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AIR INFILTRATION IN BUILDINGS

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ABSTRACT

Since the 1973/74 oil crisis the scientific community has begun to turn its attention to energy generation and conservation. To address some of these problems the American Physical Society has produced two publications resulting from cooonferences on energy conservation. The first was a summer study held at Princeton University during the summer of 1974 and produced a book entitled *Efficient Uses of Energy*, published by the American Institute of Physics, Volume 25, 1975. The second and most recent conference was held in Washington, DC, and produced a book entitled *Energy Sources: Conservation and Renewables*, also published by the American Institute of Physics, 1985. One of the topics covered was air infiltration and air leakage in residential buildings. This report, while not intended as an exhaustive description of the field can supply the reader with a brief introduction to air infiltration in buildings.

INTRODUCTION

Infiltration, the naturally-induced air flow through the building envelope, typically accounts for one-third of the energy load while at the same time acting as the primary mechanism for removing internally-generated pollutants and thus assuring adequate indoor air quality. To minimize energy use one may wish to minimize infiltration, but to insure adequate indoor air quality one may wish to increase infiltration. This apparent contradiction implies that the prediction of infiltration for a new or existing structure can be one of the more critical calculations an engineer or architect can make.

CALCULATION OF INFILTRATION USING THE LBL MODEL

To predict air infiltration in buildings it is necessary to have a model of the process that is simple enough to be practical, but one that captures the essential processes in effect. The LBL infiltration model is based on physical simplifications of the many effects that enter into the process of air infiltration. The considerations behind these simplifications have been examined in great detail in previous works and will be summarized in the sections to follow. The original work[1] was a Ph.D. thesis in physics; the first complete presentation[2] in the professional literature led to its inclusion in the *1981 ASHRAE Handbook of Fundamentals*, and was followed closely by its first international presentation.[3] The most current version[4] should be consulted for practical uses.

Infiltration is primarily a flow phenonemon; it is the (flow) response of the building to the pressures induced by the driving forces, which may either be mechanically-induced[‡] or weather-induced. There are two primary weather mechanisms which induce infiltration: wind force and stack force (i.e. temperature-induced density differences). The approach taken in the LBL model is to calculate the infiltration induced by each driving force *assuming the other driving forces are absent* and then combine them.

Stack-Induced Infiltration

The stack effect is caused by a difference in temperature between the air inside and the air outside the building. This temperature difference causes a density difference and this buoyancy creates a pressure gradient along any vertical boundary.

The leaks in a building are distributed over the entire envelope, thus a detailed summation would be required to determine the flow at each point on the envelope. To avoid this level of detail, we have grouped the envelope leakage into three categories: floor, wall, and ceiling leakage area. Within each area we assume that the leaks are evenly distributed.

$$Q_s = L \; f_s \; \sqrt{|\Delta T|} \tag{1}$$

‡ Although the references discuss how to include mechanically-induced infiltration in the total, this summary will not.

where:

Q_s	is the stack-induced infiltration $[m^3/s]$
L	is the effective leakage area $[m^2]$
f_s	is the stack parameter $[m/s\text{-}K^{1/2}]$
ΔT	is the inside-outside temperature difference $[K]$

Wind-Induced Infiltration

When wind flows around a building, it induces pressure differences across the external faces of the envelope. These pressure differences are proportional to the local wind speed and the shielding coefficient for the building environment. (We have calculated the generalized shielding coefficient for five degrees of obstruction around the building.)

Most wind data is taken from a weather tower not necessarily at the height of the building. The measured wind speed must be converted from a weather station into a local wind speed for our model. We use a method that uses two terrain parameters to describe the wind profile and do the necessary conversion; these terrain parameters are included in the description and definition of the wind parameter.

$$Q_w = L \ f_w \ v \tag{2}$$

where:

Q_w	is the wind-induced infiltration $[m^3/s]$
L	is the effective leakage area $[m^2]$
f_w	is the wind parameter $[-]$
v	is the unobstructed speed of the wind $[m/s]$

Superposition

Although we may be able to calculate the pressures induced across the shell of the building from each of the two driving forces, it is not a simple matter to sum the point pressures on the surface of the building caused by both acting in concert. To simplify the point pressure problem, we can calculate the wind-induced (Q_w) and stack-induced (Q_s) infiltration independently and then combine them. We cannot, however, simply add them to find the total infiltration, rather we assume the leaks to be simple orifice flow and infer that we approximate the combined effect by adding the flows in quadrature:

$$Q_{weather} = \sqrt{Q_w^2 + Q_s^2} \tag{3}$$

where

$Q_{weather}$ is the combined infiltration $[m^3/s]$

Like the effective leakage area, L, the parameters f_s and f_w are both time and weather-independent, but do depend on the the building and its environment. While the effective leakage area can vary by over an order of magnitude from house the house, the wind and stack parameters tend to vary less than a factor of two.

SPECIFIC INFILTRATION

If we combine the stack and wind induced terms together, the total (weather-induced) infiltration can be expressed as follows:

$$Q_{weather} = L \; s \tag{4.1}$$

$$s \equiv \sqrt{f_w^2 v^2 + f_s^2 \mid \Delta T \mid} \tag{4.2}$$

where

s is the specific infiltration $[m/s]$.

To the extent that we can ignore variations in the wind and stack parameters, the specific infiltration is dependent only upon weather and not on the leakage of the building. As such the specific infiltration is a good indicator of the severity of climate relative to infiltration. Accordingly, we have calculated the heating season average of the specific infiltration for 60 cities across the country and then interpolated the results to generate a contour map. Figure 1 (note unit change) presents these results. Once the leakage area has been determined (as described below) a reasonable estimate of the seasonal infiltration can be made by multiplying the specific infiltration by the leakage area (to convert to a volume flow rate) and then, if desired, dividing by the building volume (to convert to air changes per hour‡).

DETERMINATION OF EFFECTIVE LEAKAGE AREA

Effective leakage area provides a simplified description of the process of air leakage through a building envelope under specified pressure; it is a quantity conceptually equivalent to the sum of the areas of all the cracks and holes in the building envelope through which air is able to pass. Air flow through the building envelope is a combination of viscous (i.e. laminar) flow and turbulent flow. The former is proportional to the outside to inside pressure difference (ΔP) while the latter is proportional to the square root of ΔP. Empirically it has been found that air flow through the envelope can be characterized by the equation:

$$Q = K \; (\Delta P)^n \tag{5}$$

where:

- Q is the air flow induced through the envelope $[m^3/s]$
- K is the leakage coefficient $[m^3/s - Pa^n]$
- ΔP is the applied pressure difference $[Pa]$
- n is the leakage exponent [-].

The effective leakage area is defined assuming that in the pressure range characteristic of natural infiltration (-10 to +10 Pa) the flow versus pressure behavior of a building more closely resembles square-root (turbulent) than viscous flow. Because four Pascals is representative of the typical pressures inducing infiltration, it is common to use it as the reference pressure and assume orifice (turbulent) flow (n=1/2).

‡ Air changes per hour, ACH, is a commonly used unit. It is calculated by dividing the total infiltration by the building volume (i.e. $ACH = L \; s / V$)

Therefore, the leakage area of the envelope is defined at four pascals:

$$L \equiv \frac{Q(\Delta P_r)}{\sqrt{\frac{2}{\rho}\Delta P_r}} \tag{6}$$

where:

L	is the effective leakage area $[m^2]$
$Q(\Delta P_r)$	is the induced air flow at the $(4\ Pa)$ reference pressure $[m^3/s]$
ρ	is the density of air $[1.2\ kg/m^3]$
ΔP_r	is the reference pressure difference $[4\ Pa]$

Effective leakage area can be defined for pressurization of the building (i.e. higher internal than external pressure) or for depressurization (i.e. evacuation); depending on circumstances, one or the other or the average is used. For most U.S. housing stock the effective leakage area will run between 300 cm^2 and 1000 cm^2; super tight houses have been measured as low as 50 cm^2 and old, leaky houses have been measured as high as 3000 cm^2.

Fan Pressurization

The most common method for measuring the effective leakage area of a building is called *fan pressurization*. This method uses a blower door, a door-mounted, variable speed fan capable of moving large volumes (up to 7000 m^3/hr) of air into or out of a structure, and a differential pressure gauge such as an inclined manometer. By supplying a constant air flow with the fan, a pressure difference across the building envelope can be maintained. When the differential pressure is held constant, all air flowing through the fan must also be flowing through the building envelope.

To make the fan pressurization measurement, the blower door is sealed into an exterior doorway, and the pressure gauge is set up with one pressure tap placed outside in a location protected from the wind. The inside pressure tap should be placed out of the direct flow path of the fan. All exterior doors and windows should be closed, and if a fireplace and/or a wood-burning stove are present, their dampers are closed to prevent soot from entering the building during depressurization. All interior doors, except closet doors, should be open. The blower door is then used to blow air into (pressurize) and to suck air out of (depressurize) the building at a series of fixed pressure differentials (e.g., from 10 to 70 Pa at 10 Pa intervals). The air flow (or some quantity directly related to it) and the pressure difference are measured at each point. The resulting pressure versus air flow curves for both pressurization and depressurization are used to find the effective leakage area of the building by fitting the data to the air flow equation using a regression technique.

AC Pressurization

Another technique for measuring the effective leakage area, called AC pressurization[5], differs from fan pressurization (DC pressurization) by creating a periodic pressure difference across the building envelope that can be distinguished from naturally occurring pressure fluctuations. Assuming that there are no leaks in the building envelope and that the structure is rigid, the change in pressure can be precisely determined from the structure's volume and the piston's displacement. The airtightness of a building affects the pressure change from the periodic volume change, including both the amplitude and phase of the pressure change. Therefore, any deviation from the pressure change for a sealed building can be attributed to leakage through the envelope. The measured volume change and pressure response can thus be used to calculate the airflow through the envelope. The AC pressurization apparatus includes components that perform four basic functions: (1) volume change, (2) displacement monitoring, (3) pressure measurement, and (4) analysis/control. Several options for accomplishing each of these functions have been investigated.

The pressure-flow relationships used for AC pressurization measurements are substantially more complex than those for DC pressurization. Because the drive component provides a periodic volume change, and thereby induces a periodic pressure response, the flow through the envelope must be determined from the continuity equation for a compressible medium:

$$Q + \dot{V}_d + c\ \dot{P} = 0 \tag{7}$$

where:

Q	is the air flow through the envelope $[m^3/s]$
$\dot{V}_d$	is the induced rate of change in interior volume $[m^3/s]$
c	is the effective capacity of the envelope $[m^3/Pa]$
$\dot{P}$	is the resultant rate of change of the internal pressure $[Pa/s]$

Theoretically, this expression could be used to calculate the instantaneous air flow (Q) directly from the measured volume and pressure changes. In practice, this is not possible because of the accuracies required for both the estimation of the capacity, c, and the measurement of the pressure (especially its time derivative). However, because all the terms are periodic (i.e., AC), we can use *synchronous detection* (i.e., phase-sensitive detection) to analyze the data and increase its accuracy. Specifically, we lower our precision requirements by extracting the component that is in phase with the pressure signal:

$$\left\{ Q\,\Delta P \right\} + \left\{ \dot{V}_d\,\Delta P \right\} + c \left\{ \dot{P}\,\Delta P \right\} = 0 \tag{8}$$

where:

ΔP	is the inside-outside pressure difference $[Pa]$
$\left\{ \cdots \right\}$	indicates a cycle average.

Because the pressure signal is periodic and the outside pressure is independent of our drive signal, the term in $\dot{P}$ vanishes. Inserting the power-law definition of the air flow, simplifying, and solving for the leakage area yields the following:

$$L = -\sqrt{\frac{\rho}{2P_r}}\ \frac{\left\{ \dot{V}_d \dfrac{\Delta P}{P_r} \right\}}{\left\{ \left| \dfrac{\Delta P}{P_r} \right|^{n+1} \right\}} \tag{9}$$

This basic equation of AC pressurization is used to determine the leakage area directly from the measured rate of volume change (from the piston velocity) and pressure response.

This technique holds great promise but it is still in the development stages. Comparisons with conventional fan pressurization show reasonable agreement, but indicate a tendency for AC pressurization to treat large leaks (e.g. open flues or chimneys) differently from the more common leaks. This fact suggests that the technique may be suitable as a probe to determine the character of leaks in a building.

EXAMPLE

In this section we will go through an example of how fan pressurization and the LBL model may be used to predict infiltration. The example house is a single-story, ranch-style, (tightened) California house with a ventilated crawl-space, whose vital statistics are as follows:‡ Floor area = 100 m^2; Volume = 240 m^3; s = 0.25 $m^3/hr - cm^2$; $f_s = 0.13$ $m/s - K^{1/2}$; and $f_w = 0.12$.

To determine the leakage area, a fan pressurization test was done on the example house. The analysis of the results (for the ducts closed condition) yields a value of 400 cm^2 of leakage area. Combining the seasonal specific infiltration (0.25 $m^3/hr - cm^2$) with the effective leakage area (400 cm^2) yields a seasonal average infiltration of 100 m^3/hr or a seasonal average air change rate of 0.42 per hour.

The equations described above can also be used to find the instantaneous infiltration for a particular wind speed and temperature difference. We take for example a cool, blustery California day (i.e. 7 m/s wind speed and a 16K inside-outside temperature difference). The stack-induced infiltration (in cubic meters per hour) is the product of the leakage area (400 cm^2), the stack parameter (0.047 $m^3/hr - cm^2 - K^{1/2}$) and the square root of the temperature difference (16K) yielding 75 m^3/hr. Similarly, the wind-induced infiltration (in cubic meters per hour) is the product of the leakage area (400 cm^2), the wind parameter (0.043 $m^2 - s/cm^2 - hr$) and the wind speed (7 m/s) yielding 120 m^3/hr. Combining the stack-induced and wind-induced infiltration together with quadrature yields 142 m^3/hr or 0.59 air changes per hour.

CONCLUSION

Prior to the introduction of the LBL model, prediction of infiltration was at best ad hoc. Engineering estimates were crude and generally only used in sizing equipment for which accuracy and reproducibility were not important. The LBL model begins with the fundamental physics of air flow and then uses simplifying assumptions to create a simple, physical model of infiltration, which is accurate to 20%.

The effective leakage area and local weather data can be used as inputs to the LBL infiltration model. The fan pressurization technique is a simple method that is used to measure the air tightness of a building. AC pressurization is a potentially superior method for determining the effective leakage area of a building. Both the

‡ Note unit changes. See References 1-4 for the calculation procedure for f_s and f_w.

pressurization techniques and LBL infiltration model can be used in a variety of ways: energy estimates, air quality calculations, consensus standards, and code requirements.

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ACKNOWLEDGMENT

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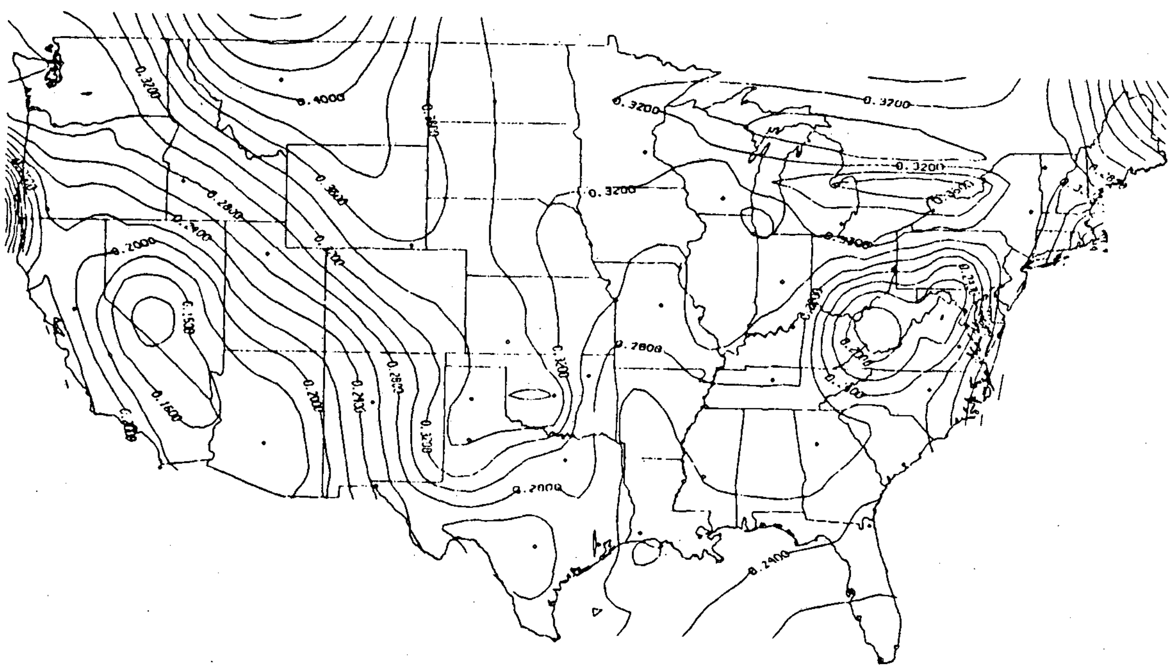
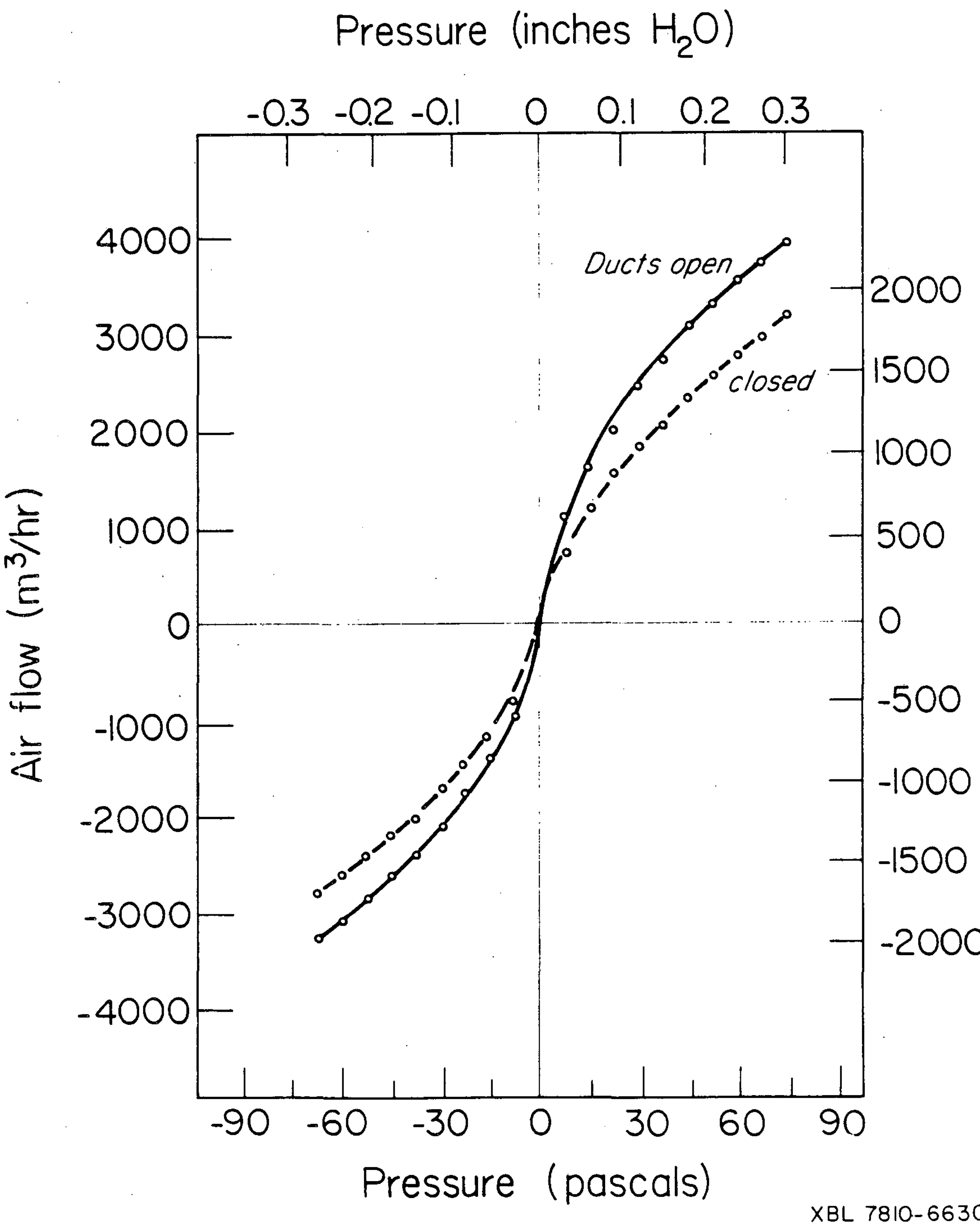
Figure 1: A contour map of the specific infiltration(s) over the heating season throughout the U.S. varying from lows below 0.2 in the southwest to highs near 0.4 in the northern tier; contour steps are 0.02.



Heating Season Infiltration (m^3/hr-cm^2)

XBL 8212-12076

Figure 2: A plot of the flow rate through the building envelope vs. applied pressure for the example house.



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