Title
Estimation of Infiltration from Leakage and Climate Indicators.:

Author
Sherman, Max

Publication Date
1987

Energy and Buildings, 10 (1987) 81 - 86

Estimation of Infiltration from Leakage and Climate Indicators

MAX H. SHERMAN

Energy Performance of Buildings Group, Indoor Environment Program, Applied Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720 (U.S.A.)

(Received August 6, 1986; accepted November 10, 1986; revised paper received December 12, 1986)

SUMMARY

A simple model is developed for the estimation of annual infiltration rates in single-family houses using indicators for both house tightness (air changes at 50 Pa) and site climate (the leakage–infiltration ratio). This technique is best suited to low-accuracy, large dataset problems where detailed data are not available. The method is similar to the method attributed to Kronvall and Persily (i.e. the K–P method), but is derived from a physical model, the LBL infiltration model. The estimation technique is developed assuming a typical, single-story dwelling; correction factors for common variations in building and environmental conditions are tabulated. A map of the leakage–infiltration ratio in the U.S. for the reference case is also presented.

Key words: Infiltration, leakage, ventilation, empirical models, climate, weather.

INTRODUCTION

Infiltration is a nonlinear phenomenon which is dependent on a great many details of the building, its environment, and the driving forces. An exact calculation of infiltration for a real building is currently beyond practical capabilities; to calculate infiltration, therefore, one must always use approximate techniques.

Approximate (or simplified) techniques range from simple to complex and more accurate ones. Many of the crudest models have been developed without any consideration of the basic physical principles at work. In this report we derive a very simple model for estimating annual infiltration, using one of the relatively more complex, but physically based models, which takes these principles into account.

BACKGROUND

Like conduction, infiltration can be separated into an essentially weather-independent part (the air leakage of the envelope) driven by a weather-dependent term (wind and temperature difference). Unlike conduction loads, infiltration loads are nonlinear (i.e. the load is not simply proportional to the inside–outside temperature difference) and depend upon wind velocity in addition to the inside–outside temperature difference. As shown below, the weather-independent part can be partially quantified by the fan pressurization technique, while the interaction with climate requires a model for the infiltration process.

Fan pressurization

The fundamental building property affecting infiltration is the air leakage of the envelope. Fan pressurization is most commonly used for measuring the air leakage of a building envelope. Currently there exists a U.S. standard [1] for determining air leakage rates using fan pressurization. Canadian and ISO standards are being developed.

The fan pressurization technique exploits the relationship between the flow through the building envelope and the pressure difference across it. The most common form [2] of the equation is a power-law relationship:

$$Q(\Delta P) = C\Delta P^n \tag{1}$$

0378-7788/87/$3.50

where ΔP is the pressure difference (Pa), Q is the total infiltration (m^3/s), C is the leakage coefficient ($m^3/h\ Pa^n$), n is the leakage exponent (—). The exponent is normally found to be between the two physically meaningful values of $n = 1/2$ (nozzle or orifice flow) and $n = 1$ (laminar flow).

Assuming the house leakage can be represented by an equivalent nozzle, the quantity that characterizes the leaks can be treated as an (effective leakage) area. For this reason we often use the effective leakage area (ELA) at a specified reference pressure to characterize the leakage of the envelope. The defining relation follows:

$$\mathrm{ELA} \equiv \frac{Q(\Delta P = \Delta P_r)}{(2\Delta P_r/\rho)^{1/2}} \tag{2}$$

where ELA is the effective leakage area (m^2), ΔP_r is the reference pressure difference (Pa), ρ is the density of air (1.2 kg/m^3). In other words, the ELA of a particular crack is equal to the area of a perfect nozzle (i.e., discharge coefficient of unity) which, at the reference pressure, would pass the same amount of air as the crack.

LBL infiltration model

Fan pressurization quantifies the leakage of the envelope, but we need a model of the driving forces and their interaction with the building to calculate infiltration. One of the simplest, most widely known physical models of infiltration is the Lawrence Berkeley Laboratory (LBL) infiltration model [3]. The LBL model calculates infiltration which occurs through the envelope of the building by assuming that envelope leaks can be treated as simple orifices whose leakage characteristics can be quantified in a single parameter. Because the driving pressures on these leaks are caused by wind, indoor–outdoor temperature differences, and mechanical ventilation systems, the flow due to each driving force is calculated separately, then combined by quadratic superposition.

Simply stated, infiltration is calculated by multiplying the ELA by the specific infiltration, s, as obtained by using the LBL model:

$$Q = \mathrm{ELA} \times s \tag{3}$$

where s is the specific infiltration (m/s). The specific infiltration is a function of both the wind speed and temperature difference, as well as some building-dependent parameters:

$$s = (f_w{}^2 v^2 + f_s{}^2 |\Delta T|)^{1/2} \tag{4}$$

where f_s is the (infiltration) stack parameter (m/s $K^{1/2}$), f_w is the (infiltration) wind parameter (—), ΔT is the indoor–outdoor temperature difference (K), v is the wind speed (m/s). Although the values of the wind and stack parameters (f_w, f_s) [4] depend upon the leakage distribution and siting of the particular structure being modeled, typical single-family houses have values of:

$$f_w \equiv 0.13 \tag{5a}$$

$$f_s \equiv 0.12 \text{ m/s K}^{1/2} \tag{5b}$$

A specific infiltration calculated using these reference values of the building-dependent parameters and averaged over the year will be denoted by s_a.

We tabulated values for specific infiltrations for major weather sites across North America [5], and the seasonal averages were found to lie between 0.45 - 1.1 m/s, with an average of 0.75.

DEVELOPMENT OF INFILTRATION INDICATORS

The earliest serious use of the fan pressurization technique was in Sweden. The Swedish standard [6] stated that fabric of the building must leak no more than three air changes per hour at a 50 Pa pressure difference. Since that time "air changes at 50 Pa", ACH_{50}, has been the most common indicator of building tightness and is also relatively well known*. In the last few years, more physically meaningful methods to describe building tightness have been developed [7], but none are as simple or as reproducible as ACH_{50}. Although ACH_{50} may not be as physically meaningful as these other quantities, it is the most suitable tightness indicator. We use ACH_{50} as our leakage indicator.

*ACH_{50} should not be confused with an infiltration rate; it is an air flow at an artificially induced condition and is an indicator of leakage *not* infiltration.

Climate indicator

As infiltration models were being developed, early work attempted to find a simple correlation between leakage and infiltration. One piece of work widely known by researchers in the field is called the K–P model and is attributed to Kronvall and Persily [8]. It holds that a good estimate of annual infiltration rate can be achieved by dividing ACH_{50} by 20:

$$ACH_{k-p} \equiv ACH_{50}/20 \tag{6}$$

where ACH_{k-p} is the air changes per hour calculated using the K–P model (h^{-1}), ACH_{50} is the air changes per hour at 50 Pa pressure difference (h^{-1}).

Persily used his [9] and Kronvall's data [10] to regress the infiltration against the leakage for more than 40 houses and achieved the following result:

$$ACH \approx \frac{ACH_{50}}{18} - 0.08 \tag{7}$$

where ACH is the air changes per hour (h^{-1}). Although this simple expression ignores many details of the infiltration process, it appears to give qualitatively reasonable results for annual ensemble averages. This qualitative agreement suggests that we use relatively more robust techniques to find an approximation of this form.

We now derive a similar type of expression for annual air change rate using our knowledge of leakage (ELA) and infiltration (the LBL model). The form we wish to derive is as follows:

$$ACH = ACH_{50}/N \tag{8}$$

where N is the leakage–infiltration ratio. Using the above definitions for ELA and infiltration (remembering that the air change rate is the infiltration rate divided by the volume), we can rewrite the LBL model's result as follows:

$$ACH = ACH_{50}\left(\frac{\rho}{8(\mathrm{Pa})}\right)^{1/2}\left(\frac{4(\mathrm{Pa})}{50(\mathrm{Pa})}\right)^{n} s \tag{9}$$

If we compare the previous two expressions, we can see that the LBL model can be cast into the desired format, without loss of generality, as follows:

$$N = \frac{1}{s}\left(\frac{8(\mathrm{Pa})}{\rho}\right)^{1/2}\left(\frac{50(\mathrm{Pa})}{4(\mathrm{Pa})}\right)^{n} \tag{10}$$

As this expression is written, the leakage–infiltration ratio is a function of time. To make it analogous to the Kronvall–Persily result, we must average over the year. We will, furthermore, take typical values for all of the building-dependent values to obtain the following result:

$$N \approx N_o \equiv 14/s_a \ (\mathrm{m/s}) \tag{11}$$

where N_o is the typical annual average leakage–infiltration ratio (—), s_a is the typical annual average specific infiltration (m/s). (The subscript "a" indicates that the reference values for f_s and f_w have been used, and a temporal weather average has been taken in the calculation of s. Furthermore, an average value of $n = 2/3$ was used, based on a survey of fan pressurization data [11].) Corrections to the indicators for variations in these assumptions are covered in the following Section.

We will use the leakage–infiltration ratio, N_o, as our basic climate indicator.

CALCULATION OF INFILTRATION INDICATORS

From the definition of leakage–infiltration ratio we see that every climate can have a different value indicator. To determine typical values, we calculate the leakage–infiltration ratio using a dataset consisting of hourly weather data for over 200 sites in the United States and Canada [12]. The ratios at the individual sites range from about 15 to 30. Figure 1 illustrates this ratio, which for most of North America lies between the values of 17 and 23. Figure 1 can be quite useful in estimating the annual infiltration rate when only the leakage at 50 Pa is known.

If one is looking for a single number with which to characterize the climate, the leakage–infiltration ratio could be calculated using an average specific infiltration for a large area. Using a value of specific infiltration typical of the U.S. (i.e., 0.75 m/s), we find a leakage–infiltration ratio approximately equal to 19. Thus, the value of 20 suggested by the K–P model was close to the mark*.

*It is interesting to note that in Princeton, New Jersey — where Dr. Persily obtained his data — the value of the leakage–infiltration ratio is just under 20.

Fig. 1. A graph of the United States indicating zones of various leakage–infiltration ratio.

Correction factors

In calculating N_0, we assumed typical values for building parameters. Although this simplification can easily cause some error in the estimate, when little is known about the building, or when estimates are being made for large numbers of houses, this simplification is necessary and unlikely to cause large errors. Often, though, an estimate of annual infiltration will be desired for a particular house for which a little more information is known. For this situation, we have developed a set of correction coefficients that can correct the leakage–infiltration ratio and reduce inaccuracy:

$$N \longleftarrow N_0 \mathrm{cf}_1 \mathrm{cf}_2 \mathrm{cf}_3 \ldots \qquad (12)$$

where $\mathrm{cf}_{1,2,3}$ are the correction factors.

We present three correction factors: one for building height, the second for site shielding, and the third for leak type (i.e., leakage exponent). The first two factors correct for variations in the reference values of f_s and f_w in the LBL model. Reference 7 should be consulted for the exact definitions of these parameters. The last correction results from uncertainties in the leakage exponent. Reference 11 indicates that the standard deviation of the leakage exponent is approximately 1/10. We have used this value in calculating the leakiness correction factor.

The first and simplest correction is for building height. The standard assumption is for a single-story structure. If you know the building height, you can correct the leakage–infiltration ratio, N_0, by multiplying the base ratio using the following factor:

TABLE 1

Height correction factor

Number of stories	1	1.5	2	3
Correction factor	1.0	0.9	0.8	0.7

The LBL infiltration model contains a parameter to indicate the building site's exposure to wind. In our calculation of N_0 we used a typical value. If, however, you have information about the environment immediately surrounding the building, you can correct the leakage–infiltration ratio as follows:

TABLE 2

Shielding correction factor

	Well shielded	Normal	Exposed
Correction factor	1.2	1.0	0.9

A leakage value of 50 Pa creates uncertainty in extrapolating to the 4 Pa value needed by the models. This extrapolation is heavily dependent on the value of the leakage exponent, n. We have, therefore, developed a set of correction factors to account for this inaccuracy. Even if the exponent is unknown, its value is highly correlated with the types of leaks. In a building with lots of little cracks, a situation typical of tighter buildings, the exponent is high (>0.8). In a building with large holes, typical of leakier buildings, the exponent is low (≈ 0.5). From this description, the following table can be used to correct the leakage–infiltration ratio:

TABLE 3

Leakiness correction factor

	Small cracks (tight)	Normal	Large holes (loose)
Correction factor	1.4	1.0	0.7

Example

To illustrate the technique we take a group of two-story houses just built near Washington, DC. First, we note that the base leakage–infiltration ratio is approximately 21 in Washington (Fig. 1). Then we correct for height, noting that the correction factor is 0.8 for a two-story house. We then look to the shielding correction, and take the exposed value of 0.9 because there is very little shielding in a new housing project. Since we know nothing at this stage about the types of leaks, we use the default value of unity. Thus, the corrected ratio is $21 \times 0.8 \times 0.9 = 15$ in our example. Should a particular house have a 50 Pa air change rate of 10 air changes per hour, we would estimate the annual infiltration rate to be 2/3 per hour.

UNCERTAINTIES

In any qualitatively simple model such as the one developed above, the uncertainties will be large. They will be both systematic and random, as well as being hard to estimate. The size of the correction factors give an indication of some of the uncertainties (i.e., 10% - 40%) depending on the building, in addition to the uncertainties from the LBL model itself.

A good error analysis would involve a detailed simulation effort to model the distribution of buildings, climates, and other relevant factors. It should also include a large set of measured vs. predicted infiltration rates. Such an effort is beyond the scope of this report, but as this model is used it may be possible to generate the necessary data for a good error analysis and validation.

CONCLUSIONS

In this paper we have used a simplified, physical model of infiltration — the LBL model — to heuristically corroborate a simple infiltration estimation technique.

The choice of model type and complexity is strongly a function of application. A detailed description of how to choose the appropriate model for a specific application is beyond the scope of this report. (Currently the Air Infiltration and Ventilation Centre is preparing a guide [13] to help users decide which kind of model to use.) However, it is clear that any time short-term or highly specific building specific estimates are required, the approach described herein is unadvisable.

For large ensembles of annual averages or for rule-of-thumb estimates, the simplified method of indicators is appropriate. Of the two indicators used, one of them — the leakage indicator (ACH_{50}) — is well known in the community. However, the climate indicator, N_o, the leakage–infiltration ratio is new.

The way we have defined N_o is purely dependent upon the average climate at the site of interest. We have, however, defined a set of correction factors which use building-specific information to improve the estimate of infiltration. Future work should involve using field data to ascertain the accuracy of this method.

ACKNOWLEDGEMENT

This work was funded by the Assistant Secretary for Conservation and Community

Systems, Buildings Division Office of Buildings and Community Systems, of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

REFERENCES

1 American Society for Testing Materials, Standard test method for determining air leakage rate by fan pressurization, *ASTM E779, 1984 Annual Book of ASTM Standards.*

2 H. Reiher, K. Fraass and E. Settele, Über die Frage der Luft- und Wärmedurchlässigkeit von Fenstern verschiedener Konstruktion (Air and Heat Transfer for Windows of Different Construction), 1. Teilbericht, Wärmewirtschaftlich Nachrichten 6, pp. 42 - 59, 1932/1933.

3 M. Sherman and M. Modera, Comparison of measured and predicted infiltration using the LBL infiltration model, *STP No. 904 of the ASTM Symposium, Measured Air Leakage Performance of Buildings, Philadelphia, PA, April 1984, Report LBL-17001,* Lawrence Berkeley Laboratory, February, 1984.

4 D. Grimsrud, R. Sonderegger and M. Sherman, Infiltration measurements in audit and retrofit programs, presented at *IEA Energy Audit Workshop, Elsinor, Denmark, April, 1981, Report LBL-12221,* Lawrence Berkeley Laboratory, April, 1981.

5 M. H. Sherman, Description of ASHRAE's proposed air tightness standard, *Proc. 5th AIC Conference, March, 1984, Report LBL-17585,* Lawrence Berkeley Laboratory, p. 7.1.

6 *SS 02 15 51, Thermal Insulation — Determination of Airtightness of Buildings,* Swedish Standards Commission, 1980.

7 M. Liddament and C. Allen, *The Validation and Comparison of Mathematical Models of Air Infiltration, Technical Note 11,* AIC, September, 1983.

8 Personal communication, David Harrje, Princeton University, 1980 - 1985.

9 A. Persily, *Understanding Air Infiltration in Homes, Report PU/CEES ≠129,* Princeton University, 1982, pp. 79 - 81.

10 J. Kronvall, Testing of homes for air leakage using a pressure method, *ASHRAE Trans., 84* (I) (1978) 72 - 79.

11 M. H. Sherman, D. Wilson and D. Kiel, Variability in Residential Air Leakage, *STP No. 904 of the ASTM Symposium, Measured Air Leakage Performance of Buildings, Philadelphia, PA, April, 1984, Report LBL-17587,* Lawrence Berkeley Laboratory, April, 1984.

12 M. Sherman, Infiltration degree-days: a statistic for quantifying infiltration-related climate, *ASHRAE Trans., 92* (II) (1986).

13 M. Liddament, *Mathematical Models of Air Infiltration — An Applications Guide, Technical Report, AIC-AG-1-86,* AIVC, Bracknell, Berkshire, U.K., 1986.