CHARACTERIZATION OF BUILDING INFILTRATION BY THE TRACER-DILUTION METHOD

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Abstract—Air infiltration is an important factor in the total energy budget of a structure. It is also a significant parameter in indoor–outdoor air pollution relationships. Air infiltration cannot be reliably calculated but must be measured in a structure of interest. The tracer-dilution method is a useful technique to determine infiltration rates. This technique entails measurement of the logarithmic dilution rate of a tracer gas concentration with respect to time.

SURVEY OF STUDIES ON BUILDING INFILTRATION

Air infiltration represents an important part of the heating and cooling load of residential, commercial and industrial buildings. It is also an important parameter in indoor–outdoor air-pollution relationships. The heat loss associated with air leakage through the enclosure of a typical house may be as much as 40% of the total heat load.[1]

Considerable energy savings can be realized by reducing the air infiltration in a structure. Recently, a numerical simulation[2] of the heating requirements for a two-story residence conforming to a minimum FHA standard demonstrated that a 24% energy saving could be realized by reducing the air infiltration rate 50% (from 1 to 1/2 air change per hour).

Air infiltration rate is difficult to quantify because it is not only a function of building tightness and configuration, but also of inside–outside temperature differences, wind velocity and direction, and possibly other factors. Standard formulae do exist to estimate air-exchange rates[3] but they are at best rough approximations, since actual infiltration rates often depend on noncalculable quantities such as the quality of workmanship in construction.

One method, the tracer-dilution method, has been used for a number of years to measure air infiltration rates. The tracer-dilution method is an ideal technique to measure infiltration rate. This technique entails introducing a small amount of tracer gas into a structure and measuring the rate of change (decay) in tracer concentration. The air change rate (generally air changes per hour, abbreviated ACPH) can be determined from the logarithmic decay rate of tracer concentration with respect to time. Helium was one of the first tracer gases used[4–8] but others such as ethane[9] and nitrous oxide[10] have been used. Since the observation that sulfur hexafluoride (SF_6) could be detected in nonogram quantities (1×10^{-9}) by an electron capture gas chromatograph,[11] it has been used as a meteorological tracer.[12–14] More recently, it has been applied to the prediction of smoke movement in fires[15] and to the measurement of air infiltration in buildings.[16–19]

The basic assumption underlying tracer-gas studies of air change is that the loss rate of tracer concentration conforms to the well-known exponential dilution law; i.e. the loss rate, or decay, of an escaping gas is proportional to its concentration. For any concentration, C, at time, t, then

$$-\mathrm{d}C/\mathrm{d}t \sim C \quad \text{or} \quad -\mathrm{d}C/\mathrm{d}t = \lambda C. \tag{1}$$

From this one can formulate the following equation:

$$C = C_0\,\mathrm{e}^{-\lambda t}, \tag{2}$$

where C_0 is the initial concentration of tracer gas when $t = 0$.

Expressed in slightly different terms, a loss in tracer gas concentration is equal to the product of the fraction of the gas which escapes and the concentration at the time of loss, or

$$-\mathrm{d}C = (L/V)\,\mathrm{d}tC, \tag{3}$$

where L = air leak rate, V = test volume and C = tracer gas concentration during the interval dt. Note that $L/V\,dt$ is the fraction of the air which escapes during the time dt. Comparing eqn (3) with eqn (1), the exponential dilution law implies that $\lambda = L/V$ and

$$C = C_0 e^{-(L/V)t} \tag{4}$$

Here L/V is the infiltration rate, commonly given as ACPH. Equation (4) is the theoretical basis of tracer studies of room and building air exchange.

Stated another way, we have shown that the air change rate in an enclosed space during a selected time interval is directly proportional to the natural logarithm of the ratio of the concentrations of the tracer gas at the beginning and end of the time interval, assuming that the forces causing infiltration remain constant. A constant infiltration rate is then represented by a straight line on semi-logarithmic paper.

Published information[5] on infiltration measurements in two test houses at the University of Illinois, one a two-story brick veneer structure over a basement and the other a one-story frame structure over a basement, indicated that the air change rate in each was directly proportional to the indoor–outdoor temperature difference and also to the wind velocity. These data showed that an increase in wind velocity of one mph was equivalent to an increase in indoor–outdoor temperature difference of 2 to 4°F in its effect on the infiltration rate. Thus, an expression of the form of eqn (5) can be used to approximate the effect of wind and temperature difference on the air change rate for a test house.[6] This is represented by

$$I = A + BW + CT, \tag{5}$$

where I = infiltration rate (hourly air change rate), W = wind velocity (mph), T = inside–outside temperature difference (°F), A = the air change rate with no wind and no temperature difference (hr^{-1}), and B,C = the increase in the air change per unit increase in wind velocity and temperature difference, respectively. Under field conditions, it is difficult to isolate the effects of wind and temperature without an extensive measurement program. However, eqn (5) implies that upper bounds may be placed on infiltration by performing measurements during those times in which wind velocity or inside–outside temperature difference is the greatest.

While tracer-gas data are not abundant for residential structures, there do exist sufficient measurements to make general inferences about the nature of infiltration. For large structures, we know of only two infiltration studies. In one,[20] tracer-dilution infiltration data were obtained on two eight-story dormitory buildings. The data are somewhat suspect since a very cumbersome sensing device (an electronegative gas detector utilizing an ozone lamp) was used to measure the decay in tracer-gas concentration. These data do show, however, that air change rates for the two buildings are comparable with those measured for smaller structures. Systematic investigations of the effects of wind and temperature have not been forthcoming.

The second study[21] utilized sulfur hexafluoride concentration decay to infer an infiltration rate in a nine-story building. This study found almost a factor of three (0.36–0.92 ACPH) variation in infiltration rate, depending on whether outside air vents were open or closed.

Residential infiltration measurements utilizing tracer gas are relatively straightforward to accomplish. Generally, a small amount of tracer gas is released in the structure and either the central heating system or a few optimally placed fans are used to assure a homogeneous tracer gas concentration in the structure. After this, the decay in tracer gas concentration as a function of time is monitored. In the case of electronegative gases such as SF_6 and the halocarbons, the monitoring instrument of choice is a gas chromatograph equipped with an electron capture detector. By repeating this procedure a number of times, it is possible to characterize the effects of climatological (temperature and wind) and structural (walls, windows, floors, ceilings, doors, etc.) factors on the infiltration rate.

Approaches are not so straightforward for large buildings. The sheer volume of the building indicates that a simple tracer release/sampling operation may not provide data which are valid for the structure as a whole. Two general approaches, however, can be undertaken. If one is more concerned about the relative contribution of a given floor to total structure infiltration (as would be the case in deciding on a retrofitting program), it is generally sufficient to perform measurements in a manner similar to that for residential structures for each floor. An anomalously high ACPH for a given floor would imply that retrofitting should concentrate on this floor.

A useful improvement on this established technique is the use of multiple tracer gases to characterize air exchange between the floors immediately above and below the floor being studied. By releasing three different tracer gases on three consecutive floors and monitoring their relative concentration decays with time on all three floors, one can completely characterize infiltration across the floor, ceiling and external envelope of the middle floor. This technique is identified as the "sandwich approach" and depicted in Fig. 1.

On the other hand, to characterize the total infiltration of a large structure, it is necessary to provide a tracer supply and sampling network. In this technique (identified as the "simultaneous approach"), each floor is provided with the same tracer gas and sampled independently of all

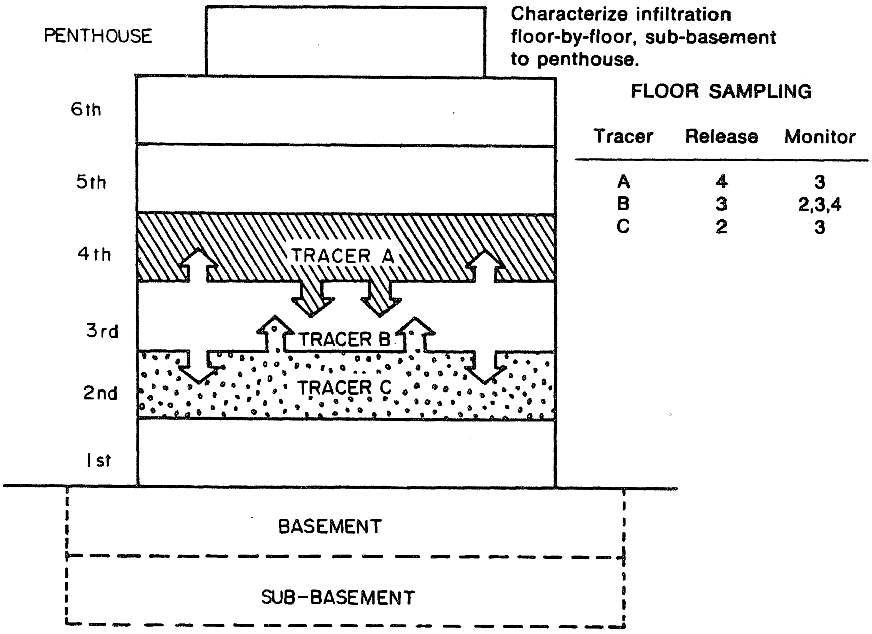

Fig. 1. Multiple tracer "sandwich approach" for characterizing air infiltration in highrise buildings.

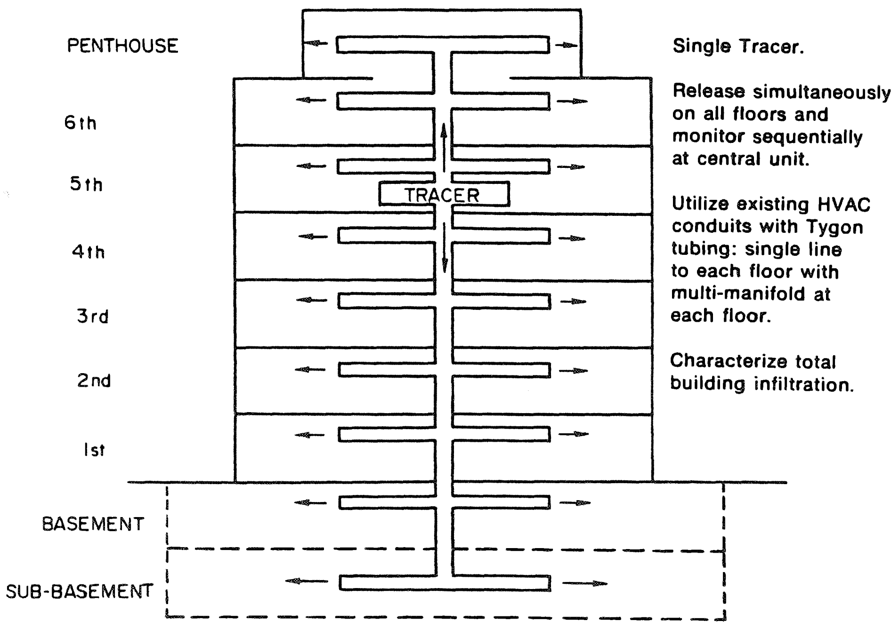

Fig. 2. Single tracer "simultaneous approach" for characterizing air infiltration in highrise buildings.

other floors. As shown in Fig. 2, flexible tubing is run to each floor generally through the heating/ventilating or air-conditioning ducting or the service channel in a particular building. Sampling and gas injection are performed at one central location within the structure. Actual installation details are strongly dependent on the physical characteristics of each individual building.

The "simultaneous approach" allows one to obtain individual decay rates for each floor at approximately the same time. Suitable averaging then provides the average infiltration rate for the structure, thereby allowing one to study systematic variations in infiltration rate due to temperature, wind, or other factors.

The problem of characterizing building infiltration in its entirety has only recently become important. Understanding of the phenomenon and proper procedural methods and instrumentation to measure and characterize it is only beginning. The authors of a recent[22] NBS report on energy conservation in buildings concluded: "One of the greatest causes of building energy waste is due to unwanted air leakage, which is usually affected by the way the buildings are constructed and by the outdoor weather conditions, particularly the temperature and wind. Yet the present technology for estimating the heat gain and heat loss due to infiltration is relatively weak as compared to other modes of heat transfer such as conduction and solar radiation. Methods of testing and evaluating building air infiltration under field conditions are presently available, but such methods need to be further developed and reduced to consensus standard procedures".

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