INFILTRATION IN RESIDENTIAL STRUCTURES

J. E. Janssen
Senior Staff Engineer

J. J. Glatzel
Senior Research Technician

R. H. Torborg
Senior Research Scientist

U. Bonne
Staff Scientist

Honeywell Corporate Research Center
Bloomington, Minnesota

ABSTRACT

Heat loss or gain in residential structures occurs by conduction through the walls and by infiltration of outside air. The ASHRAE Handbook and other publications contain data necessary for relatively precise calculation of these conduction losses. However, infiltration losses depend on the condition of the structure. One has to depend on actual measurements or judgement of what average conditions can be expected.

Infiltration measurements are usually made by filling the structure with a tracer gas and observing the rate of decay of its concentration. Tests are described in which a dilute concentration of chemically pure methane has been used with considerable success. Measurements are made with a non-dispersive infrared analyzer. Methane concentrations of 1000 ppm maximum give a factor of safety of 50 below the lower flamability limit.

The amount of methane added to the air and its initial equilibrium concentration are measured. From this the house volume is computed and compared to geometrical measurements. Agreement usually within 2-3% indicated uniform distribution of the tracer.

Infiltration exchange rates of 0.4 to 0.6 air changes per hour are typical for good construction. A high wind and open fireplace dampers can double this rate. Loose construction, i.e. single glazing with loose fitting windows and doors, exhibits infiltration rates in excess of 1 air change per hour. Data are presented for homes in Minneapolis, Denver and Kansas City.

NOMENCLATURE

C_T = Tracer concentration
t = Time or Time interval
V_h = House volume
$\dot{V}_i$ = Infiltration flow rate
$\dot{V}_s$ = Combustion and draft control air flow up stack
V_T = Tracer flow rate
ϕ = Stack loss weighting factor
τ = Time constant

Subscripts:
0 = Time at end of charging period and start of decay period
1,2 = Later times in decay period
p = Furnace off, stack plugged
f = Stack open, furnace on or off

INTRODUCTION

An important objective for everyone today is to reduce energy waste and inefficiency in every way possible. Studies of the seasonal fuel utilization efficiency of residential heating systems (1,2,3,4,5) have shown that excess capacity is a source of inefficiency. More accurate sizing of heating appliances requires better knowledge of the heat loss characteristics of residential structures. This heat loss occurs both by conduction through the walls and by infiltration of outside air.

Procedures and data presented in the ASHRAE Handbook of Fundamentals (6) provide means for calculating the conduction heat loss with reasonable accuracy. This is not true for infiltration, however. And infiltration accounts for about 1/3 of the total heat loss in many contemporary, well insulated houses.

There are two general methods for estimating infiltration, the crack method and the air change method. The crack method employs a detailed measurement of the length of cracks or joints around all windows and doors. The crack clearance and pressure differential due to wind and temperature differences must be estimated. Handbook tables (6) based on laboratory measurements then enable one to estimate the infiltration flow through the cracks. This is a very laborious method with large uncertainties.

The air change method estimates the rate at which the volume of air within the structure is exchanged with outdoor air. It is based on judgement and statistical data from measurement of infiltration in existing structures. While the opportunity for error is large, the ease of making the estimate justifies its preference over the crack method for use by heating contractors in sizing residential heating systems.

A tracer method is usually employed for measurement of infiltration in structures. A trace gas which is easily measured in dilute mixtures is added either batchwise or continuously to the air in a building. Then the rate of decay in concentration (batchwise process) or the steady state concentration (continuous addition method) is measured.

A number of gases have been used by different investigators (7) including helium (NBS), ethane (IGT), nitrogen oxide, sulfur hexafluoride (Princeton, NBS) and clorothene (8). We chose methane and the batch method for reasons discussed below.

Infiltration is influenced by wind, indoor-outdoor temperature difference, tightness of the structure, type of structure (i.e. one story, two story or split level) and humidity. Various investigators (7,8,9) have studied infiltration in order to better understand its dependence on outdoor temperature and humidity. Our objective was to survey contemporary residential structures in three different climates, Minneapolis, Denver and Kansas City. The data represent an estimate of what can be expected under average operating conditions in moderate to cold climates.

ANALYSIS

The tracer method we used for measuring infiltration consisted of adding a known amount of easily detectable tracer gas to the air in a house. The rate of decay of the tracer concentration was then measured as a function of time.

The decay in the tracer concentration is given by

$$C_T = C_{To} e^{-t/\tau} \qquad (1)$$

or

$$\tau = \frac{t_2 - t_1}{\ln\left[\frac{C_{T1}}{C_{T2}}\right]} \qquad (2)$$

In one time interval equal to the time constant, τ, the volume of air infiltrated will be equal to the volume of the house.

$$V_h = \tau \dot{V}_i \qquad (3)$$

or

$$\dot{V}_i = \frac{V_h}{\tau} \qquad (4)$$

The volume of the house, V_h, can be measured from its geometry. The volume also can be measured by the amount of tracer gas added and noting the concentration it produces. Since the tracer is added over a period of time and some is lost through exfiltration while charging the house, allowance must be made for this loss.

The amount of tracer added is:

$$\dot{V}_T t \qquad (5)$$

and the amount lost is

$$\dot{V}_i \int_0^t C_T dt \qquad (6)$$

Thus the tracer left in the house at the end of the charging period is,

$$V_h C_{To} = \dot{V}_T t - \dot{V}_i \int_0^t C_T dt \qquad (7)$$

or

$$C_{To} = \frac{\dot{V}_T t}{V_h} - \frac{\dot{V}_i}{V_h} \int_0^t C_T dt \qquad (8)$$

The integral term in eq. (8) is the loss of tracer during the charging period. Integration (see Appendix) yields

$$V_h = \frac{\dot{V}_T}{C_{To}} \tau (1 - e^{-t/\tau}) \qquad (9)$$

The infiltration rate is then

$$\dot{V}_i = \frac{V_h}{\tau} = \frac{\dot{V}_T}{C_{To}} (1 - e^{-t/\tau}) \qquad (10)$$

EXPERIMENTAL PROCEDURE

Equations (2), (9) and (10) provide the basis for the measurements. Figure 1 shows a schematic of the instrumentation and its location with respect to the furnace. This technique works best in a residence heated with a warm air furnace. The furnace fan and duct work provide an ideal distribution system. Measurements in houses with hydronic, electric baseboard, etc. heating systems will require

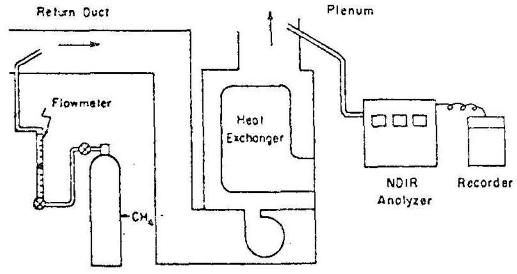

Fig. 1 Infiltration Measurement with Tracer

means to distribute tracer to, and obtain samples from each room.

We chose methane as a tracer gas for several reasons. Its molecular weight is relatively close to but somewhat less than that of air. Thus its diffusion characteristics are similar to air but it will not tend to collect in low places. It does not adsorb readily on surfaces in a house, is non-toxic and odorless if reasonably pure. Technical grade methane is available in the larger cities and is of relatively low cost. Its concentration can be easily and accuractly measured in the 10 to 1000 ppm range with non-dispersive infrared analyzers or hydrogen flame ionization instruments.

The explosion or fire hazard might seem to rule out the use of methane. The lower flamability limit of methane in air is 5.3%. A maximum concentration of 1000 ppm in the house gives a safety factor of 53. During the charging period, the concentration in the duct work will exceed this level unless the tracer flow rate is carefully controlled. Measurement of the concentration down stream of the injection point permits one to hold the duct concentration to an acceptable level. If the air flow rate is known approximately, the tracer charging rate can be adjusted to give a maximum duct concentration of about 5000 ppm. This gives a safety factor of 10 in the ducts. In general we have found a tracer charging rate of 15 to 20 liters/min will raise the average house concentration to the 500-1000 ppm range in 15 to 20 min. Faster charging produces poor distribution in the house at the end of the charging period. This generally increases errors in the measurement.

When the desired tracer level is reached, the tracer supply is shut off and the decay rate is recorded for a period of 1 to 3 hours. A simple computer program could be written to analyze the data. However, we found some advantage in plotting the concentration as a function of time on semi-log paper. The data points should fall on a straight line. Departure from a straight line usually indicates poor dispersion of the tracer or a non-representative sample. The decay rate during the first part of the decay period sometimes did show a departure from the line that developed later on. This indicated that mixing was incomplete at the beginning of the decay period. We found, however, that if the straight line from the latter part of the decay period was extrapolated back to the start of the decay period, we could get an initial tracer concentration, C_{To}, that was a good estimate of the well mixed concentration. This was used to compute house volume.

It was necessary to make certain that all interior doors including those to rooms, closets and cupboards were open to eliminate poorly sealed dead volumes in the house. Tight fitting doors like those on refrigerators, freezers and stoves were left closed. The object was to have free circulation to all spaces except those which were well sealed against diffusion of the tracer gas.

RESULTS AND DISCUSSION

The methods described were used to measure the infiltration in two houses located in Minneapolis, Minnesota during the 1975-76 heating season. Figure 2 shows the tracer decay curve for these houses under average winter weather in Minneapolis for a tri-level house. The three living levels of this house

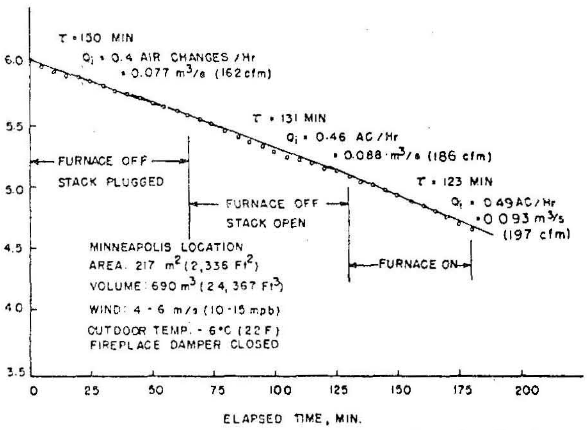

Fig. 2 Tracer Decay - Normal Operation Conditions

had a floor area of 217 m^2 (2,336 ft^2). The internal volume of the house, including the basement, based on geometrical calculations was 690 m^3 (24,367 ft^3). Figure 2 shows three different conditions: furnace off and stack plugged, furnace off and stack open, and furnace on. Differences in the infiltration for the three conditions are due to the effect of the flow of combustion and draft control air out the stack. If the amount of air flow out the stack is also measured during the on- and off-periods of the furnace, this flow can be compared to the change in infiltration to calculate a weighting factor for use in calculating the stack losses.

$$\phi = \frac{\dot{V}_{i,p} - \dot{V}_{i,f}}{\dot{V}_s} \qquad (11)$$

Flow out the chimney or stack of a combustion heating system is a form of exfiltration loss that must be balanced by increased infiltration or decreased exfiltration. The infiltration rate for the structure is measured with the stack plugged. Infiltration air flows into the building through openings in the lower part of the structure and on the windward side. An equal amount of air exfiltrates from the upper part of the structure and the leeward side since there is no net accumulation or loss of air in the building. When the stack is opened additional exfiltration air flows up the stack that must be balanced by increased infiltration. However, the pressure inside the building must be slightly lower to increase the infiltration. This then decreases the normal exfiltration. Thus only part of the air flow out of the stack comes from increased infiltration; the remainder comes from decreased exfiltration.

The energy needed to heat the combustion and draft control air from outdoor temperature to indoor temperature is a loss that is charged against the furnace when computing system efficiency by the loss method. However, since only part of the stack flow represents increased infiltration, this loss is reduced by the factor, ϕ. (1,2,3,4,5)

If the infiltration and exfiltration openings were of equal area and uniformly distributed, ϕ would be 0.5. In practice we have found $\phi=0.7$ is quite common. In a losely built structure $\phi<0.5$ is frequently found. Wind, height of building, location of windows and location of the furnace (basement, closet, attic) have a large influence on ϕ. For a furnace supplied with outdoor air for combustion, $\phi=1$ since all of the air flowing up the stack must be heated from outdoor temperature to stack temperature.

Figure 3 shows the infiltration for the same house as Fig. 2 under extreme conditions. The wind was very gusty with maximum velocity of about 13 m/s (30 mph). The gusts were sufficient to open the fireplace damper. It is seen that this maximum infiltration was about twice the normal infiltration rate.

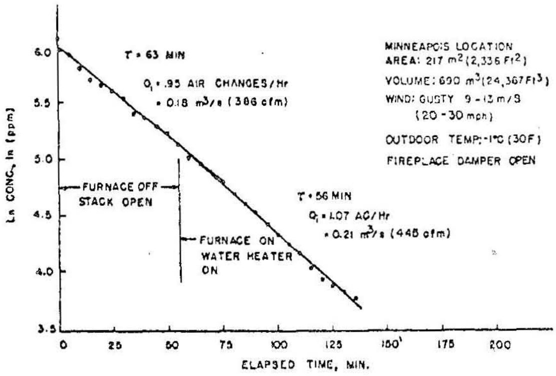

Fig. 3. Tracer Decay - Maximum Infiltration

Table 1 shows a summary of this data along with that of a second house located in Minneapolis. The volume of the tri-level house was calculated from the floor area and wall height. It is and estimated volume because the displacement of interior walls and furnishings was ignored. The method of measuring the volume from the tracer input was not developed until

Table 1. Infiltration in Two Minneapolis Houses

Type House	Volume		Weather		Furnace On		Furnace Off	
	Estimated	Measured	Temp.	Wind	Qi	Qi	Qi	Qi
	m^3	m^3	°C	m/s	m^3/s	AC/hr	m^3/s	AC/hr
Tri-level, thermopane normal	690		-6	4-6	.093	.49	.088	.46
Tri-level, thermopane maximum	690		-1	9-13	.205	1.07	.18	.95
Rambler+walkout thermopane		687	-8	8-14			.057	.30
Rambler+walkout thermopane		543	6	3			.036	.24

after these data were taken.

The volume of the walkout rambler was computed from tracer measurements. There is substantial disagreement in the two measurements. The exact reason is not known but is assumed to be inaccurate measurement of the amount of tracer added to the air. The tracer flow rate during charging may not have been constant. The larger volume probably is more correct since an infiltration rate of only 0.24 air changes per hour is a very tight house.

Tables 2 and 3 show the results of measurements in Denver and Kansas City made in November 1976. Denver has a heating season of about 6000 deg days and Kansas City about 4700 compared to about 8000 for Minneapolis. It was expected that any differences in construction practices associated with climate would show up in this comparison.

The house volume in each case was computed both from the known floor area and from tracer measurements. The floor area calculation did not make allowance for the basement volume in the case of the tri-level house since there was no basement under the family room. We found, however, the effect of the basement volume could not be isolated. Leakage from the ducts filled the basements with tracer. Thus the tracer measurements included the basement volume in all cases. For those cases where basement volume could be estimated with reasonable accuracy, there was generally good agreement between the estimated and measured volumes of the houses. The estimates based on floor area tended to be too large because they ignored the displacement of the walls, sofits, etc. The agreement between estimated and measured house volume increased confidence in the infiltration measurements.

The infiltration flow increased as expected in all but two cases when the furnace turned on. The effect of flow up the stack should increase infiltration when the furnace is on. The first two houses in the Denver study decreased slightly during the furnace on period. It is possible for the furnace to have little or no effect on infiltration, but probably not a negative effect. Flow of combustion and draft control air out the stack can increase infiltration only if the flow slightly decreases the pressure in the house. There is a flow of infiltration air in through cracks on the windward side of a house and at the lower levels of the house. There must be an equal amount of exfiltration out the leeward side and the upper levels (due to the buoyancy of the warmer inside air). If a house has substantial crack area, i.e. high infiltration, the furnace combustion and draft control air may come primarily from decreased exfiltration. The two story house in Denver had two fireplaces which were not equipped with dampers. This acounts for the high infiltration rate and the lack of effect when the furnace was on.

If a house is relatively tight in the lower half and on the windward side, infiltration is inhibited but exfiltration may not be. Again, the stack flow would come mainly at the expense of exfiltration. This would be most likely to happen in a single story, basementless house such as the one tested in Denver.

The benefit of double glass, storm windows or thermopane is evident in the tests. The basementless ranch house in Denver was the only one with single glass that was relatively tight. The single story construction probably contributed to low infiltration.

The Denver tri-level with single glass had a high infiltration rate. The windows and doors fit very loosely.

The three split level houses in Kansas City all had partial basements that were connected to the house only through the garage. The garage doors were closed and the door from the house to the garage was closed. In all three cases the duct work leaked enough to bring the basement to the same tracer concentration as the house. Thus the basement volume was measured along with the rest of the house.

Table 2. Infiltration in Five Denver Homes

House Type	Windows	Volume		Weather		Furnace On		Furnace Off	
		Estimated	Measured	Temp.	Wind	Qi	Qi	Qi	Qi
		m^3	m^3	°C	m/s	m^3/s	AC/hr	m/s	AC/hr
Two story (no fireplace damper)	Single	510	504	0	.7	.133	.95	.137	.97
Basementless Ranch	Single	380	362	4	1.3	.041	.41	.044	.44
Tri-level (open fireplace damper)	Double	544+	718	4	1.0	.138	.69	.116	.58
Tri-level	Single	430+	513	1	0	.170	1.19	.097	.67
Tri-level	Double	294+	349	5	0	.093	.96	.040	.41

Table 3. Infiltration in Five Kansas City Homes

House Type	Windows	Volume		Weather		Furnace On		Furnace Off	
		Estimated	Measured	Temp.	Wind	Qi	Qi	Qi	Qi
		m^3	m^3	°C	m/s	m^3/s	AC/hr	m^3/s	AC/hr
Two story	Double	612+	747	21	9-13	.100	.48	.087	.42
Tri-level	Thermopane	362+	483	4	1	.063	.47	.070	.52
Split level	Single	272+	473	2	0	.097	.74	.075	.57
Tri-level	Single	334+	418	-3	.7	.087	.75	.066	.57
Walkout,ramb.	Double	612	550	1	.5	.099	.65	.087	.57

CONCLUSIONS

The methane tracer technique works well for measuring residential infiltration. We found it to be safe when the procedures described were followed. Comparisons of the house volume measured by the tracer technique with geometrical calculations provides a check on uniformity of tracer mixing.

Contemporary houses in the Mid-West exhibit infiltration rates of 0.4 to 0.6 air changes (AC) per hour under normal conditions if equipped with double glass windows. Single glass windows usually exhibit infiltration rates of around .75 AC/hr. Poor fitting windows and doors give infiltration rates of around 1 AC/hr.

The infiltration rate generally increases somewhat during the furnace on period.

A strong gusty wind and an open fireplace damper can double the infiltration rate.

A factor for weighting the stack losses can be determined by comparing the flow rate of combustion and draft control air to the change in infiltration when the furnace is on or off. This factor, ϕ, is used in computing seasonal system efficiency of a combustion heating system.

ACKNOWLEDGEMENT

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APPENDIX

Integration of equation (7) gives:

$$V_h C_{To} = \dot{V}_T t - \dot{V}_i \int_o^t \left[\frac{\dot{V}_T t}{V} - \frac{\dot{V}_i}{V} \int_o^t C_T dt \right] dt \qquad (12)$$

$$= \dot{V}_T t - \frac{\dot{V}_i \dot{V}_T t^2}{V \ 2} + \frac{\dot{V}_i^{\,2}}{V} \int_o^t \int_o^t C_T dt dt \qquad (13)$$

We can substitute (8) in (12) and integrate again.

$$VC_{To} = \dot{V}_T t - \frac{\dot{V}_i \dot{V}_T t^2}{2\ V} +$$

$$\frac{\dot{V}_i^{\,2}}{V} \int_o^t \int_o^t \left[\frac{\dot{V}_T t}{V} - \frac{\dot{V}_i}{V} \int_o^t C_T dt \right] dt dt \qquad (14)$$

$$= \dot{V}_T t - \frac{\dot{V}_i \dot{V}_T t^2}{2\ V} +$$

$$\frac{\dot{V}_i^{\,2} \dot{V}_T t^3}{2 \cdot 3\ V^2} - \frac{\dot{V}_i^{\,3}}{V^2} \int_o^t \int_o^t \int_o^t C_T dt dt dt \qquad (15)$$

Further substitution and integration will yield an infinite series in which the integral term will be integrated an infinite number of times. It can be shown that this term is small compared to the rest of the equation and can be dropped. Equation (15) can then be written

$$VC_{To} = \dot{V}_T \left[t - \frac{\dot{V}_i t^2}{2V} + \frac{\dot{V}_i 2t^3}{2 \cdot 3V^2} - \frac{\dot{V}_i 3t^4}{4!V^3} + \ldots \right] \qquad (16)$$

$$C_{To} = \frac{\dot{V}_T}{\dot{V}_i} [X - \frac{X^2}{2} + \frac{X^3}{3!} - \ldots] \qquad (17)$$

where

$$X = \frac{\dot{V}_i t}{V} = \frac{t}{\tau}$$

$$1 - \frac{C_{To} \dot{V}_i}{V_T} = 1 - X + \frac{X^2}{2!} - \frac{X^3}{3!} + \ldots \qquad (18)$$

$$= e^{-X} \qquad (19)$$

$$\therefore \quad C_{To} = \frac{\dot{V}_T}{\dot{V}_i} (1 - e^{-X}) \qquad (20)$$

or

$$-X = \ell n \left(1 - \frac{C_{To} \dot{V}_i}{\dot{V}_T}\right) \qquad (21)$$

$$\frac{\dot{V}_i t}{V} = \ell n \left(\frac{\dot{V}_T}{\dot{V}_T - C_{T_o} \dot{V}_i} \right) \qquad (22)$$

Substituting equation (4) in (23)

$$\frac{t}{\tau} = \ell n \left(\frac{\dot{V}_T}{\dot{V}_T - C_{T_o} \dot{V}_i} \right) \qquad (23)$$

$$e^{t/\tau} = \frac{\dot{V}_T}{\dot{V}_T - C_{T_o}\dot{V}_i} \tag{24}$$

$$\dot{V}_T - C_{T_o}\dot{V}_i = \dot{V}_T e^{-t/\tau} \tag{25}$$

Thus the infiltration rate is

$$\dot{V}_i = \frac{\dot{V}_T}{CT_o}\,(1-e^{-t/\tau}) \tag{26}$$

and the house volume is

$$V = \dot{V}_i\tau = \frac{\tau\dot{V}_T}{C_{T_o}}\,(1-e^{-t/\tau}) \tag{27}$$