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Air Leakage in a Building at Low Pressures Using an Alternating Pressure Source

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ABSTRACT

Many models have been devised to correlate air infiltration in buildings with weather parameters. A particularly promising strategy is to predict the air flow through the building envelope from surface pressures which, in turn, are predicted from measured weather parameters. Because of the interference of the weather conditions, it is difficult to measure the pressure-flow relationship in a manner that is valid for the low surface pressures which have been observed to drive infiltration. Conventional techniques rely on steady-state (DC) fan pressurization or depressurization of the structure, but DC flow measurements are unreliable at pressures less than 5-10 Pa. Since the pressures that drive infiltration are usually found in this range, direct measurements of air leakage vs. pressure in this low-pressure region would be useful. This paper reports low-pressure measurements of the leakage function using an alternating (AC) pressure source with variable frequency and displacement. Synchronous detection of the indoor pressure signal created by the source eliminates the noise due to fluctuations caused by the wind. Good agreement is seen between AC and DC leakage results in pressure regions where the results can be compared. The low-pressure leakage values made with the AC source suggest that the air flow is dominated by orifice flow effects down to pressures less than one Pascal. An extended version of this contribution is available as Lawrence Berkeley Laboratory Report #9162.[3]

Keywords: Pressurization, infiltration, low pressure leakage, ventilation

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INTRODUCTION

Conceptually, infiltration (air leaking through openings in the shell of a building due to weather-induced pressures) is a simple process. The hydrodynamic details of the flows for real buildings, however, are complex and make the problem of calculating or modeling infiltration difficult.

Infiltration models are useful primarily in performing energy load calculations either by simple steady-state procedures or by dynamic computer programs. However, model development also contributes to our basic understanding of infiltration which better enables us to develop both the instrumentation required for measurement and procedures to reduce infiltration in buildings.

Historically, infiltration models have developed slowly. The simplest and perhaps oldest calculation model assumes that infiltration is constant in time, i.e., independent of outside weather conditions. An energy load calculation then requires information only about the steady infiltration value for a structure and the total number of degree-days in order to calculate the load.

The next level of modeling uses field measurements of infiltration values and weather to find an empirical relationship between infiltration, wind speed and indoor-outdoor temperature differences. This multiple linear regression technique produces a result which can predict infiltration for a structure when the outside weather is known; however, it is not a good predictor of infiltration for structures other than the one used to develop the regression. Furthermore, data have to be collected during a wide variety of weather conditions to assure statistical significance.

Physical models of infiltration are based upon a different set of assumptions and measurements than those described above. In these models, pressure differences across openings in the building shell cause the air flow through the openings which is identified as infiltration. Measurements of (a) the leakage of the shell and (b) surface pressures (or weather parameters inserted into a model to predict the surface pressures) are combined to compute the air flows through the openings and thus determine the amount of infiltration.

Leakage measurements are generally made by applying a steady pressure to the building shell using a variable speed fan and measuring the flow through the fan (which is assumed equal to the flow through the leaks in the shell) to determine the pressure-flow characteristics of the structure. These measurements are most reliable when made at pressures which are large compared to the weather-induced differential pressure already present. Measurement ranges typically used extend to at least 50 Pascals; since ambient surface pressures are usually less than 5 to 10 Pascals, so it is leakage at low pressures (-10 Pa $< \Delta P <$ 10 Pa) that is needed to model infiltration.

It is tempting to fit a curve to the high pressure leakage function in order to extrapolate to the low pressure region of interest. Many forms of the equation have been used, but two of the most typical ones are:

$$Q(\Delta P) = A\,\Delta P + B\,\Delta P^{1/2} \tag{1}$$

and

$$Q(\Delta P) = C\,\Delta P^{n} \tag{2}$$

where:

Q is the leakage [m^3/hr]

ΔP is the applied pressure [Pascals]

A, B, C, n are empirical parameters.

Any attempt to use these forms, however, will fail because the regression constants (A,B,C,n) themselves are functions of pressure. If the leaks in the building shell were all simple cracks, we would see a flow characteristic dominated by linear leakage at low pressures ($Q \simeq \Delta P$) and quadratic leakage at high pressures ($Q^2 \simeq \Delta P$). [1] The transition between low and high pressures depends critically on the crack geometry; since we are considering a collection of cracks of many dimensions as well as orifices whose edges can be both sharp and broad, the transition between low-and high-pressure flow will be indistinct and blurred in any real structure.

Because of the difficulty of measuring the low-pressure portion of the leakage function and the inherent uncertainty associated with extrapolating from high-pressure to low-pressure measurements, a technique is needed to measure the important low-pressure leakage. We call our technique AC pressurization because it uses an alternating pressure signal, as opposed to the standard DC pressurization which uses a constant pressure drop across the envelope. The technique is an extension of the work of Card et al. [2]

The AC technique allows accurate measurements of the low-pressure leakage function because it is insensitive to noise induced by weather. The pressure signal used in AC pressurization is dominated by one well-known frequency, while the pressures caused by wind have a broad range. Accordingly, the amount of interference caused by the weather at the frequency of interest will be small. Thus, the complete leakage curve can be measured using AC pressurization.

AN OVERVIEW OF AC PRESSURIZATION

AC pressurization measurements are obtained by changing the volume of the structure and measuring the pressure response due to this change. By selecting only the pressure response that is at the same frequency as the volume drive (i.e., synchronous detection) we eliminate the noise associated with DC measurements. This allows measurement of the leakage at very low pressures.

The volume is changed using a large piston and guide assembly installed in place of an existing exterior door (cf. Fig 1). The piston is driven in the guide using a motor/flywheel assembly that allows adjustable displacement and frequency control. The piston rides on sliding teflon seals to prevent leakage and reduce drag. The pressure is monitored by means of a differential pressure sensor with 0.1 Pa resolution and a full-scale reading of 70 Pa. Leakage measurements reported in this paper were made at frequencies between 6 and 60 rpm.

If the structure is rigid we can use the measured volume drive and pressure response to calculate the airflow through the envelope during AC pressurization. If there were no leakage, the change in pressure would be precisely determined, given the volume of the structure and the displacement of the piston. Therefore, any deviation from this predicted pressure can be attributed to leakage through the envelope. The continuity equation allows us to calculate exactly how much air leaks out for a given drive. Then this leakage value can be used to calculate the air flow for a given (constant) external pressure.

In general, the structure will not be rigid. Therefore, when the pressure inside the structure changes, the envelope will flex in response. By assuming that the flexing is proportional to the differential pressure across the shell we can correct for this effect.

The air flow through the envelope caused by the movement of the piston results in an increase in the infiltration. If the piston movement is regular, the change in infiltration can be measured by standard tracer gas methods. This measurement has the potential of being an independent check on the leakage measurement.

THEORY

In DC pressurization the calculation of the leakage is straightforward. Because the applied pressure is constant and small compared to ambient pressure, we can treat the air inside the structure as incompressible. If we assume that the pressure applied to the structure is greater than any weather induced pressure, the continuity equation gives the leakage.

$$Q(\Delta P) = F_{fan}(\Delta P) \tag{3}$$

where:

ΔP is the pressure [Pa] across the envelope,
Q is the airflow [m^3/hr] through the envelope at pressure ΔP and
F_{fan} is the air flow [m^3/hr] through the fan

The flow through the fan is that flow necessary to keep the pressure drop across the building envelope constant; it is therefore a function of the leakage of the structure.

In AC pressurization the calculation of the leakage is not as simple. The continuity equation must take into account both the effect of the compression of the air as well as the change in the volume of the structure with our drive. Taking these two effects into account we obtain a different continuity equation.

$$Q(\Delta P) = -\frac{dV}{dt} - \left[\lambda + \frac{V_o}{\gamma P_a}\right]\frac{d(\Delta P)}{dt} \tag{4}$$

where:

Q and ΔP are air flow and pressure as above,
dV/dt is the time change in volume of the structure [m^3/hr],
λ is the flexing constant of the envelope [m^3/Pa],
V_o is the volume of the structure [m^3],
γ is the ratio of specific heats of air (1.4),
P_a is the atmospheric pressure (1.013×10^5 Pa) and
$d(\Delta P)/dt$ is the time change in internal pressure [Pa/hr]

The term in brackets in eq. 4 is the effective capacity of the structure. It contains two parts: the first part accounts for the flexing of the envelope when a pressure is applied to it; the second part is due to the compressibility of air and depends only on the volume of the structure and fundamental constants.

The equation above can be used to calculate the air flow through the structure, given the change in volume and associated change in pressure. However, the quantity of interest is the steady-state flow associated with a steady-state pressure. In order to calculate this flow, we must introduce a model of leakage to relate the flow to the pressure difference across the envelope.

The simplest model assumes flow to be linearly proportional to the pressure difference.

$$Q(\Delta P) = L_o \, \Delta P \tag{5}$$

where:

L_o is the leakage constant[m^3/hr-Pa].

This model would be adequate if the flow of air through the building envelope were dominated by laminar viscous flow. Because of the complexity of this process, however, the flow is likely to be a mixture of viscous and turbulent flows which destroys the linearity of the model.

To account for this effect, we allow the leakage constant to become dependent on the applied pressure thus making it a leakage function ($L(\Delta P)$). The flow equation then becomes,

$$Q(\Delta P) = L(\Delta P) \, \Delta P \tag{6}$$

where:

$L(\Delta P)$ is the leakage function[m^3/hr-Pa].

Even though the form of the leakage function is not known, we do know that there are physical restrictions on its behavior. The function must be slowly varying and monotonically decreasing as the pressure increases. Ideally, the leakage function should be independent of the sign of the applied pressure, but it is frequently observed that the airflow may be larger on pressurization than on depressurization (or vice versa). To account for this difference and still maintain the symmetry of the leakage function, we introduce an asymmetry constant.

$$Q(\Delta P) = \left[L(\Delta P) \; (1 + \alpha \, \Delta P) \right] \Delta P \tag{7}$$

where:

α is the asymmetry constant[Pa^{-1}] and

$L(\Delta P)$ is an even function of the applied pressure[m^3/hr-Pa].

The effect of this asymmetry term is to cause a DC offset in the internal pressure. If the structure has greater leakage on depressurization than pressurization, the internal pressure averaged over many cycles will be higher than the average external pressure.

Using eq. 7 as the defining relation for the leakage function, we can compute its value as a function of pressure from measurements obtained using the AC pressurization source. The calculation procedures and measurement technique are summarized briefly below; a more detailed description is contained in the report of Sherman, et al. [3]

The leakage function is evaluated as a function of pressure. The equivalent DC pressure assigned to a particular measurement is the root mean square of the fluctuating pressure obtained when the house is driven at an angular frequency, w, and a volume displacement V_d. A complete expression for the leakage function is:

$$L(\Delta P_{DC}) = \frac{w}{(1 - \alpha^2 \Delta P_{AC}{}^2)} \sqrt{\left[\frac{V_d}{\Delta P_{AC}}\right]^2 - \left[\lambda + \frac{V_o}{\gamma P_a}\right]^2} \qquad (8)$$

where:

ΔP_{DC} is the equivalent DC pressure [Pa]
w is the angular frequency of the drive [hr^{-1}]
α is the asymmetry parameter
ΔP_{AC} is the amplitude of the (AC) pressure response [Pa]
V_d is the amplitude of the volume displacement [m^3]
λ is the flexing constant [m^3/Pa]
V_o is the normal structure volume[m^3]
γ is the ratio of the specific heats of air and
P_a is the normal internal pressure (1 atm.)

Knowledge of the leakage function can be used to compute the effective leakage area or the effective open area of the structure. [4] These latter values are often central to models for predicting infiltration.

EXPERIMENTAL PROCEDURE

The experiments described below were made in our research house in Walnut Creek, California. The house is a single-story ranch-type house of wood frame construction with a volume of $230m^3$ and a floor area of $100m^2$. There is a fireplace and a forced-air heating system with ductwork in the attic and crawl space.

Pressure Source: The source of the pressure signal is a large cross-section ($\simeq 1m^2$) rectangular piston which moves in and out of the shell through a suitably sized guide (cf. Fig 1a). The guide is installed in an exterior door of the test structure. The guide is made of plywood and has teflon seals all around it to minimize both friction and air leakage through the guide.

The piston is connected via a connecting rod to a light flywheel. The diameter of the flywheel is about 0.5m; there are nine different holes in the flywheel to allow for different displacements of the piston during a drive stroke. The maximum displacement peak-to-peak is about 0.3 m^3.

The flywheel is driven through a gearbox by a variable-speed 3/4 hp motor. With the current arrangement of motor, gearbox, piston and guide, the frequency of oscillation can be varied between 2 and 250 rpm.

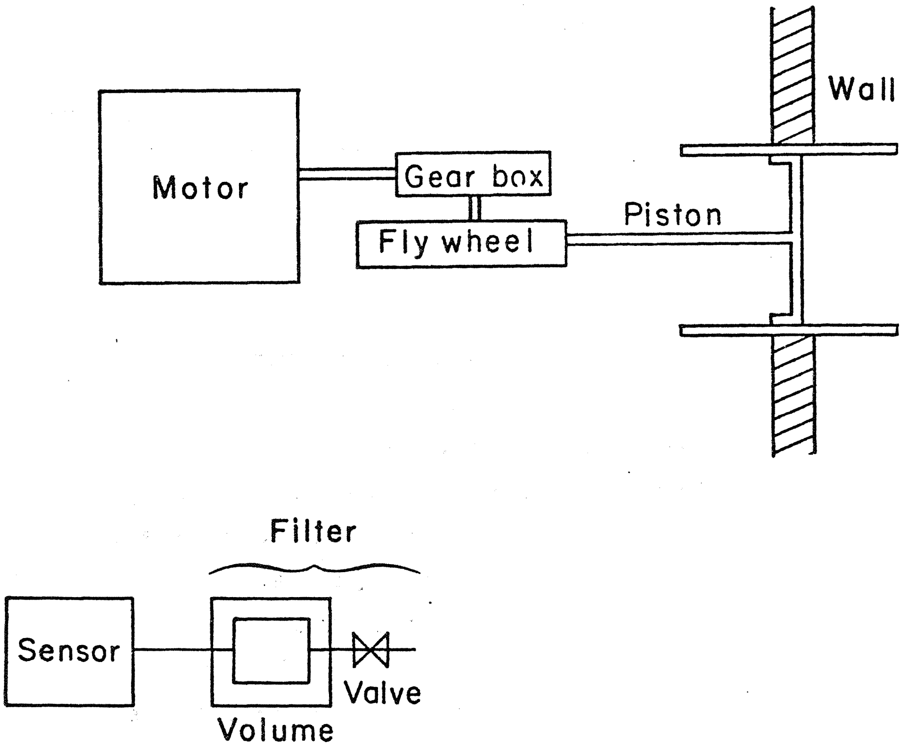


Figure 1. Sketch of experimental set-up and apparatus.
Fig 1a is a schematic of the piston motor and flywheel assembly. The piston is driven by a shaft connected to an 18 inch diameter flywheel that is driven through a gear box by a variable speed motor.
Fig 1b is a schematic of the pressure sensor and physical filter. The reference end of the differential pressure sensor is connected to a thermally insulated volume that has a high resistance leak in it. This volume and leak combination is a low pass filter with a time constant of roughly 5 minutes. Thus the reference end of the pressure sensor is at the average interior pressure.

<u>Pressure Detection:</u> The pressure response of the envelope is measured with a differential pressure sensor whose range is ± 70 Pascals. The reference end of the pressure transducer must be at a constant pressure in order to measure the pressure response of the system; however, if connected to the outside, a

large amount of noise is introduced due to the wind. Accordingly, rather than use the outside as our reference pressure, we used the time-averaged interior pressure. We built a low-pass filter that responds to slow pressure drifts but does not respond to high-frequency fluctuations (i.e. both weather and the pressure response due to the piston). The filter consists of a volume and a resistance: the volume is a large brass cylinder of about 3 liters and the resistance is a micrometering valve (cf. Fig 1b).

Data Acquisition and Analysis: Only two quantities are measured during the course of the leakage experiment: the time-dependent pressure and the frequency. The stroke of the piston is an experimental parameter that may be adjusted; the quantities V_o, P_a and γ are known.

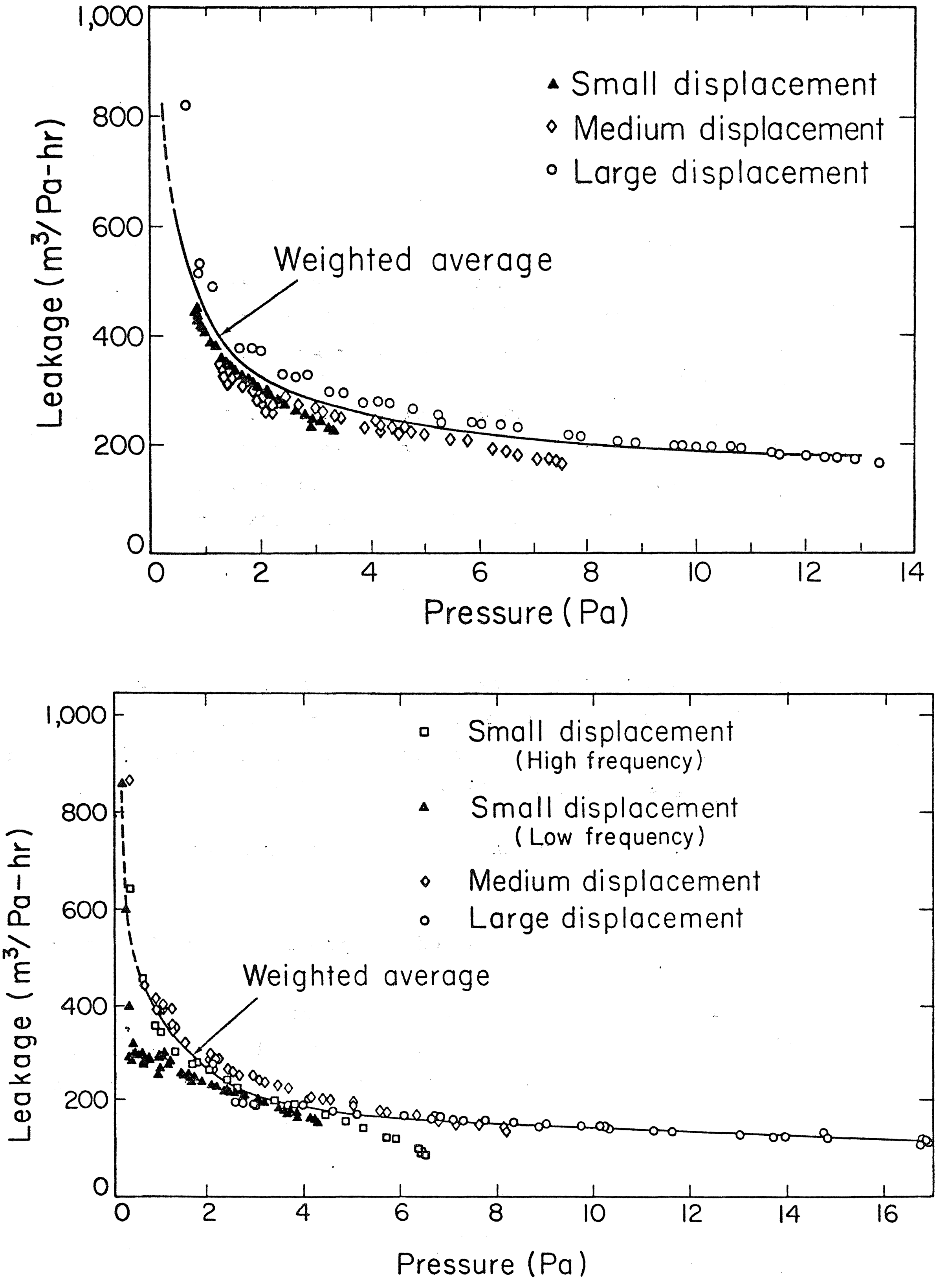
The pressure is recorded both on a strip chart recorder and by a microprocessor. The frequency is monitored by the microprocessor by use of an infrared diode system that records each revolution of the flywheel. Digital filtering of the incoming data is used to remove noise.

RESULTS

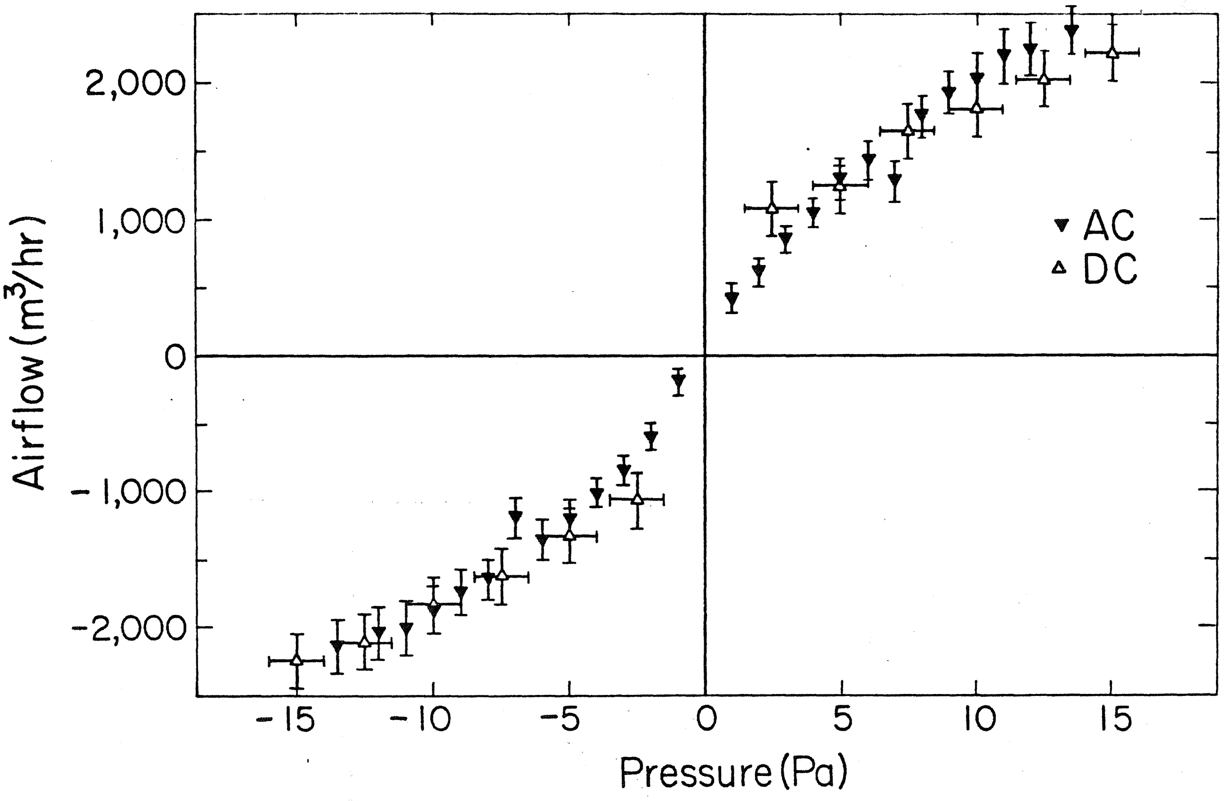
The house was tested in two configurations: loose and tight. The loose configuration of the structure is its normal operating condition: i.e., all vents open, all dampers and windows shut. In the tight configuration, all vents and the heating system (registers, return duct and furnace closet) are sealed.

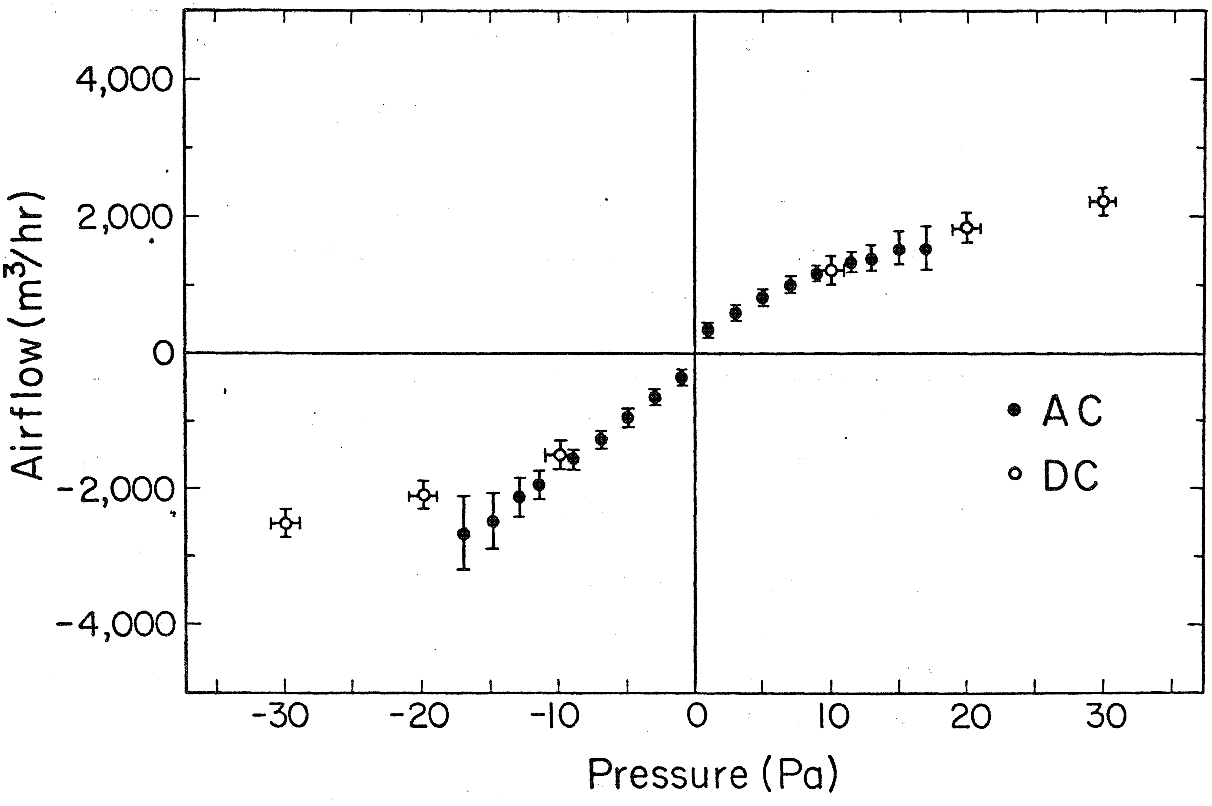
Figs. 2 and 3 show the leakage function calculated from eq. 8 for the AC pressurization data in both configurations.

Figs. 4 and 5 are graphs of the predicted air flow vs applied pressure for the house in the loose and tight configurations. The predicted air flow is obtained by multiplying the leakage function for a particular pressure by that pressure. Each graph has the points from the AC pressurization run as well as the points from the DC pressurization run. Each point has the error bars associated with the measurement.



Figures 2 and 3. The leakage function of the structure in the loose(2) and tight(3) configurations vs the applied pressure. Each point represents a one-minute average reading at a particular frequency and displacement. Points of the same displacement have the same symbol. The curves are the weighted averages of all of the data points.





Figures 4 and 5. The air flow through the envelope vs. the applied pressure for the structure in the loose(4) and tight(5) configurations. Both the AC pressurization graphs as derived from the low pressure leakage function, and the DC pressurization results are shown. The error bars are calculated from the measurement errors and displayed for each point.

Fig. 6 is a plot of both the loose and tight configurations for the full range of DC leakage points. The low pressure range is duplicated on Figs. 4 and 5.

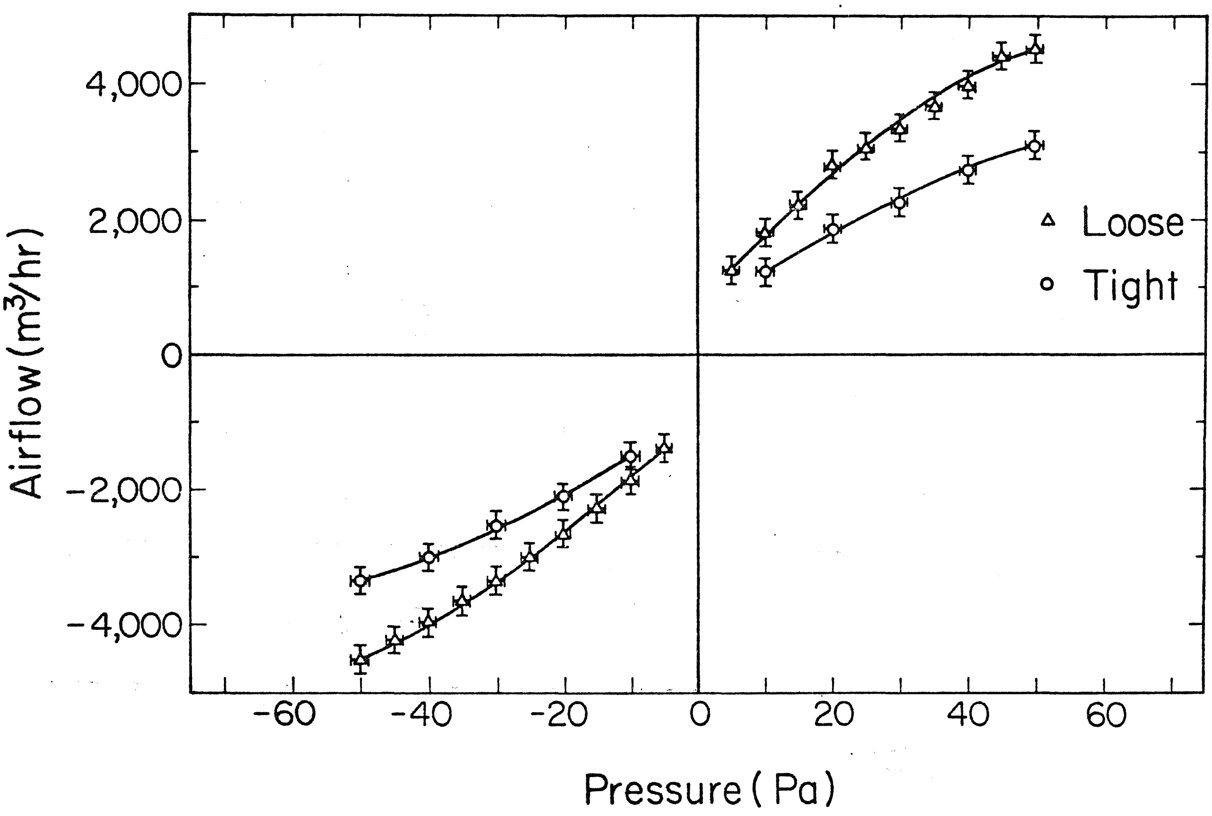


Figure 6. The DC leakage curves for both the loose and tight configurations. The error bars are derived from the measurement error and equipment calibration errors.

All AC tests were made with a variety of different piston displacements and frequencies. There appeared to be a systematic difference between sets of data at different displacements, but this difference is within the error bars and does not affect the interpretation of the data.

There is some difference between the leakage curves for pressurization and depressurization, as reflected by a non-zero value for the asymmetry constant. The asymmetry is a reflection of one-way leakage in the structure and is commonly seen in measurements using DC pressurization. [5]

Calculations of the effective leakage area of the structure in its tight configuration are shown in Fig. 7. This calculation assumes that air flow through structural openings is proportional to the square root of the pressure difference.

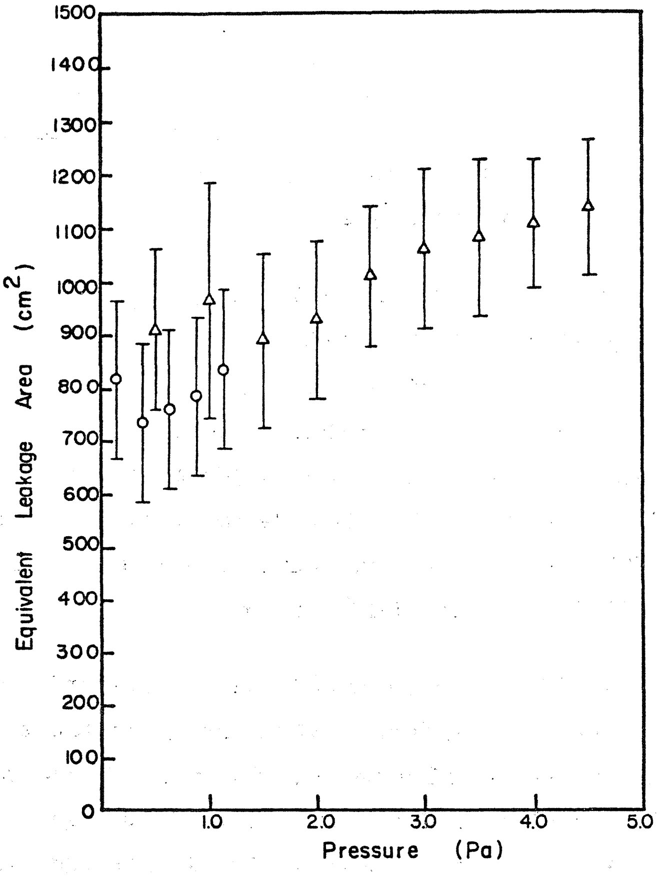


Figure 7. The effective leakage area of the structure in its tight configuration. The triangles and circles are computed from data obtained in two separate experiments. The error bars are uncertainties calculated from experimental uncertainties.

When infiltration measurements made concurrently with AC pressurization measurements were compared with the predicted air flow through the envelope, measured infiltration was always found to be far less than the predicted value. The prediction assumes that all of the air forced out of the envelope by the piston mixes with the outside air and disperses before air is pulled back in. However, using smoke tracers, we have observed that the air forced out lingers in the neighborhood of the exit leak and is pulled back into the structure with little mixing. Under these circumstances, the amount of infiltration measured by tracer gas is only a small part of the sum of all the air flows through the envelope as measured by AC pressurization. In our experiment, the pronounced lack of mixing indicates a significant amount of leakage into the attic, crawl space, or wall cavities. This lack of mixing in the connected spaces is equivalent to a cut-off frequency in the leakage characteristic of the structure. That is, there is some frequency above which weather-induced pressures do not cause any infiltration. Our experiments indicate that this frequency may be very low (a frequency of about 1 Hz).

DISCUSSION

In their range of overlap, the AC and DC techniques show good agreement in their prediction of the leakage of the structure. Because they represent independent determinations of the same quantity, we feel that the agreement corroborates both techniques.

Each technique has its own strengths; together they provide an excellent characterization of the leakage of a house. DC pressurization is simpler, faster and uses inexpensive equipment. AC pressurization is more accurate in the range of pressures typically associated with infiltration. Since this technique does not measure flow directly, it is not subject to the problems of measuring low velocity flows. Because of the synchronous detection inherent in the system, the AC technique is capable of measuring the leakage at far lower pressures than the DC techniques.

The most intriguing result of this experiment was unexpected. We anticipated that the leakage function at low pressures, assuming laminar flow, would approach a constant and, hence, the air flow would be linear in the applied pressure. However, the leakage function seems to increase without bound at low pressures. In our DC measurements we often measure a curve that extrapolates to a non-zero air flow at zero pressure (cf. Fig 6). We usually attribute this offset to poor data at low pressures, but the AC results indicate that the effect may be the result of the large slope of the air flow vs. pressure curve near the origin which cannot be measured with DC techniques.

At high pressures the flow is dominated by turbulence and the air flow is proportional to the square root of the pressure. The fact that the low pressure leakage does not approach a constant implies that, in this structure, the low pressure leakage is dominated by orifice flow rather than by viscous flow. Consequently, even at pressures as low as 0.2 Pa there is no evidence of flow dominance from viscous effects.

CONCLUSION

A new technique for measuring low pressure leakage of a building is presented, based on AC pressurization. In this technique the volume of the building is modulated at a fixed frequency using a piston assembly sealed into a door or window. Our results indicate that measuring the interior pressure response synchronously to the volume oscillation eliminates the pressure fluctuations caused by the weather that make DC measurements difficult in the low pressure range.

The leakage characteristic of the our experimental house was measured in both a tight and a loose configuration with both the AC and DC pressurization techniques. The correlation is good in the pressure regime of overlap.

Low pressure leakage measurements using the AC pressurization technique can provide valuable information about the leakage characteristic of a structure that is available from no other source.

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