds up to 27 km/h. These results again support the conclusion that stack action is the dominant driving potential for passive ventilation.

9. EFFECT OF VENT SIZE

Figure 16 shows the measured house air change rates with two 10 cm vents (5.3 m apart) in the same wall (VII). The house air change rates with two vents were only slightly greater than those with one vent, probably because the air flow through the vents (on average 7.5 L/s per vent) did not have a significant influence on house air change. The air change rate calculated from Eq. 3 for two vents overpredicted the measured values.

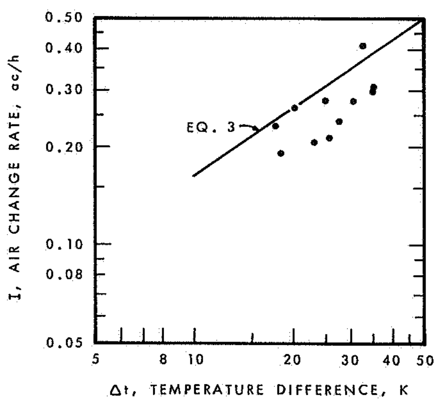

Figure 16. House air change rate - configuration VII

10. SUMMARY

10.1 All the passive ventilation systems tested increased the house air change rate over that of the house with no vents (Table 1). Of the five basic systems, configuration V produced the highest house air change rate, followed by configurations IV, II, III, and I. For example, at Δt = 34K, the measured house air change rates were about 0.42 and 0.35 ac/h for V and IV, and they were about 0.33, 0.3 and 0.26 for II, III and I, respectively.

10.2 Stack action was the dominant driving potential for passive ventilation with wind speeds less than 30 km/h. However, significant flow augmentation was provided by the air circulating fan of the forced-air heating system when the vent was connected directly to the heating system.

10.3 The orientation and elevation of the vent opening appeared to have very little effect on house air change with wind speeds less than 27 km/h.

10.4 The location where the exhaust stack withdraws indoor air had very little effect on house air change rate with the furnace fan operating, but could have a significant effect on the efficient mixing of outdoor air with the air in the living space.

10.5 An air distribution system significantly improves the distribution and mixing of outdoor air that enters through vent openings and infiltrates through openings and cracks in the basement wall with the indoor air.

10.6 Methods for estimating the airtightness characteristic of a house with vent openings and the effect of these openings on the neutral pressure level have been presented. The derived characteristics and Eq. 3 provide a reasonable estimate of house air change resulting from passive ventilation systems for temperature differences greater than 15 K.

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Acknowledgement

The authors wish to thank D.L. Logan for his assistance in conducting the tests. This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

12. APPENDIX A ESTIMATION OF C, n AND NEUTRAL PRESSURE LEVEL FOR HOUSES WITH VENTS

12.1 Flow Coefficient and Exponent

The air leakage characteristic of a house before installation of a ventilation system can be defined by the equation,

$$Q = C\,A\,(\Delta P)^n \qquad \text{(A1)}$$

where:

Q = air leakage rate, L/s,
C = flow coefficient, $L/(s \cdot m^2 \cdot Pa^n)$,
A = area of building envelope, m^2,
ΔP = pressure difference, Pa,
n = flow exponent.

After the installation of a passive ventilation system, the total air leakage of the house as determined by a fan pressurization test, would be the sum of the air leakage through the building envelope and the air flow through the vent. Thus,

$$Q' = C\ A\ (\Delta P)^n + Q_v \tag{A2}$$

where:

Q' = air leakage rate with vent, L/s,
Q_v = air flow rate through the vent, L/s.

To estimate the value of Q_v, the following two cases are considered:

(a) If the vent is connected to the forced air heating system with the furnace fan operating continuously, then Q_v can be assumed to be constant because of the large suction in the supply duct induced by the furnace fan. Measurements conducted on the test house having a 10 cm supply duct indicate that Q_v was about 18 L/s under typical winter conditions. For similar or less airtight houses, Q_v would be proportional to the size of the supply duct,

$$Q = 0.18\ D^2\ \text{L/s} \tag{A3}$$

where D is the diameter of the supply duct in cm.

(b) If the vent is just an opening in the building envelope, Q_v would be a function of the pressure difference induced by the pressurization fan, ΔP. Thus, Q_v could be approximated by the orifice equation,

$$Q_v = 1000\ C_d\ (2/\rho)^{\frac{1}{2}}\ A_v\ (\Delta P)^{\frac{1}{2}}\ \text{L/s}$$

Let the orifice discharge coefficient C_d = 0.6, the above equation becomes

$$Q_v = 600\ (2/\rho)^{\frac{1}{2}}\ A_v\ (\Delta P)^{\frac{1}{2}}\ \text{L/s} \tag{A4}$$

where:

ρ = density of indoor air, kg/m^3,
A_v = area of the vent, m^2,
ΔP = pressure difference across house envelope as induced by a pressurization fan, Pa.

Substituting Eq. A3 or A4 into Eq. A2, values of Q' can be calculated for the range of ΔP normally used in a pressurization test. By fitting these data to the air flow equation (A1), the values of C and n for the house with vents can be derived.

Values of C and n were calculated for configurations I, II, III, IV, V and VII. Because the calculated and the measured values of n were very close, the values of C were recalculated using Eq. A1 and the measured values of n, to facilitate comparison of the measured and the calculated C. The calculated and measured values of C, presented in Table A1, show good agreement.

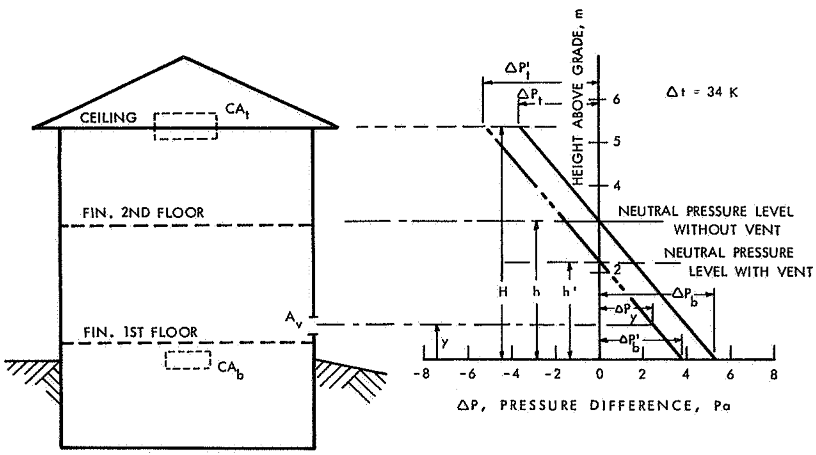

Figure A1. Distribution of leakage openings and pressure difference profile caused by stack action

12.2 Neutral Pressure Level

If vent openings are installed in a house envelope as shown in Fig. A1, the neutral pressure level (NPL) will shift to h' from h and the pressure difference across the house envelope due to stack action will change accordingly. Assuming that: (1) the air leakage characteristic of the house without vents can be represented by two openings: one located at grade level and the other at the ceiling level of the top storey, and that (2) the vertical distribution of pressure difference of the house without vents is known, the new neutral pressure level (h') can be estimated from the mass flow balance equation:

$$CA_b\ (\Delta P_b')^n\ \rho_o + (\Sigma Q_v \rho_o)_b = CA_t\ (\Delta P_t')^n\ \rho_i + (\Sigma Q_v \rho_i)_t \qquad \text{(A5)}$$

where:

CA_b = overall flow coefficient below neutral pressure level, $L/(s \cdot Pa^n)$,
CA_t = overall flow coefficient above neutral pressure level, $L/(s \cdot Pa^n)$,
$\Delta P'$ = inside-outside pressure difference due to stack action with vents, Pa,
n = flow exponent,
ρ = air density, kg/m^3

and subscripts b = grade level, t = ceiling level, o = outdoor, i =indoor.

In the above equation, the terms, CA_b and CA_t define the air leakage characteristic of the house before the installation of the vents. They can be estimated from the mass flow equation:

$$CA_b\ (\Delta P_b)^n\ \rho_o = CA_t\ (\Delta P_t)^n\ \rho_i \tag{A6}$$

where ΔP is the pressure difference across the house envelope due to stack action.

Since,

$$\Delta P_t = \left[(H - h)/h\right] \cdot \Delta P_b$$

and

$$(\rho_i/\rho_o) = (T_o/T_i)$$

therefore, Eq. A6 can be rewritten as:

$$CA_b = CA_t\ \left(\frac{H-h}{h}\right)^n \cdot \left(\frac{T_o}{T_i}\right) \tag{A7}$$

and,

$$CA = CA_b + CA_t \tag{A8}$$

where:

h = neutral pressure level without vent, m,
H = ceiling height, m.

Equation A5 can be used to estimate the neutral pressure level for a house with a passive ventilation system. It can be simplified for the following three basic venting arrangements:

(1) One vent below NPL, $(Q_v)_t = 0$

The mass flow balance equation simplifies to,

$$CA_b\ (\Delta P_b')^n\ \rho_o + Q_v\rho_o = CA_t\ (\Delta P_t')^n\ \rho_i$$

However,

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

$$\Delta P_t' = \left(\frac{H-h'}{H-h}\right)\ \Delta P_t = \left(\frac{H-h'}{h}\right)\ \Delta P_b,$$

$$\Delta P_\gamma = \left(\frac{h'-y}{h'}\right)\ \Delta P_b' = \left(\frac{h'-y}{h}\right)\ \Delta P_b\ .$$

Hence, the mass flow balance equation can be rewritten as

$$CA_b\ \left(\frac{h'}{h}\right)^n + 600\ \left(\frac{2}{\rho}\right)^{\frac{1}{2}}\ A_v\ \left(\frac{h'-y}{h}\right)^{\frac{1}{2}}\ \Delta P_b^{(\frac{1}{2}-n)} = CA_t\ \left(\frac{H-h'}{h}\right)^n\ \left(\frac{T_o}{T_i}\right) \tag{A9}$$

(2) One vent above NPL, $(Q_v)_b = 0$

The mass flow balance equation simplifies to,

$$CA_b\ (\Delta P_b')^n\ \rho_o = CA_t\ (\Delta P_t')^n\ \rho_i + Q_v \rho_i\ .$$

Substituting for $\Delta P_b'$, $\frac{\rho_o}{\rho_i}$, Q_v, and $\Delta P_t'$, we have

$$CA_b\ \left(\frac{h'}{h}\right)^n \left(\frac{T_i}{T_o}\right) = CA_t\ \left(\frac{H-h'}{h}\right)^n + 600\ \left(\frac{2}{\rho}\right)^{\frac{1}{2}} A_v\ \left(\frac{y-h'}{h}\right)^{\frac{1}{2}}\ \Delta P_b^{\left(\frac{1}{2}-n\right)} \quad (A10)$$

An exhaust stack would be treated as a vent opening located at the ceiling level of the top storey.

(3) Outdoor air supply to forced air heating system, Q_v = constant

If an outdoor air supply duct is connected directly to a forced air heating system with the furnace fan operating continuously, the air flow rate supplied by the system could be assumed as constant. Thus,

$$CA_b\ (h'/h)^n + (Q_v/\Delta P_b{}^n) = CA_t\ \left(\frac{H-h'}{h}\right)^n \left(\frac{T_o}{T_i}\right) \quad (A11)$$

For comparison, the neutral pressure levels for configurations I, II, III, IV and V were calculated using these equations. The results (Table A1) show good agreement between the calculated and the measured neutral pressure level.

Table A1 Measured and Estimated Flow Coefficients, Exponents and Neutral Pressure Levels

Configurations	Flow Coefficient and Exponent: Estimate C L/(s·m²Paⁿ)	Estimate n	Measurement C L/(s·m²Paⁿ)	Measurement n	Neutral Pressure Level: Estimate m	Neutral Pressure Level: Measurement m
I	0.106	0.71	0.103	0.71	2.4	2.6
II	0.119	0.66	0.126	0.66	2.0	2.1
III	0.113	0.71	0.101	0.71	4.1	4.2
IV	0.150	0.66	0.134	0.66	3.4	3.6
V	0.144	0.66	0.139	0.66	3.2	3.2

Table 1 Measured Flow Coefficients; Exponent; Neutral Pressure Levels; House Air Change Rates; and Comparison of Measured and Calculated r

Configuration	Vent Size m^2		Fan pressurization test		Pressure difference under no wind conditions		r		House air change rate	Remarks
	Intake	Exhaust	C Flow coefficient $L/(s \cdot m^2 Pa^n)$	n Flow exponent	Approx. neutral pressure level above grade, m	ΔP stack at grade for Δt=34K Pa	B/0.32 (Measured)	$1+\Sigma^{J}\left\lvert\frac{h_v-h}{h}\right\rvert$ (Calculated)	Δt=34K ac/h	
0	0	0	0.092	0.71	3.2	5.3	1	1	0.2	House as is
I	0.0081	0	0.103	0.71	2.6	4.3	1.13	1.19	0.26	Vent in south basement wall
II	0.0081	0	0.126	0.66	2.1	3.5	1.22	1.34	0.33	Supply to forced air heating system
IIa	0.0081	0	0.102	0.71	-	-	-	-	0.26	Furnace fan off
III	-	0.0127	0.101	0.71	4.2	6.9	1.31	1.31	0.3	Stack inlet in basement
IV	0.0081	0.0127	0.134	0.66	3.6	6	1.41	1.5	0.35	I and III
V	0.0081	0.0127	0.139	0.66	3.2	5.3	1.63	1.66	0.44	II and III
VII	2×0.0081	0	0.141	0.66	-	-	1.16	1.38	0.32	Two vents in south basement wall
IX	0.0127	0	0.132	0.66	4.2	6.9	-	-	0.34	Vent in second storey window
X	0.0127	0	0.135	0.66	-	-	-	-	0.32	Vent in first storey window