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WATER VAPOR MASS BALANCE METHOD FOR DETERMINING AIR INFILTRATION RATES IN HOUSES

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Abstract. A water vapor mass balance technique that includes the use of common humidity-control equipment can be used to determine average air infiltration rates in buildings. Only measurements of the humidity inside and outside the home, the mass of vapor exchanged by a humidifier/dehumidifier, and the volume of interior air space are needed. This method gives results that compare favorably with those obtained with standard methods that include the use of CO_2 as a tracer gas.

Air infiltration commonly accounts for about one-third of the total heat loss from houses. Hence, there is considerable interest in measuring air infiltration as a means of evaluating energy saving efforts. Forests and windbreaks reduce air infiltration by reducing wind speed (DeWalle 1978; Mattingly et al. 1979). Air infiltration also can be reduced considerably by various retrofitting techniques.

The standard practice for determining air infiltration rates (ASHRAE 1972; Blomsterberg and Harrje 1979) usually includes injecting a tracer gas into the interior air space and using sensitive gas detection equipment to monitor the exponential decay of gas concentration over time. Unless automated instrumentation is used, this method requires constant attention in obtaining averages over long periods. Such automated equipment has recently been developed and used (Harrje et al. 1975; Harrje and Grot 1978; Kumar et al. 1979; Mattingly et al. 1979), but it is not commercially available and is relatively expensive.

In recently completed research on the effects of forest and windbreaks on air infiltration and energy consumption in houses (DeWalle 1980), a water vapor mass balance method was developed for determining air infiltration rates in small mobile homes. The technique is based on measuring the amount of water exchanged by a common humidifier/ dehumidifier in maintaining the humidity of the interior air at a desired level and measuring the humidity of the interior and exterior air. On the basis of its successful application in small mobile homes and in a large, two-story residence, the vapor balance technique would seem to offer the possibility of accurately determining average air infiltration rates with the use of commonly available equipment. This paper describes the theory and application of the vapor balance method and gives results of a comparison of air infiltration measurements by the water vapor mass balance method and measurements obtained from the use of CO_2 as a tracer gas.

THEORY

The vapor balance method is based on a mass balance of water vapor in the air in the house as:

$$W_i - W_e + S = 0 \quad (1)$$

where W_i is the mass flow rate of water vapor in the air infiltrating the house, W_e is the mass flow rate of water vapor in the air exfiltrating the house, and S is the mass of water vapor added or lost from the air within the house per unit time. The water vapor content of the air within the house is assumed to be constant with time.

The mass flow rate of water vapor in infiltrating and exfiltrating air can be calculated as:

$$W_i = Q_i \cdot M_i \quad (2)$$

$$W_e = Q_e \cdot M_e \quad (3)$$

where Q is the mass flow rate (kg/hr) of either infiltrating or exfiltrating dry air and M is the mixing ratio (kg vapor per kg dry air) for infiltrating or exfiltrating air. Although the volume of air passing through the house may change due to changes in temperature and pressure within it, it is assumed that the mass of air entering during a time period equals the mass of air leaving the house:

$$Q_i = Q_e = Q \quad (4)$$

Substituting Equations 2 through 4 in Equation 1 gives a solution for the mass flow rate of dry air infiltrating or exfiltrating the house (kg/hr) as:

$$Q = S/(M_i - M_e) \quad (5)$$

Equation 5 allows the evaluation of air infiltration rates (Q in kg/hr) if the source or sink strength for water vapor (S) is known and the difference in humidity between inside and outside air is measured. Mixing ratios for either infiltrating or exfiltrating air can be computed from:

$$M = 0.622e/(P\text{-}e) \quad (6)$$

in which e is the water vapor pressure in the air, P is total atmospheric pressure, and 0.622 is the ratio of the molecular weight of water to the molecular weight of air. In this expression, the same pressure units must be used for both P and e. It can be assumed that total atmospheric pressure is the same both inside and outside a house.

The use of Equation 5 to obtain air infiltration rates depends on controlling the interior humidity and S through the use of humidification/dehumidification equipment. Specifically, the interior humidity is elevated above normal levels in winter or depressed below normal levels in summer.

Two calculation procedures must be used: one for houses with and one for those without other internal sources of water vapor due to normal human activity such as bathing, washing, cooking, and breathing. In houses without internal vapor sources:

$$S = S_H$$

where S_H is the source or sink strength for vapor due to humidification or dehumidification equipment. In this case, Q may be obtained directly as:

$$Q = -\frac{S_H}{(M_i - M_e)} \quad (7)$$

It is also assumed that exfiltrating air represents the only sink for water vapor in the house—condensation on or absorption by interior surfaces is negligible.

In homes with additional vapor sources:

$$S = S_H + S_p \quad (8)$$

where S_p is the vapor source strength from the normal activity of people. Thus, with the humidification/dehumidification equipment in operation, Equation 1 becomes:

$$W_i - W_e + S_p + S_H = 0 \quad (9)$$

Without the equipment in operation but with normal human activity, Equation 1 could be written as:

$$W_i - W_{ep} + S_p = 0 \quad (10)$$

where W_{ep} is the mass flow of water vapor that exfiltrates the house. If both sources of vapor operate simultaneously and complete mixing of water vapor from S_H and S_p is assumed within the house, Equation 10 may be combined with Equation 9 to give:

$$W_{ep} - W_e + S_H = 0 \quad (11)$$

which can be reduced using Equations 2 through 4 to:

$$Q = -\frac{S_H}{(M_{ep} - M_e)} \quad (12)$$

where M_{ep} is the mixing ratio of the exfiltrating air or interior humidity that would exist without the influence of S_H. Again, it must be assumed that there are no sinks for vapor other than the exfiltrating air within the house.

Typically, air infiltration rates are expressed as house volume changes per unit of time. Air infiltration rates in mass/time units computed with either Equation 7 or 12 can be converted to volume changes/hr as:

$$AIR = Q/1.204V, \text{ volume changes/hr} \quad (13)$$

where Q = air infiltration rate, kg/hr
V = volume of interior air space in dwelling, m^3

and 1.204 is the density of dry air in kg/m^3 at an air temperature of 20°C and 1013 mb pressure. To be directly comparable, air infiltration rates expressed as volume changes per hour should be standardized to a common temperature and pressure; 20°C and 1013 mb are used in Equation 13. The use of air infiltration rates expressed as a mass flow rate of dry air would avoid this problem as well as problems that arise from the effects of varying interior humidity on air density.

APPLICATION

The vapor balance method was tested in a small mobile home without vapor sources from occupants ($S_p = 0$), and also in a large two-story frame house where the effects of vapor sources from occupants were included. In practice, the humidity of the interior air can be controlled with readily available equipment. In all our tests we used a home humidifier/dehumidifier equipped with a controller to regulate humidity levels. The humidifier/dehumidifier was placed on a platform balance and was weighted to the nearest 5 gm so that S_H could be easily determined by weighing at the beginning and the end of each period. The mass of water also could be determined volumetrically. We used either hygrothermographs with sensing elements of human hair or dewpoint hygrometers (EG & G Model 800A)[1] to obtain M_1 and M_e. Perhaps the simplest device that could be used is a sling psychrometer with wet- and dry-bulb thermometers.

Both the vapor balance and tracer gas techniques are best adapted to determining average air infiltration rates over periods of several hours. The shortest periods we used were 3½ hr; these probably are close to the minimum for most conditions. Much shorter periods are not possible because of the time required for mixing of air in the house and the response time of humidification/dehumidification equipment. The typical variations of mixing ratio in the mobile home in March 1979 (Fig. 1) show that the humidifier cycled on about two times per hour during periods with low air infiltration and about four times per hour when air infiltration was relatively high. Note also in Figure 1 that fluctuations in mixing ratio are more erratic on a windy day because of greater variations in air infiltration rates.

Typical results from computing air infiltration in a small mobile home serve as an illustration of the magnitudes of measured quantities (Table 1). With summer dehumidifica-

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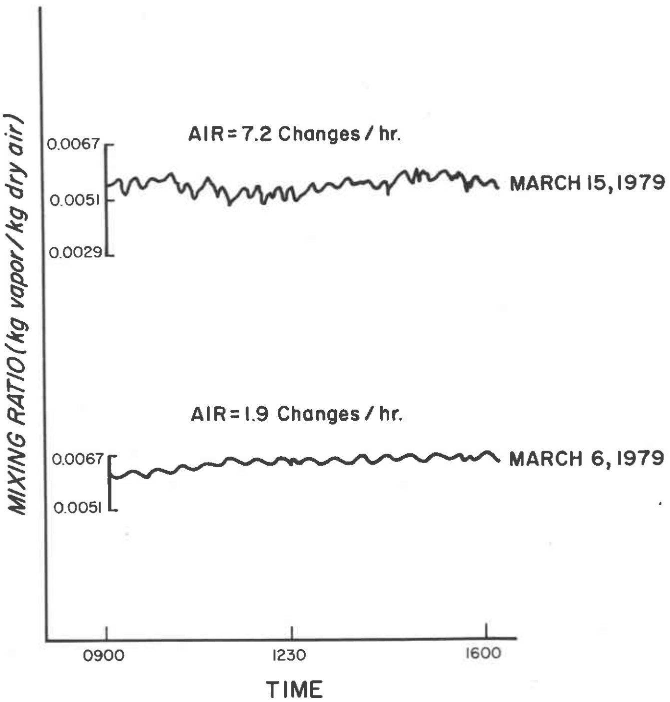
Figure 1.—Fluctuations in mixing ratio in a mobile home during periods when air infiltration was being measured and humidity was controlled.



tion on 29 August, the mixing ratio of infiltrating air (M_i) is greater than the mixing ratio of exfiltrating air (M_e). However, for winter conditions with humidification this is reversed, the mixing ratio of exfiltrating air being greater on both March 2 and 7. The total mass of water lost or gained (S_H) during the 24-hr periods used in these tests was between 2.5 and 3.5 kg, which could be measured accurately on a platform balance.

Data for 2 winter days are included in Table 1 to illustrate the sensitivity of the method to the effects of wind velocity on air infiltration rates. On 2 March, the air infiltration rate computed with Equations 7 and 13 was 2.53 volume changes per hour for a wind velocity of 3.00 m/s, while on 7 March the ratio was only 1.68 volume changes per hour for a velocity of 1.28 m/s. Although differences in density between cold exterior and warm interior air also can cause air infiltration, the differences in temperature on these 2 winter days were quite similar.

In an occupied, two-story frame house in Boalsburg, Pennsylvania, humidification was used to determine the air infiltration rates in mid-January. Just before humidification there was a mean mixing ratio of 0.0056 in the house due to normal habitation; the concurrent exterior mixing ratio was about 0.0019. The prior interior mixing ratio was assumed to represent the mixing ratio due to the occupants (M_{ep}) during the entire test period. Slight differences in the humidity of air on each floor were accounted for by computing a mean weighted by the volume of interior air space on each floor. A humidifier located on the first floor was used to increase the mixing ratio to 0.0087 (M_e). A period of about 10 to 12 hr was required to produce a stable humidity on both the first and second floors.

Table 1.—Typical data from computation of 24-hr mean air infiltration rates in a small mobile home, at an open site, in summer and winter

Date	Air temperature (°C)		Wind velocity	Mixing ratio		Water evaporated or condensed (S_H)	Air infiltration	
	Exterior	Interior		M_i	M_e		Q	AIR
			m/s	*kg vapor/kg dry air*		*kg/hr*	*kg/hr*	*Vol. Changes/hr*[a]
29 Aug	23.2	21.6	0.97	0.01520	0.00898	-0.141	22.67	1.54
7 Mar	-0.4	21.1	1.28	0.00298	0.00733	0.107	24.60	1.68
2 Mar	-2.6	18.1	3.00	0.00186	0.00574	0.144	37.11	2.53

[a]Volume changes computed using trailer volume (V) of 12.23 m^3.

After the stable humidity level had been achieved, the humidifier evaporated 4.988 kg of water during a 7.58-hr period to give S_H = 0.658 kg/hr. The indicated air infiltration rate of 212 kg/hr obtained from Equation 12, with 0.0056 substituted for M_{ep} and 0.0087 for M_e, was equivalent to an exchange rate of 0.59 volume changes per hour in the 300-m^3 interior air space at 20°C and 1013 mb pressure. This is a reasonable air infiltration rate for such a dwelling. Malik (1978) reported air infiltration rates of about 0.55 to 0.60 volume changes per hour for a townhouse in New Jersey under similar meteorological conditions—the inside-outside temperature difference was 29°C, and the wind velocity was less than 10 km/hr. Air infiltration rates in the mobile home (Table 1) were higher than in the New Jersey townhouse or two-story frame house.

In houses with internal vapor sources, the mixing ratio in the inside air with the occupants (M_{ep}) must be obtained. As in the foregoing example, the humidity in the house just before or after the test is conducted can be used for an approximation of M_{ep}. However, this requires the additional assumption that M_{ep} remains constant during the test. Dutt (1979) found that the mixing ratio in the upstairs living space of a New Jersey townhouse remained essentially constant at 0.0050 from 0400 to 2000 hr on a winter day, even though the exterior mixing ratio fell slowly from about 0.0026 to 0.0020 during the same period.

Our measurements in the occupied, two-story frame house mentioned earlier also indicate that interior humidities in winter are quite stable over periods of 1 day or less, responding only slowly to changes in exterior humidity. The average difference in mixing ratios between inside and outside air on 11 test days in winter was 0.0030. Differences rose to 0.0035 immediately after bathing and fell to 0.0027 during evening sedentary periods. It is recommended that air infiltration tests be conducted during noncooking and nonbathing periods to minimize errors due to variations in M_{ep} or S_p.

There are several other considerations in using the water vapor mass balance method. These are: avoiding excessive humidification, condensation of vapor on interior surfaces, absorption or release of water by porous materials, the need for mixing of interior air, and changes in air density caused by the addition or removal of water vapor.

Excessive prolonged humidification is to be avoided to maintain human comfort, to prevent accelerated growth of microorganisms, and to avoid condensation in walls. Interior humidities usually need not be increased to near saturation levels to achieve accurate results, even when simple humidity measurement equipment is used. In the example of the mobile home on March 2 and 7 (Table 1), the mixing ratios of exfiltrating air correspond to relative humidities of 46 and 44 percent. This range is quite satisfactory for comfort.

Condensation on cooler interior surfaces during humidification could conceivably represent a significant sink for water vapor. Properly located vapor barriers within the walls of a house should prevent this condensation over a large surface area. Condensation did occur on the windows of the mobile homes during the experiments in winter; however, measuring the mass of vapor condensed on windows simply by absorbing the water with tissues and weighing indicated an insignificant sink for vapor. No condensation was detected on the double-pane glass windows in the two-story house during humidification. However, condensation would make this method unsuitable for measuring air infiltration in structures without insulation, such as greenhouses, when inside surface temperatures of the walls fall below the dewpoint.

In a house there also may be interior sinks and sources for water vapor caused by absorption or desiccation by solid materials. Humidification or dehumidification should proceed for a time after the desired, stable interior humidity has been achieved to minimize effects of absorbants. A tendency for calculated air infiltration rates to decline gradually over time when humidifying may indicate the effects of gradually declining rates of absorption by household materials. Similarly, when dehumidification is used, computed air infiltration rates would tend to increase gradually if there is significant desiccation. Any noticeable trends indicate the need for extended periods of humidity control. Effects of desiccation or absorption were not detected in the mobile homes or in the two-story house.

Mixing of interior air is required to accurately determine air infiltration by the vapor balance method (and also by the tracer gas method). Consequently, the method would work best in a house with central, forced-air space conditioning. We used a small rotating fan in the mobile home to circulate and mix the air. The frame house had baseboard heat, so interior doors were left open to allow air mixing, and air infiltration was measured over long periods so that adequate mixing would occur due to general convective air movement in the house.

Humidification and dehumidification of interior air changes air density slightly and theoretically could increase the air infiltration rate. However, we ignored this effect because it is relatively small. As an example of the potential influence of added humidity on infiltration, we can look at the differences in air density during measurements of air infiltration in the two-story house. The difference in density between inside and outside air before humidification was calculated to be 0.1346 kg m^{-3}, or about 10.09 percent. When humidity was added by the humidifier, the inside air density decreased further; but the outside-inside difference increased to only 0.1368 kg m^{-3}, or about 10.25 percent. Hence, most of the outside-inside density difference was caused by the difference of 29°C in air temperature.

COMPARISON OF WATER VAPOR BALANCE AND TRACER GAS METHODS

The water vapor mass balance and tracer gas techniques were compared in a small mobile home on 3 test days. For the tracer gas method, CO_2 gas was used along with an infrared gas analyzer to monitor CO_2 concentrations. The infrared gas analyzer was calibrated periodically from a standard gas supply at 13 percent CO_2 by volume. Carbon dioxide levels were raised to about 5 percent by volume at the beginning of a test run. Air infiltration rates were determined from the slope of the ln c/c_o vs. time graph, where c_o is the initial CO_2 concentration and c is the instantaneous CO_2 concentration at time t (ASHRAE 1972). Average air infiltration rates were determined by the tracer gas technique over a number of 10- to 25-minute periods during each day. Equations 7 and 13 were used to obtain a vapor balance estimate of the mean air infiltration rate for the total concurrent period.

Table 2.—Mean air infiltration rates in a small mobile home computed with the water vapor mass balance and CO^2 tracer gas methods

Date	Hourly periods	Air temperature (°C)		Wind velocity (m/s)	Air infiltration rates (Volume changes/hr)	
		Exterior	Interior		Vapor balance[a]	CO_2 tracer gas[b]
24 Jan 78	5	-7.5	21.7	0.34	3.5	3.2 ± 0.78
26 Jan 78	12	-4.9	20.2	6.00	7.2	6.8 ± 1.13
27 Jan 78	9	-9.1	20.6	4.49	4.3	5.2 ± 1.64

[a] Air infiltration rate corrected to air temperature of 20°C and 1013 mb atmospheric pressure.

[b] Mean of estimates for period plus or minus the 95 percent confidence limits.

The mean air infiltration rate computed by the vapor balance method was not significantly different from rates determined with the CO_2 tracer gas method on each of the 3 test days in 1978. (Table 2). The comparison must be on a statistical basis since the air infiltration rates determined with the tracer gas technique varied considerably, whereas with the vapor balance method, only a single value was obtained. On 24 and 26 January, the techniques yielded air infiltration rates which differed by only 0.3 and 0.4 volume changes per hour, respectively. However, on 27 January, the difference was 0.9 changes per hour. In all cases, this difference still did not exceed the 95 percent confidence limits on the mean determined by the tracer gas technique.

CONCLUSION

The water vapor mass balance method can be used by homeowners and researchers to determine average air infiltration rates in houses. This technique requires only simple, inexpensive equipment, and is adapted to determine average air infiltration rates over periods of several hours or more. The method is best suited to determining air infiltration rates in buildings without internal sources of water vapor, but can be modified to account for effects of vapor added by occupants. This technique could be used to determine the effects of forests and windbreaks or home retrofitting programs on air infiltration and home energy use.

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