APPROACHES TO EVALUATION OF AIR INFILTRATION ENERGY LOSSES IN BUILDINGS

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INTRODUCTION

Air infiltration is an important component of energy loss in all heated buildings. The question of how to evaluate the magnitude of air infiltration in a given building is a vital part of any energy audit. Simplified methods that provide an accurate evaluation of this often elusive energy loss component could play an important role in any national energy audit or even in the approach taken by a local retrofit contractor.

In this paper the parameters governing air infiltration are outlined. Problem areas of house-to-house comparisons of air leakage are discussed. The methods primarily dealt with here are the tracer gas-dilution method as compared to the pressurization/depressurization approach. The testing takes place in townhouses of recent construction as well as in a number of older homes of varied design. A rooftop laboratory test chamber is used to clarify the important quantity of the placement of openings in the house envelope. Wind tunnel results are used to provide other important data on pressure distributions around the test houses. All of these factors help to clarify the problems and the potential for evaluation of air infiltration in buildings. Both energy related and internal air quality issues are involved in the level of air exchange rate finally achieved.

A. FACTORS AFFECTING INFILTRATION

It is important to review the factors affecting air infiltration. In an ordinary house the air leakage through cracks and crevices in the building envelope typically accounts for a third or more of the energy losses. This leakage is strongly linked to the weather at the site. However, many factors of house design and location must also be taken into account.

Weather can cause air infiltration by two separate physical mechanisms, wind and temperature-induced convection (stack effect). Unfortunately, these mechanisms do not act independently; i.e., the effects cannot be simply added.[1] The only statement that can be made in general is that the sum of the separate effects ($N_T + N_W$) is greater than the actual combined effect (N). The driving force behind the air leakage in buildings is the inside-to-outside pressure difference caused by these two mechanisms.

Wind effects, based on mean wind speed over and around a building, cause a pressure difference from inside to outside. This wind pressure is found to vary over the surface of the building envelope. For every point the stagnation wind pressure on a building can be expressed as:[2]

$$\Delta P_i = C_i \, 1/2 \, \rho \, V^2 \quad \text{(Pa)}$$

where:

C_i = dimensionless pressure coefficient depending on the form of the building and the exposure

ρ = density of air (kg/m^3)

V = wind velocity measured at a height equal to that of the building (m/s)

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The wind direction is an important factor, when calculating air infiltration into a building. A wind approaching prependicular to the front wall of a building isn't necessarily that which results in the highest leakage.[3]

The mean wind speed varies with height, and the vertical profiles of wind velocity vary with the roughness of terrain over which the wind is passing. Local topographical features such as hills and valleys can greatly influence wind profiles. For different types of terrain a simple formula can be used to describe the wind speed variation as a power-law profile.[4]

$$\frac{V}{V_m} = K\ z^a \qquad \text{(see Table 1)}$$

where:

V = wind speed (m/s)

V_m = wind speed at height equivalent to 10 m (m/s)

K = coefficient

Z = height (m)

a = exponent

A second type of wind induced ventilation through an opening is due to fluctuating external air velocity. This factor is very complex. The low-frequency content of the fluctuating velocity will produce a pulsating flow through the opening which will depend on the compressibility of the air in the enclosure, i.e., the size of the enclosure. The high-frequency fluctuations will produce a turbulent diffusion of air through the opening, less dependent on compressibility. For a net exchange of air to take place, some fraction of the fluctuating airflow passing through the opening must be mixed with the air inside the enclosure, the remainder passing back out without mixing.

Cockroft and Robertson show in their study[5] that as the air velocity (turbulent wind) increases from zero, the measured ventilation rate (in a test box with only one opening) increases quite rapidly. At very high velocities there is a levelling-off effect. Their study provides some indication of the magnitudes of ventilating airflows which may be generated by turbulent wind.

Temperature differences between inside and outside cause differences in air density. This leads to pressure differences and can be expressed as:[2]

$$\Delta P = (\rho_o - \rho_i)\ gh \qquad \text{(Pa)}$$

where:

ρ = air density (kg/m^3)

o = outside

i = inside

g = gravitational force (m/s^2)

h = height between inlet and outlet openings (m)

The air flow through any kind of opening can be expressed as a function of the pressure across the latter;[2]

$$\phi_i = C_i\ (\Delta P_i)^{\beta_i}$$

where:

ϕ_i = volume flow rate of air (m^3/h)

C_i = airflow coefficient, defined as the volume flow rate of air at a pressure difference of 1 Pa (m ^{3}/h at 1 Pa)

ΔP = pressure difference across the opening (Pa)

β_i = flow exponent, depending on the character of the flow

$1/2 \leq \beta_i \leq 1$

$\beta_i = 1/2$ for pure turbulent flow

$\beta_i = 1$ for pure laminar flow

This empirical equation is acceptable for flow through openings with pressure differences in the range of 1 to 100 Pa.[2]

If a building is considered as having a certain porosity with an overall leakiness (using pressurization, see section B) of the form:

$$Q = C\,(\Delta P)^{\beta}$$

where:

Q = volume flow rate (m^3/m^2h)

then the natural ventilation could be calculated as:[6]

$$\int_A Q_{in} = \int_A Q_{out}$$

where:

$\int_A Q_{in}$ = sum of air flow into the building

$\int_A Q_{out}$ = sum of air flow out of the building

A = building leakage envelope

The pressure difference, used in the formula above, is the pressure difference from wind and temperature calculated as stated earlier. The resulting interior pressure is based on the fact that the average air flow into and out of the building must be equal. To perform such a calculation the pressure difference and its distribution over the building envelope, as well as the overall leakness, must be known. The calculation will, in many cases, give an air exchange rate for the natural ventilation that is up to 100% too high (see section E describing calculation of natural ventilation).* This is due to a number of factors which must be taken into account. These include:

(1) microclimate (protection offered by terrain etc.)

(2) differences in wind pressure distribution depending on building shape

(3) location of openings

(4) bypasses inside the building (shafts etc.)

(5) internal flow resistance

As mentioned earlier the vertical profile of wind velocity varies with the roughness of the terrain. In addition, the wind pressure distribution is changed and the absolute level of the pressure is decreased on the building if there are obstacles upwind within a few building lengths. For example, it has been shown that trees reduce air infiltration in housing by converting directed kinetic energy in the approaching wind into random turbulent energy by passing air through tortuous paths in their crowns. These trees must be properly placed on the windward side to give the maximum reduction in air infiltration. Trees placed on the windward side of otherwise unprotected buildings can give up to 45% reduction in the natural air infiltration.[7]

The building shape influences the wind pressure distribution and therefore the area exposed to the wind should be minimized. Preferably the relation between building envelope and volume should be as small as possible. The higher the building, the stronger the stack effect. Thus if one is constructing an energy efficient high-rise building it should incorporate a number of relatively tight zones in the design in order to diminish the stack effect produced air infiltration.

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*Bilsborrow made the same calculations for a test box <u>in a wind tunnel</u> and came up with numbers that were 30% too high.[19]

A theoretical model confirmed by limited testing, shows that for a fixed overall leakiness (based upon the total of leakage paths through the building envelope) the actual location of openings, using reasonable assumptions, could affect natural ventilation rates by a factor of two or more. This subject is discussed further in Section F.

Bypasses, unsuspected air flow routes through the structure, can make important contributions to the natural ventilation. In Twin Rivers townhouses, two of the more obvious bypasses[8] are openings along the party wall and the opening around the flue which provides a free path from the basement up into the attic. These have been largely eliminated by packing them with fiberglass. This retrofit together with sealing plumbing and wiring bypasses reduced the air leakage at 50 Pa. by 35% in one townhouse under study (from 13.3 to 8.7 h^{-1}; see Fig. 1).

The internal flow resistance is supposedly low in a one-family house. The communication between different floors is normally quite good, for example, flow through the staircase opening.

B. DESCRIPTION OF TEST METHODS

In order to test for the naturally occuring air infiltration in a building and to evaluate air leakage levels, several approaches can be used.

The test methods employed in this paper are the tracer gas-dilution method and the pressurization-depressurization technique. In the later procedure both the overall house and individual components, such as windows, may be tested.

a) Tracer gas-dilution method

The tracer gas dilution method and the associated automated air infiltration unit (AAIU) have been used many times in the past by our research group.[9-11] The equipment is shown in Fig. 2. The method is based upon the use of a tracer gas, in this case sulphur hexafluoride (SF_6), which is injected into the warm air duct system. The amount of gas and the method of injection are carefully controlled to provide rapid mixing and to achieve concentration levels of approximately 40 parts per billion (ppb) within the house under study. With the particular AAIU deployed for these tests, measurements of concentration were made every five min. using the electron capture detector and gas chromatograph which are part of the AAIU. The data were stored on magnetic tape cassettes. Tape cassettes could store the data for one week but were normally changed on a four or five day schedule.

Each AAIU has a slightly different calibration factor and the units were recalibrated periodically. The general form of the governing relationship is based upon Beers law:

$$-\ln \frac{I}{I_o} = kC^B$$

where:

I is the current reading for the SF_6 concentration present

I_o is the standing current (i.e., steady-state reading prior to sampling)

k is a constant

C is the concentration

and

B is the concentration exponent which is the item checked in the calibration procedure.

In determining air exchange rates, one measures concentrations at two times, C_t and $C_t + \Delta t$, where Δt is the time between tests. In this calculation the air infiltration rate is simply

$$A = \frac{1}{\Delta t} \ln \frac{C_t}{C_{t + \Delta t}}$$

and the k factor cancels out.

Throughout the test period, in a warm air heated home,* the AAIU was placed next to the furnace in the basement, monitoring the duct air. The samples are made upstream of the SF_6 injection point with the furnace blower operating throughout the tests to insure complete mixing. Such mixing is normally completed in less than 15 min. after injection.

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*Limited studies have been made in hydronic and electrically heated homes where auxiliary fans are required for tracer gas mixing.

One version of this method[12] involves collecting individual bag samples at selected times after injection of the tracer gas. In this way inexpensive, remote testing can be performed and the bags sampled and the infiltration rates determined under laboratory conditions.

(b) Pressurization/depressurization

Using a blower door device, developed as part of our home energy audit procedure,[13] the entire test house can be pressurized and depressurized according to well-established methods.[14-15] The blower door is shown in Fig. 3 and is designed to fit tightly into a wide variety of door frames. The procedure is then to provide a differential pressure between inside and outside the house under test. This pressure difference* is completely adjustable using a variable-speed axial fan motor (d.c. motor and solid-state control). In the step-by-step changes in differential pressure the fan speed is read simultaneously. Within a matter of minutes a pressure-flow rate profile is established for the house. The flow is determined from previous laboratory calibrations of the fan speed and flow rate. The technique used also allowed internal door closure to provide an additional plot of pressure vs flow rate and isolation of leakage sites.

In the case of individual house envelope components, such as doors and windows, the depressurization technique can be used together with a plastic cover tightly taped to the window or door frame (see Fig. 4). Depressurization is accomplished with a vacuum cleaner(suction side) and the flow is measured with a sensitive gas flow meter over a timed period. The differential pressure was measured as in the house tests using a sensitive pressure gauge. In order to minimize the chance for any leakage, other than through the house component under test, the pressure in the house was lowered to the component pressure level using the blower door. In this procedure no differential pressure existed between component and house interior; hence, even if a small opening developed along the taped plastic at the window frame edge or hoses, the leakage would be negligible. See Refs 16 & 20 for details of other similar studies.

C. HOUSE COMPLEXITIES AND PRESSURIZATION TESTS

Using the pressurization method, one is confronted with the problem of comparing leakiness from one house to the next. Kronvall[15] attempted to make such comparisons for a number of Swedish houses using the parameter Q/A (flow/surface area), and then derived a relationship between pressurization tests and natural air infiltration. One factor helping those comparisons was the high degree of similarity of newer Swedish homes as compared to those encountered in the United States.[17] For example, it is important to consider the basis for calculation of representative surface area and how zones communicate.

One factor that complicates house-to-house comparisons is the variety of heating methods. The use of ducting in warm air systems tends to provide a good means of communication between floors and often provides a flow path to the basement (or attic) depending on the actual duct routing in the house. The older floor furnace represents an even more severe case of zone-to-zone communication. In contrast, electrical resistance heating tends to provide the least flow communication between different zones. Hydronic systems cover a middle ground, but if pipes fit tightly through floors and walls, tightness can approach the electrically heated house.

The question of surface area can be quite complex in the variety of homes found in the United States. In the Southeast and West one finds a high percentage of slab construction;[17] hence, the leakage surface is considered to be simply the walls and ceiling above the slab (typical of Ref 14 and 15). Other areas of the country prefer basements, crawlspaces or a mixture of the two sometimes with slab construction involved as well. This complicates matters.

These construction features, heating methods and basement treatments are further complicated by side wall construction. During much of America's history, braced frame and balloon-type construction prevailed.[17] In many versions of these designs the walls are essentially open from basement to attic. Thus, when pressurizing or depressurizing such a house large volumes of air are drawn into the basement through these paths. Depending upon the degree of communication between basement and living space, the air infiltration can be directly affected. Refer to Table 2 and Fig. 5 for illustrations of the various effects. Looking first at the air exchange rate in Figures 5a and 5b, the inclusion of the basement is shown to improve the leakage performance of the warm air heated homes (Fe, Ha, TR(2) and La) and decrease performance in the hydronic heating home (Cr). The latter occurs because the Cr house has limited communication with the basement

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*Tests are made over a range of pressures up to 50 Pa or somewhat higher. Outside weather influences are evident at the lower pressures, $\sim$ 10 Pa, making comparisons difficult at such pressures which actually correspond more closely to the natural pressure differences.

and was shown to gain more in air changes than was offset by added volume. The warm air heated homes already communicated well with the basement so that the additional volume served to provide a lower air exchange rate.

When comparisons are made using the leakage parameter Q/A (the volume divided by envelope area) the relative positions of the houses is seen to change considerably (see Fig. 5 c,d). Whether the Twin Rivers townhouse is considered as an interior unit or as a detached house, where the party walls counted as part of the envelope, almost makes this identical floor space and volume house the best or the worst on the graph. In the case of house Cr, if the leakage were based upon the same envelope but the basement door were closed, then this house would fall to 11.3h^{-1} at 50 Pa, by far the best in the group. The question then becomes: should the envelope be ceiling plus walls down to the ground, or since the basement has been largely excluded by closing the basement door (in some cases it was even taped closed) should the floor surface then be included? Applied to house Cr the value would fall to 8.3 (if taped). Just by using this house as an example, it is easy to see some of the sources of confusion - confusion that would not be present using slab construction.[14 and 15]

D. PRESSURIZATION TEST RESULTS VS SWEDEN

A sample, including ten Twin Rivers townhouses and five detached houses, has been tested using the depressurization technique. (See Table 2.)

Fig. 1 indicates that the townhouses tested at 50 Pa experienced a ∿ 12.2 exchange rate per hour and detached houses ∿ 13.3. These air exchange rates are very high compared to what can be achieved in modern housing using well-sealed windows and doors and a continuous plastic vapor barrier. Swedish tract housing built during the seventies and employing plastic vapor barriers were found to provide exchange rates of 1-6.[14] The average value was 4.5 h^{-1}, or approximately one third the value found in the U.S. housing tested in this research.

If the leakage is related to the building envelope, $\frac{Q}{A}$, instead of the volume, the difference between the tested houses and modern housing in Sweden is still greater. The average value for the Swedish houses is 6.3 $m^3/m^2/h$, which is only one quarter of the same measurement in American housing 25.3 m^3/m^2h (average detached house in these tests). A Twin Rivers townhouse leaks 39.4 m^3/m^2h (or 22.8 m^3/m^2h if party walls are included).

However, it has been shown in two leaky houses that it is often quite simple to drastically reduce the air leakage while depressurizing is in progress. The reason is that in a leaky house there are often a number of larger openings, which are easy to find during a depressurization test. Normally, these are simple to block off. For example, the first house in which this depressurization retrofit was employed was the Twin Rivers townhouse. Prior to corrective action, the house leaked at a rate of 13.3 air exchanges per hour at 50 Pa (see Fig. 1 Sa-house). The house was examined under depressurization and efforts were concentrated on plugging all basement openings associated with bypass routes leading up into the attic. The post test reading was 8.7 h^{-1} at 50 Pa. This was a 35% reduction in air leakage, which should result in a major reduction in the natural air infiltration.*

In several townhouses the leakage sites had earlier been blocked off in a step-by-step process, without access to a blower unit. Four of those houses were depressurized after the retrofit was done and their average leakage rate (∿12h^{-1}) was then ∿40% higher than the leakage rate of the Sa-house. It has to be mentioned in this context that those six houses, with their average leakage rate of 12, have an average natural ventilation of 0.4 h^{-1}. Before retrofit the average ventilation was 0.7 h^{-1}.

The second retrofitted dwelling was an apartment. The before retrofit number was 24.4 h^{-1} (see Fig. 7). The same procedure as in the Sa townhouse was applied. Closing a bathroom closet door and covering a fireplace reduced the air flow to 19.7 h^{-1}. Taping windows changed the leakage to 17.4 h^{-1}. Taping the joint on bathroom closet door gave an additional reduction to 15.3. The last step was taping the water manifold door and the end result was 14.4 h^{-1}. This is a reduction from 24.4 to 14.4 h^{-1}, or a 40% reduction. The conclusion is that the rate of air exchange, as measured by depressurization, in a leaky house can readily be reduced 30-50%, (within the period of an hour if one were to judge by these tests). This leakiness level still falls short of such codes as the current Swedish standard(3.0 h^{-1} for detached houses after July 1978) and also brings

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*A calculation, using the model in Section E was made which showed a 50% (rather than 35%) reduction in natural ventilation. This was because of the change in the flow exponent, .68 to .72. This calculation was made assuming the same distribution of openings before and after retrofitting which is always open to question.

one face-to-face with the question of how tight is too tight, based upon internal air quality.

E. CALCULATION OF NATURAL VENTILATION FOR TR-HOUSES

In four retrofitted townhouses at Twin Rivers the air infiltration has been measured with both the pressurization technique and the tracer gas technique.* Data from tracer gas measurements[3] was used to determine the natural ventilation. This was done for a typical winter day in New Jersey ($t_i = + 20°C$, $t_o = + 3°C$, wind at 10 meters height = 4 m/s). Pressurization tests were used to calculate the air leakage characteristic. The houses had an average overall leakiness of 11.8 air changes per hour at a 50 Pa pressure difference inside-outside. The air leakage for a variety of pressure differences was plotted for every house. This gave as a result an equation of the form:

$$Q = C\,(\Delta P)^{\beta}$$

Wind pressure was calculated from wind tunnel test results (Section A). This was done for a wind speed of 4 m/s at 10 m height. A correction was made for height, i.e., the wind speed at a height equal to that of the building (7.25 m) was used. The terrain was regarded as "country with scattered windbreaks"[4] or "urban" depending on the location of the house compared to other houses at Twin Rivers. In addition to the calculated wind pressure the pressure caused by the temperature difference was taken into account. This combined pressure difference was then used to calculate the natural ventilation for the four townhouses.[6] The openings were assumed to be evenly distributed around the entire house except on the party walls which were assumed to have no openings. All four townhouses were interior units.

The average natural ventilation for the four townhouses was calculated to be 0.88 h^{-1}, or 2.4 times the average measured value ($0.37h^{-1}$) using tracer gas. Several reasons can be sited for this occurance. One is that the openings in any real house are distributed in a different manner than the uniform distribution assumed here and that furthermore no attention has been paid to bypasses going from the basement up into the attic. Another important factor is that the microclimate, wind speed and temperature <u>at the house</u>, isn't known accurately enough for these computer calculations which were based upon 36 surface locations on the wind tunnel house model. In all, the following data had to be supplied to the computer in order to calculate the air infiltration rate from depressurization data: (1) the pressure distribution as determined from wind tunnel tests, (2) matrix size, (3) dimensions of the townhouse (4) wind speed (5) temperature difference inside-outside (6) air flow when depressurizing/pressurizing at 50 Pa, and (7) average flow exponent for the entire building envelope.

One point has to be made in this context, to mention only the air leakage at 50 Pa as characterization of a house isn't sufficient. The flow exponent has to be specified as well. For the townhouses, the exponent is in the range 0.59 - 0.72. Fig. 8 illustrates the air leakage characteristic for three houses, all with the same leakage at 50 Pa, but with different flow exponents. For an unprotected townhouse under average N.J. winter conditions,the calculated pressure difference is approximately 5 Pa. The average value for the calculated houses is $\sim$ 4 Pa. If this pressure value is used, the natural ventilation would increase by (1.25 - 0.8)/0.8 = 55% in changing the flow exponent from 0.7 to 0.5. However, these two houses have the same air leakage at 50 Pa. The flow exponent differences are an area of current investigation.

F. IMPORTANCE OF LOCATION OF OPENINGS

To find out how the natural ventilation changes when openings are moved from the top to the bottom and from the front side to the back side on a house, a preliminary test series was run in a test-box.** The box (2.4 x 2.4 x 3.8 m) was built on top of a flat roof of a 2-story building. Four "windows", each consisting of six 1-in.-diameter openings, were built into the test-box, two on the front side and two on the back side. The natural ventilation was measured with twelve of 24 vents open.***

The highest ventilation was achieved with openings low on the windward side and high on the leeward side (for numbers, see Table 3). Both wind effects and the stack effects aid in ventilating the box in this case. Ventilation driven by temperature differences causes the air to come in through the lower openings of the wall and leave through the higher openings. In case two the

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* These townhouses are listed in Fig. 1.

**Final weather metering equipment had not been installed at the time of the tests.

*** In this simulation, based upon pressurization, the test box was operated with 50% leakage through the 12 vents, 25% leakage around the door, and the remainder through small openings in the box envelope.

stack intake is on the windward side, which means that the wind effect is helping the temperature effect in driving the air into the box. On the leeward side the temperature and the wind effect together suck air out of the box.

The lowest ventilation was achieved with all openings on the windward side (case four). In this case the wind tries to push air in through all openings. There is, however, no outlet for the air. And depending upon the evenness of the pressure, the wind effect can cancel out. The temperature will thus be the main driving force in this case.

The other cases lie between those mentioned above. For the case with openings high on the windward side and low on the leeward side (case 3), there can be a set of weather conditions where the effects essentially cancel each other out and hence the ventilation will be very low.[1]

The test-box study can be used to explain "airing", i.e., to explain what happens when you open various windows in an actual house. Natural ventilation has been measured for different window openings in an instrumented Twin Rivers townhouse (interior unit). Fig. 9 shows the natural ventilation if only windows on the 1st floor [5[or only windows on the 2nd floor [6] are open. This gives a relatively low ventilation, which corresponds to the results in the test box. If one window on the 1st floor and one window on the 2nd floor were open [3] natural ventilation is increased, as was shown in the test box. Windows open on all floors [1] give a much higher ventilation; however, this was not shown in the box since, unlike the house, total open area remained fixed.

An additional survey[6] was made using the calculation model of a TR-house, mentioned earlier. In all calculations for a TR-house it was assumed that the number of openings was constant. The only difference between the cases is that the openings are located in different ways. All studied cases would give exactly the same air leakage characteristic when using the blower-unit. The overall leakage was assumed to be the following: $Q/A = 1.87 + \Delta p^{0.7}$ which gives 29 $m^3/h\ m^2$ at 50 Pa. In each case, three wind-temperature conditions are considered: (1) a wind of 4m/s perpendicular to the front side and an inside temperature of + 20°C, and an outside temperature of + 3°C; (2) the same wind with zero temperature difference; (3) the same temperature difference with zero wind.

Six different patterns of openings were studied (see Fig. 10):

(1) Openings evenly located around the whole house .

(2) Openings evenly located on the front and the back side and roof absolutely tight.

(3) Openings only on the lower part of the walls and on a limited area at the center of the roof.

(4) Openings evenly around the whole house, except that there are no openings in the area between 1.2 m and 4.2 m on the front side.

(5) Openings only on the lower part of the front wall and on the upper part of the back wall.

(6) The same as (5) but with the wind coming from the backside.

When considering the combined effect of wind and temperature difference, the highest ventilation is for cases (2) (1.29 h^{-1}) and (5)* (1.30 h^{-1}); the lowest ventilation is for case (4) (0.70 h^{-1}). This is assumed to be the most realistic case.

The cases with ventilation caused only by wind show a maximum of 1.35 h^{-1} for case (6) and a minimum of 0.6 h^{-1} for cases(3) and (4). This latter result may seem surprising since one might expect a strong Bernoulli suction at the peak of the roof. The case assumed to be the realistic case (case 1) has 0.93 h^{-1}.

The last cases are those with ventilation caused only by temperature. The maximum ventilation is 0.52 h^{-1} for case (3) and the minimum ventilation 0.30 h^{-1} for cases (2), (5) and (6). Case (1) has 0.38 h^{-1}.

The relations between maximum and minimum ventilation for the three wind-temperature conditions are as follows: 1.30 / 0.70 = 1.87, 1.35 / 0.60 = 2.25, and 0.52 / 0.30 = 1.73. The results also show that the wind is a dominant factor under test conditions such as the ones used here (see case (2) and case (6), Fig. 10). Again, remember that all of the modeled houses would give the same air leakage if tested with a blower-unit. The model tests made here confirm that the case with openings only on the lower part of the walls and on the top of the roof has the

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* Which corresponds to the results in the test box.

highest ventilation caused by temperature, and that the case with openings only on the windward and the leeward side has the highest ventilation caused by wind. In one case the ventilation caused by wind was higher than the ventilation caused by the combination of wind and temperature; i.e., the two effects counteract each other (see case (6) Fig. 10).

All calculations show that the location of openings could be of great importance. Therefore, such calculations should be done for different houses, temperatures, winds and flow exponents. With sufficient data on typical homes one could search for the model of openings which is closest to a real house. The retrofit experience at Twin Rivers viewed from infiltration results would tend to indicate a preference to models which emphasize openings high and low in the townhouse (3). For a fixed overall leakiness (as measured by a blower unit) it appears that the location of openings, under reasonable assumptions, could affect natural ventilation rates by a factor of two or more. This is shown by the TR-model and the test box.

The results mentioned here indicate that when a house is to be tightened, it is quite important where this is done on the building envelope. This question was studied in a 1940's house (see Table 2, Fe house). Windows were weather stripped which reduced the average natural ventilation under winter conditions by 10% (tracer gas test). The house leakiness (using the blower door), however, was reduced ~ 15%. The house in question is fairly well protected, which implies that the main driving force for the ventilation is the temperature difference. Important for the reduction in natural ventilation is then how close to the neutral zone the tightened openings are located.

In this case, it should be possible to regard the weather stripped windows as being close to the natral zone, which means that windows are less important than what a blower test indicates.

CONCLUSIONS

This paper outlines what problems one might have in trying to estimate the natural ventilation knowing the air leakage characteristics as measured by the pressurization method, e.g. using the blower door. The physical mechanisms for ventilation, which are the basis for the analysis, are wind and temperature (stack-effect). The basic equation used in the calculations is the equation for air flow through an opening driven by a pressure difference. A computer model was derived for infiltration prediction of the whole house. The input data were: air leakage characteristic as measured by a blower unit, temperature, wind speed (corrections were made for the roughness of the terrain) and wind pressure coefficients as measured in a wind tunnel. The calculated values of air infiltration for each of four Twin Rivers townhouses were shown to be 2.4 times higher than that measured. The most likely sources of error are a lack of knowledge or accounting for the following factors:

microclimate
building proportions
location of openings
bypasses
internal flow resistance

For example, a change in the location of openings was shown to be able to increase the natural ventilation by 100% or more. These conclusions were the result of measurements in a test box and computer calculations for a Twin Rivers townhouse. An analogy with the test box study was made with the opening and closing of different windows in an instrumented house which basically showed the same results.

In the actual leakage measurements, the tracer gas technique and the pressurization technique for whole buildings and individual components were used. When evaluating the results from a pressurization test the question arises how to normalize these results. Should basement or crawl space be included in the volume when using this factor for normalization? What should be considered as the building envelope when relating the air flow to this factor? Depending on how this is done, the houses will have a different air leakage characteristic relative to each other.

A major difference in house leakiness, as determined by the pressurization technique, was shown to exist between modern Swedish housing and American housing represented by Twin Rivers townhouses and a variety of older homes. This difference was found to be of the order of 3 or 4 times. However, it was shown in two houses that it is fairly easy to accomplish major tightening by blocking off openings in a leaky house during depressurization. In this way the air leakage was reduced by 35-40%. In one test house built in the 40's it was shown that weather stripping reduced the natural ventilation by 10% (measured by tracer gas) and reduced depressurized air exchanges by 15%. This is further indication that when retrofitting a house it is quite important where the house is tightened, and that a pressurization test doesn't necessarily give the same importance to various openings and how they influence air infiltration under natural conditions.

More research is needed in order to better understand such factors as the microclimate and how the openings are distributed around a building. This will make it possible to do a more accurate calculation of the true ventilation in a house which has been assigned an air exchange value using the pressurization technique.

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Table 1. Factors for determining mean wind speed at different types of terrain from Meteorological Office wind speed U_m measured at 10 m in open country (see ref. 4)

Terrain	K	C
Open flat country	0.68	0.17
Country with scattered windbreaks	0.52	0.20
Urban	0.40	0.25
City	0.31	0.33

Table 2. Test House Information

House	Sa	Sp	Mu	Mi	Ka	Re	Wa	He	Ta	Har	Me	Fe	La	Ha	Cr
Year of Const.	1972 - 1973		-	-	-	-	-	-	-	-	1958	1947	1972	1959	1955
No. of storys	2	2	2	2	2	2	2	2	2	2	2	2	1-2	1.5	1
Town House	T	T	T	T	T	T	T	T	T	T					
Det. House											D	D	D	D	D
Crawl space											C		C	C	
Basement	B	B	B	B	B	B	B	B	B	B		B	B		B
Vol. excl. C or B	336.5	-	-	-	-	-	-	-	-	-		358	511	426	250
(m^3) incl. C or B	494.4	-	-	-	-	-	-	-	-	-	548	466	591	580	525
Floor area (m^2)	138.3	-	-	-	-	-	-	-	-	-	183	152	210	196	109
Bldg.envl. (m^2) excl. C,B	217	-	-	-	-	-	-	-	-	-		329	470	464	310
incl. C,B	153.6	-	-	-	-	-	-	-	-	-	295	268	334	344	255
Nat. Vent.* (air exch. / hr.)	0.38					0.31	0.36	0.42				0.82 (0.74)			
Air leakage at 50 Pa (depressurization)															
Air exch. incl. C,B	13.3 (8.7)	12.6	15.2	11.9	13.4	9.8	12.6 (11.9)	11.3	10.8	11.2	14.4	16.6 (14.2)	12.2 (11.7)	13.5	13.0
Retrofit** A,B,C,D	AB*** D	ACD	ACD	ABCD	ABCD	ABCD	BCD	ABCD	ACD	ACD					

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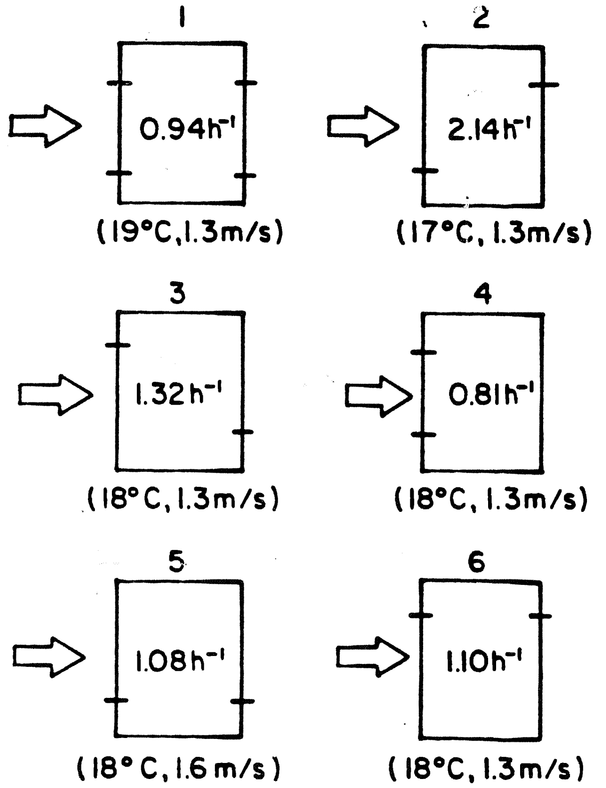
* Natural ventilation is given for a temperature difference of 17°C and a wind speed of 4 m/s.

** Retrofit A = attic insulation to R-30 (incl. plugging off the openings along party walls)
B = caulking and sealing windows and doors
C = insulating warm air distribution system in the basement
D = plugging off the shaft around the furnace flue in attic

*** Done by private company

Table 3. Natural Ventilation For A Test Box (temperature difference inside/outside, wind speed)



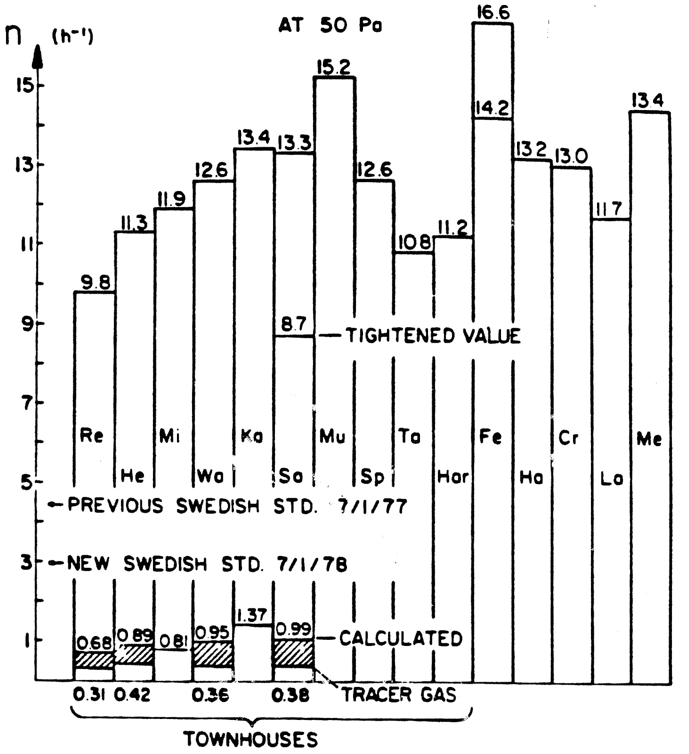


Fig. 1 Number of air exchanges at 50 Pa for individual houses

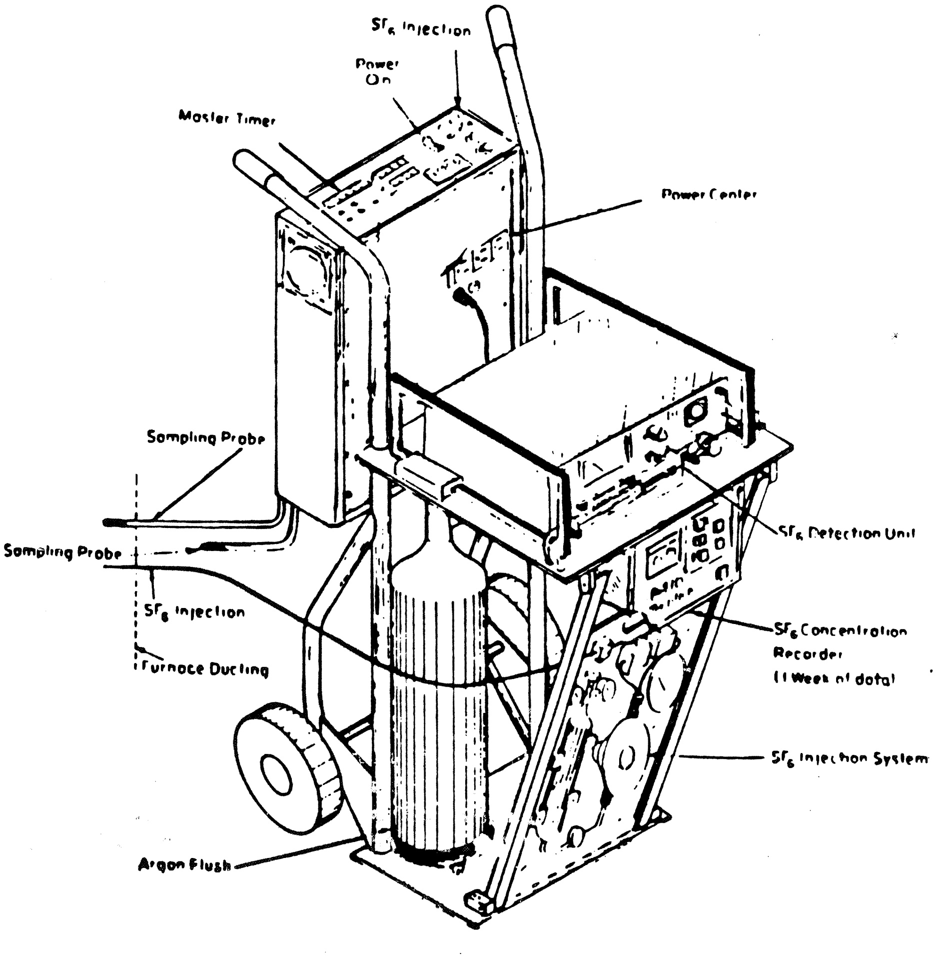


Fig. 2 Automated air infiltration unit

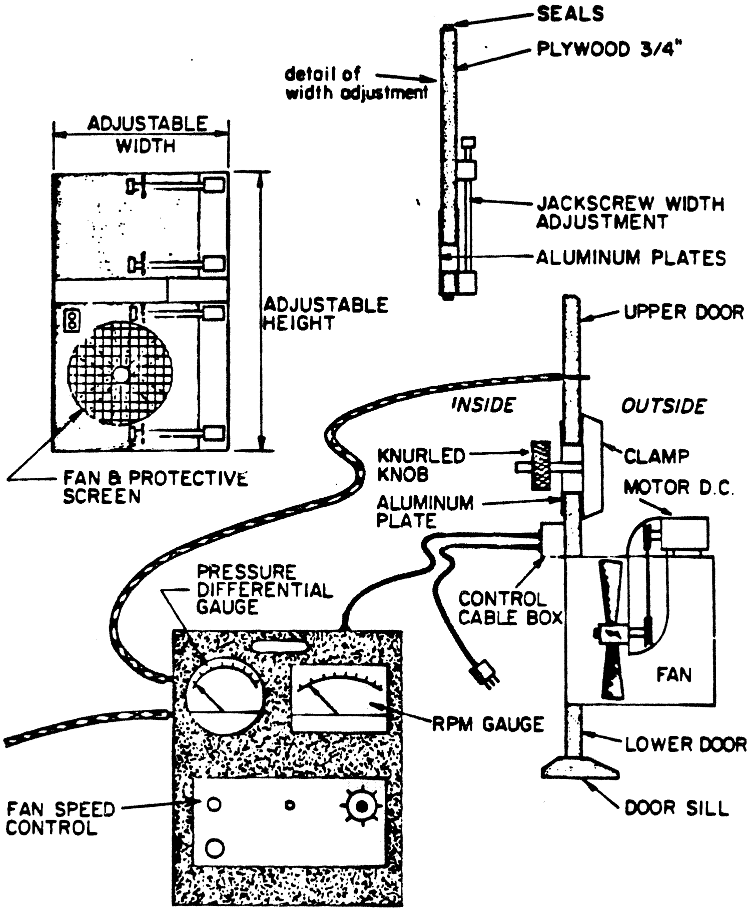


Fig. 3 Blower door and control panel

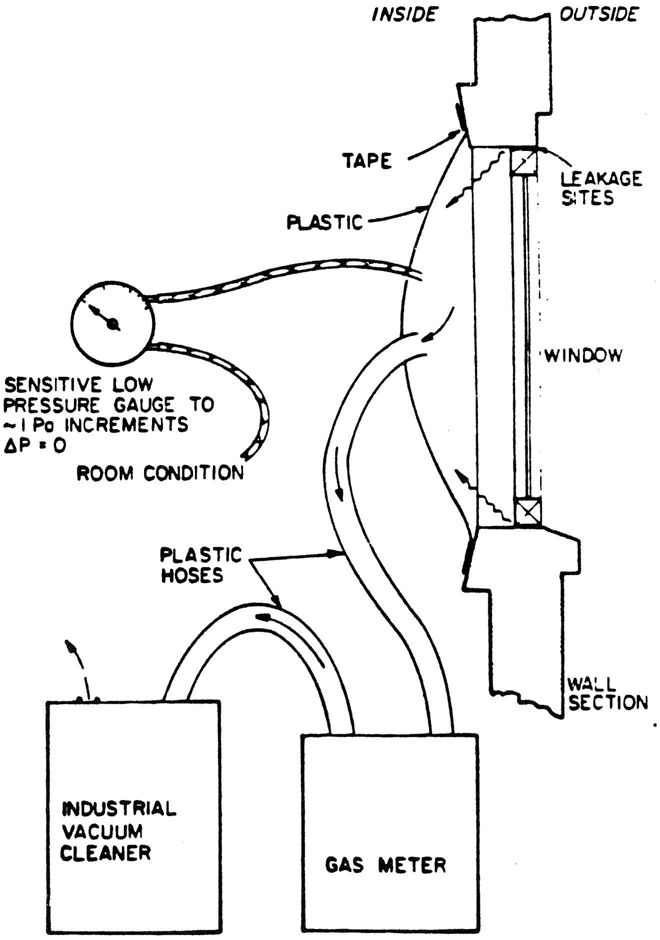


Fig. 4 Test arrangement for window leakage measurements

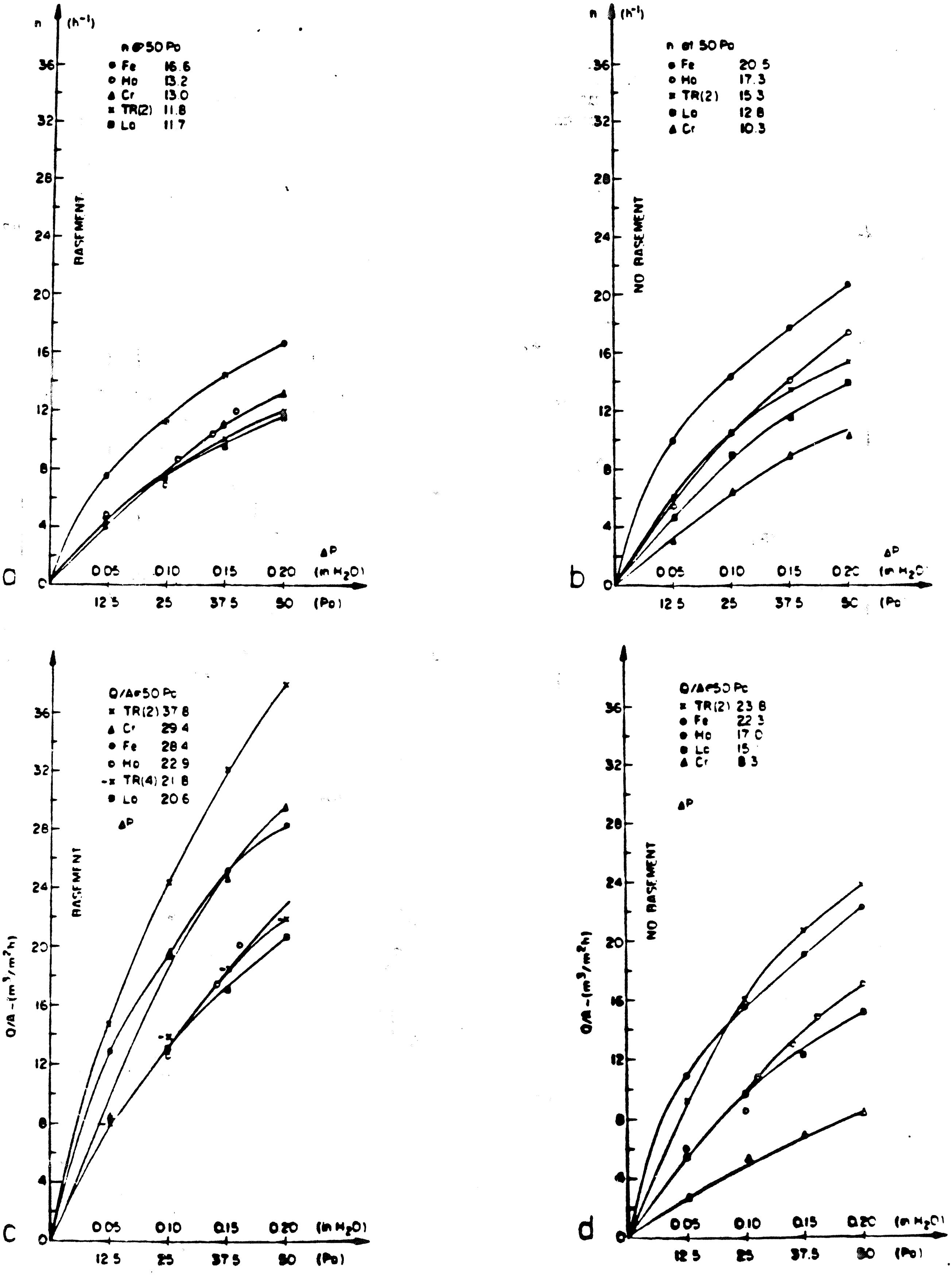


Fig. 5 Air leakage as a function of pressure difference

--number of air exchanges incl. (a) and excl. (b) basement/crawlspace

--related to building envelope incl. (c) and excl. (d) basement/crawlspace

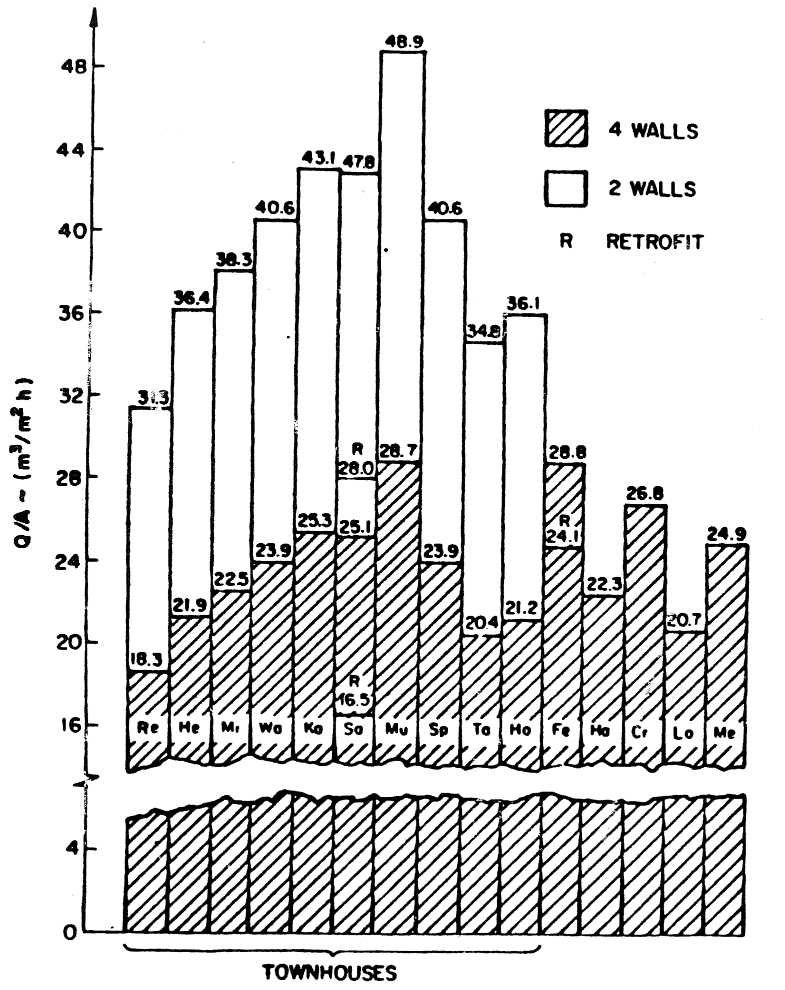


Fig. 6 Air leakage at 50 Pa related to building envelope (basement or crawl-space included)

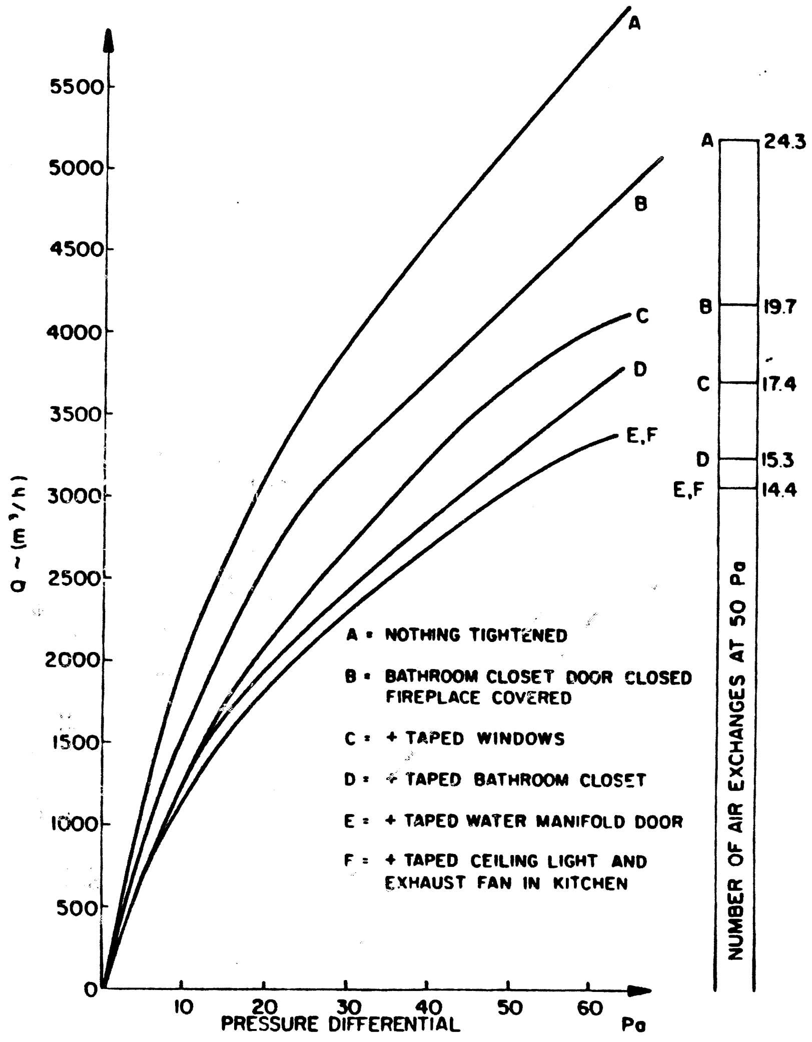


Fig. 7 Air leakage as a function of pressure difference for an apartment

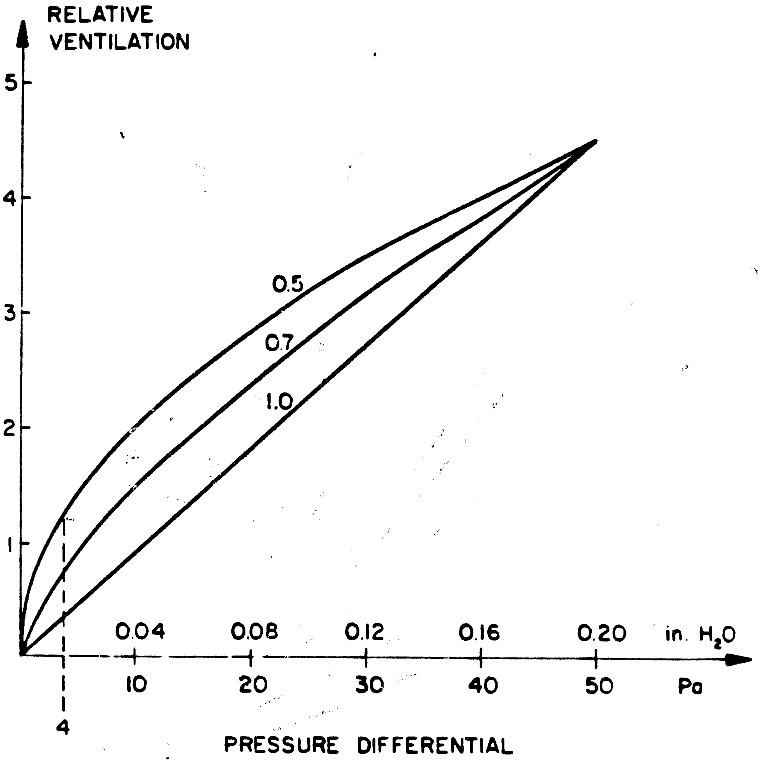


Fig. 8 Relative natural ventilation for different flow exponents as a function of pressure difference

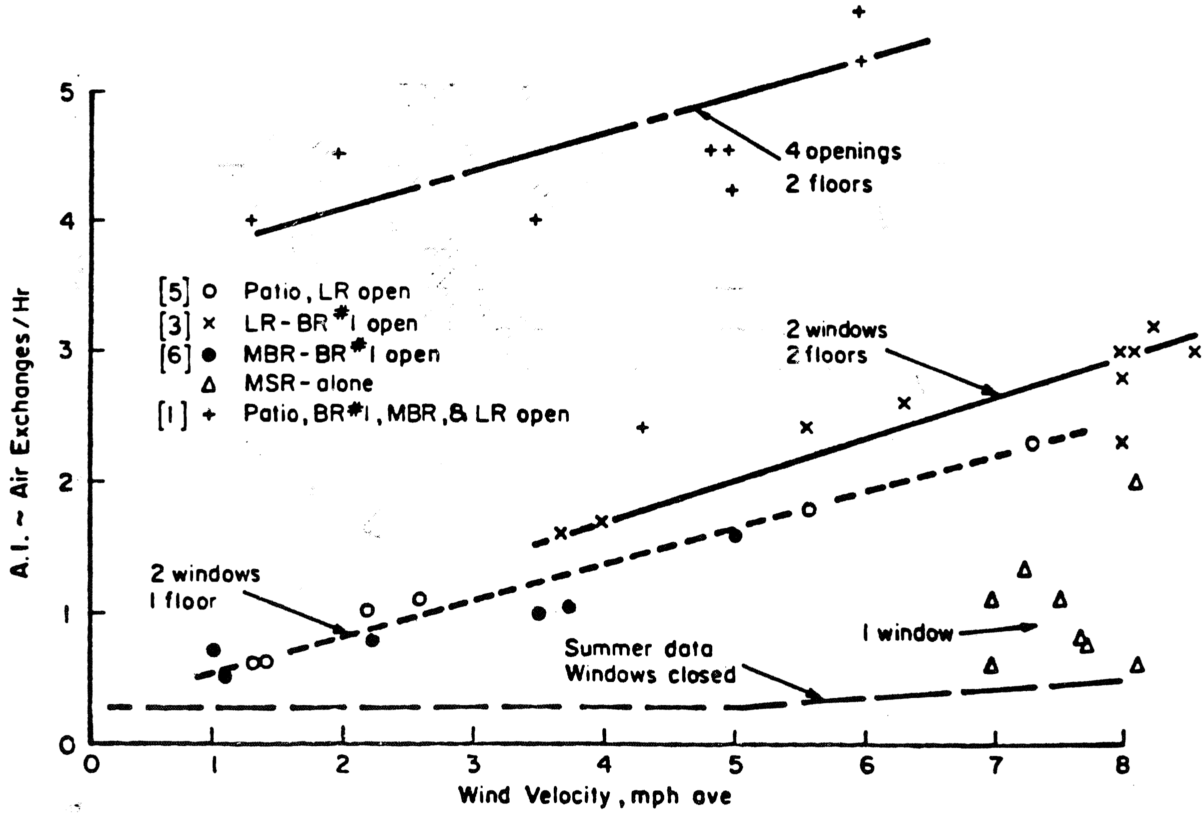


Fig. 9 Influence on air infiltration of window openings (house #1)

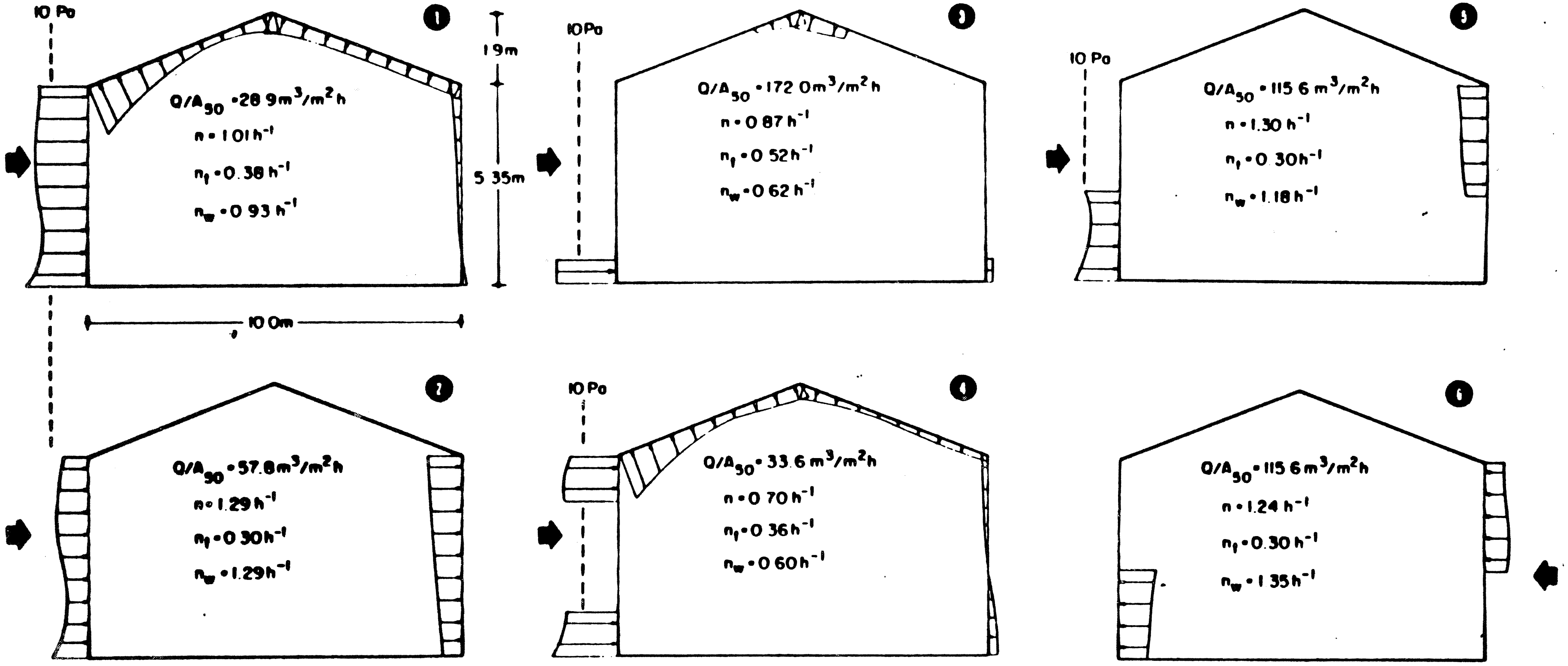


Fig. 10 Natural ventilation for a model of a Twin Rivers townhouse

n_t = ventilation caused by temperature, n_w = ventilation caused by wind,
n = combined ventilation, Q/A_{50} = air leakage through building envelope (area with openings) at 50 Pa. Shown is the pressure difference inside-outside for combined ventilation.