NO. 2339

MEASUREMENT OF AIR LEAKAGE CHARACTERISTICS OF HOUSE ENCLOSURES

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The heat loss associated with air leakage through the enclosure of a typical detached house may be as much as 40 percent of the total heat loss. It is essential, therefore, to be able to estimate this component of the heating load with reasonable precision. This paper describes a series of tests conducted on six wood-frame houses which established rates of overall air leakage and leakage through windows, doors, walls and ceilings, separately.

The rate of air exchange depends on the air leakage characteristics of the house enclosure and the pressure differences across it caused by weather and the operation of household equipment. Air leakage values for various wall components, such as windows, doors and wall constructions, are given in Chapter 19 of the ASHRAE HANDBOOK OF FUNDAMENTALS(1). These values are based on laboratory tests, and there are several published cases on overall air change rates of houses determined experimentally by means of the tracer gas technique. To complement these studies, field tests were undertaken during the summers of 1967 and 1968 to measure the air tightness of six single-family houses located in the Ottawa area.

The houses selected for these tests are described in Table 1. All were detached single-family residences located in built-up areas, constructed during the early nineteen-fifties. Houses No. 1 to 4 were bungalows; houses No. 5 and 6 were two stories. All were of insulated wood-frame construction. Houses No. 1 and 2, which were identical in construction, had brick and wood siding on the front and stucco finish on the remaining walls. Houses No. 3 and 4 had brick facing on all sides. The exterior walls of the first story of houses No. 5 and 6 were faced with brick; the second story of house No. 5 was finished with asbestos shingles. House No. 6 had aluminum siding. All the houses were heated by forced warm-air heating systems with high-pressure gun-type oil burners.

TEST PROCEDURE

The test arrangement is shown in Fig. 1. A vane axial fan of 3000-cfm capacity was connected at the opening of the basement window by a metal duct, 1 ft in diameter and 12 ft in length. The metal duct was connected to the suction side of the fan and was calibrated in the laboratory with a pitot traverse to permit measurement of flow rate with a single reading of air velocity (with the probe at the centerline of the duct). A damper was placed at the inlet of the 12-ft duct to permit control of the air exhaust rate. A pressure tap for measuring inside-to-outside pressure difference was installed in the basement wall.

Prior to each test, the outside surface of the roof, including the soffits, was covered with plastic sheets and sealed with adhesive tape. Windows and doors were covered and sealed to the frames, but joints between window frames and walls were not sealed. All openings of the exhaust vents were sealed at the exterior, but fireplace and chimney openings were sealed inside the house. The plastic sheets were held in place during the tests by suction pressures as well as adhesive tape. Prime windows were closed and locked, and storm windows and doors were installed before sealing. Interior doors, including the basement door, were left open to assist in equalizing pressures inside the house.

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The initial test was conducted with the house sealed except for the outside-wall construction. The damper was adjusted to achieve a pressure difference across the exterior walls of 0.30 in. of water and the exhaust rate, representing the leakage flow through the wall construction, was recorded. Pressure measurements were made with a strain gauge, diaphragm-type pressure transducer with a sensitivity of 0.002 in. of water.

The test was repeated with plastic sheets and storm units, each removed in turn. The order of removal was as follows: roof seal, door seals, storm doors, window seals, storm windows and fireplace seal. Each flow measurement was taken with the damper adjusted to maintain a pressure difference across the exterior walls of 0.30 in. of water. The increase in the exhaust air rate caused by the removal of each seal or storm unit represents, therefore, the leakage rate through that particular component. An average leakage rate for each type of window or door was obtained with the single flow reading with seals of all similar units removed.

These tests were conducted during the summer months and during relatively calm conditions, with wind speeds of less than 5 mph, so that uniform and stable pressure differences across the house enclosure were insured.

RESULTS

The test results are given in Table 2. As specified, the total and component leakage flows (ceiling, outside walls, and combined window and door leakage) were based on a pressure difference of 0.30 in. of water. The given values were with storm units on and both fireplace and chimney openings and exhaust vents sealed. Houses No. 1 and 2 (identical in construction) gave similar leakage values, as expected. Values of total leakage for houses No. 1 and 2 were approximately one-half those of houses No. 3 to 6. Leakage flow through windows and doors varied from 15 to 24 percent of total leakage flow for all test houses, with the remainder flowing through the wall and ceiling construction. Leakage flows through the fireplace with the damper closed were 80, 110, and 70 cfm for houses No. 3, 4 and 6, respectively.

Leakage characteristics are given in Table 3 in terms of equivalent orifice area. Note that they are based on assumed orifice characteristics (flows measured at 0.30 in. of water). The overall leakage characteristics are also given in terms of square feet of opening per cubic foot of house volume. They indicate that houses No. 1 and 2 are significantly tighter than all the others tested. The apparent leakage area for the ceiling construction varied from 0.03 to 0.10 sq in. per sq ft of ceiling area. Such values are quite significant in terms of problems associated with moisture transfer from living spaces into roof spaces during winter(2).

Leakage areas for the wall construction varied from 0.016 to 0.130 sq in. per sq ft of net wall area. The values for ceiling and wall constructions are also given in Table 4 in terms of cfm per square foot of area at 0.30 in. of water. Results show that the flow rates through the exterior walls of houses No. 1 and 2, which had stucco finishes are considerably lower than the flow rates of houses with masonry or a combination of masonry and aluminum siding or asbestos shingles.

The leakage values for windows and doors with and without storms are given in Table 5. All the figures for sash leakage are for the locked condition. The average leakage values for the wood double-hung windows without storms varied from 0.60 to 2.10 cfm per ft of crack at 0.30 in. of water pressure difference.

These values should be compared with those given in the ASHRAE HANDBOOK OF FUNDAMENTALS: 2.50 for nonweatherstripped, loose fit; 0.95 for nonweatherstripped, average fit. The average leakage values of 2.55 cfm per ft of crack for wood horizontal siding windows for house No. 6 and 0.98 and 1.26 cfm per ft for houses No. 1 and 2 falls within the range of leakage values for horizontal sliding windows given in the ASHRAE HANDBOOK.

The average leakage values for doors varied from 0.78 to 3.93 cfm per ft of door crack. Values in winter can be expected to be higher than those measured in summer because of increased clearance from warpage, which usually occurs during cold weather. The percentage reduction in leakage values with storm units is also given in Table 5. The leakage values were reduced by 26 to 79 percent of those obtained without storm units.

Air leakage measurements using the tracer gas technique reported in Ref 3 were carried out on houses No. 1 and 3 from the winter of 1960-61 through the winter of 1961-62. Measurements of air change rate per hour (based on total house volume, including basement) during the summer indicated that the increase for each mph of wind, up to wind speeds of 8 mph (measured with an anemometer located adjacent to the test houses and 25 ft above ground level), was 0.017

for house No. 1 and 0.020 for house No. 3. Wind speeds measured on site were approximately one-half to two-thirds of those recorded at a meteorlogical station. Winter measurements indicated that air change rates varied from 0.20 to 0.40 for house No. 1 and from 0.40 to 0.60 for house No. 3.

These changes were found to be caused by furnace operation and by stack action resulting from differences in temperature between the inside and outside and wind action. The effect of furnace operation was greater for house No. 1 than for house No. 3. The measured rate of air flow through the chimneys of houses No. 1 and 3 was approximately 0.40 air change per hour with approximately two-thirds of this value caused by the flow of air into the barometric damper and up the chimney. The upper value of air change rate for house No. 1 was close to this value. With the furnace in operation, the normal flow of air caused by stack action from the living space to the attic space was reversed for house No. 1 but unchanged for house No. 3 which indicates a tighter construction for house No. 1.

The measured air change rates indicate that the enclosure of house No. 1 is much tighter than that of house No. 3. This is substantiated by the respective overall leakage characteristics of 0.66×10^{-4} and 1.08×10^{-4} sq ft per cu ft of house volume. During the second winter tests of house No. 3, adhesive tape was applied to the exterior perimeter of all storm sashes on the first floor and to the interior perimeter of all basement windows. The reduction in the air change rates was roughly 15 to 20 percent of the first winter tests. Leakage flow through windows and doors in percentage of total for house No. 3 (as given in Table 2) is within this range.

CONCLUSIONS

Leakage tests on a limited number of houses indicate the following:

1. Leakage values of windows and doors with storm units contribute from 15 to 24 percent of overall leakage values.
2. Measured leakage values of prime windows are in reasonably good agreement with those given in the ASHRAE HANDBOOK OF FUNDAMENTALS. The reduction in leakage values with storm units installed varied from 26 to 71 percent.
3. Leakage values of exterior walls with stucco finish are significantly lower than those of masonry or a combination of masonry and aluminum siding or asbestos shingles.
4. Comparison of overall leakage area on a unit volume basis and the measured air change rates for houses No. 1 and 3 indicate that the former can serve as a useful index for air tightness.

REFERENCES

1. 1972 ASHRAE HANDBOOK OF FUNDAMENTALS, Chapter 19, Infiltration and Natural Ventilation.
2. G.T. Tamura, G.H. Kuester and G.O. Handegord, "Condensation Problems in Flat Wood-Frame Roofs," Second International CIB/RILEM Symposium on Moisture Problems in Buildings, Rotterdam, The Netherlands, September 1974.
3. G.T. Tamura and A.G. Wilson, "Air Leakage and Pressure Measurements on Two Occupied Houses," ASHRAE TRANSACTIONS 1964, Vol. 70, p. 110-119.

ACKNOWLEDGMENT

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Table 1

Description of Test Houses

House	Structure	Window	Floor Area sq ft	Volume cu ft
1	Brick veneer and stucco bungalow	Wood sashless horizontal sliding	830	13,400
2	Brick veneer and stucco bungalow	Wood sashless horizontal sliding	830	13,400
3	Brick veneer bungalow	Wood double-hung	1070	17,200
4	Brick veneer bungalow	Wood double-hung	960	15,400
5	1st story brick veneer, 2nd story asbestos shingles	Wood double-hung	1160	14,500
6	1st story brick veneer, 2nd story aluminum siding	Wood sashless horizontal sliding	1380	16,640

Note:

1. Floor area based on inside dimensions.
2. All houses with full basement.
3. All houses heated with oil-fired warm-air heating system.

Table 2

Total and Component Leakage Rates

(values in cfm at 0.30 in. of water)

House	Total leakage	Ceiling	Outside Walls	Windows and Doors
1	1,160	750 (65)	170 (15)	240 (20)
2	1,100	630 (67)	230 (21)	240 (22)
3	2,410	390 (16)	1560 (65)	460 (19)
4	2,620	900 (34)	1100 (42)	620 (24)
5	2,170	100 (8)	1680 (77)	330 (15)
6	2,240	250 (11)	1490 (66)	500 (23)

Note:

1. Leakage values exclude those of fireplace, smoke pipe and exhaust vents.
2. Windows and doors with storm units.
3. Figures in parentheses indicate percentage of total leakage rate.

Table 3

Leakage Openings in Terms of Equivalent Orifice Area*

House	Overall: Total sq ft	Overall: Sq ft per cu ft of house volume	Ceiling: Total sq in.	Ceiling: Sq in. per sq ft of ceiling area	Outside Wall**: Total sq in.	Outside Wall**: Sq in. per sq ft of wall area
1	0.88	0.66×10^{-4}	82.0	0.100	18.5	0.016
2	0.84	0.63×10^{-4}	69.0	0.085	25.0	0.022
3	1.85	1.08×10^{-4}	42.5	0.040	155.0	0.130
4	2.00	1.30×10^{-4}	98.5	0.100	120.0	0.105
5	1.65	1.14×10^{-4}	17.5	0.030	184.0	0.110
6	1.70	1.02×10^{-4}	27.5	0.040	160.0	0.071

* $A = Q/2400\ (\Delta P)^{1/2}$
A = Equivalent orifice area, sq ft
Q = Flow rate, cfm
ΔP = Pressure difference, in. of water (0.30 in. of water)

** exclusive of windows and doors, but including leakage between wall and door and window frames.

Table 4

Leakage Values for Ceiling and Outside Walls

(cfm per sq ft of area at 0.30 in. of water)

House	Ceiling	Outside Wall*
1	0.95	0.15
2	0.75	0.20
3	0.37	1.22
4	0.90	0.98
5	0.27	1.00
6	0.37	0.67

* exclusive of windows and doors, but including frame-wall leakage.

Table 5

Leakage Values for Windows and Doors

(cfm per ft of crack at 0.30 in. of water)

House	No. of Samples	Without Storm	With Storm	Percent Reduction
Wood Double-Hung Window				
3	10	0.60	0.33	44
4	10	2.10	1.50	29
5	13	1.33	0.98	26
Wood Horizontal Sliding Window				
1	4	0.98	0.28	71
2	4	1.27	0.42	67
6	9	2.55	1.78	30
Basement Wood Casement Windows				
2	4		2.77	
3	5		1.40	
4	7		1.08	
5	4	2.00		
6	3		3.33	
Wood Doors				
1	2	3.05		
2	2		1.37	
3	2	2.05		
4	2	3.93		
5	2	0.92	0.53	42
6	2	0.78	0.53	32

Note
1) all windows nonweatherstripped.
2) all doors weatherstripped; condition of weatherstripping fair to poor.
3) no edge cover at perimeter of glazing of horizontal sliding windows.
4) casement type storm units for double-hung windows.
5) storm units for horizontal sliding and casement windows similar to prime units.

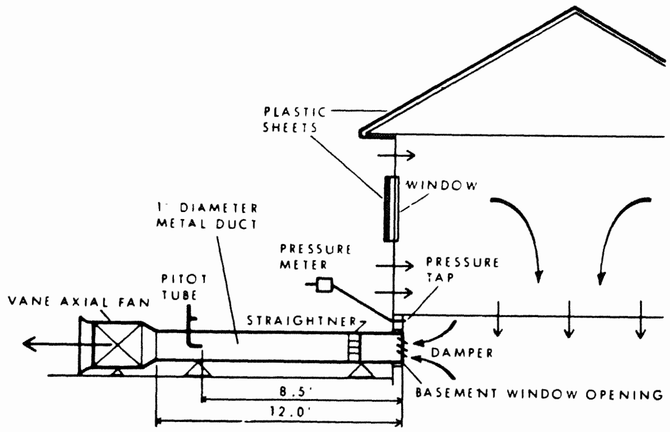


Fig. 1 Test arrangement

DISCUSSION

URICH BONNE (Honeywell, Inc., Corp. Res. Ctr. Bloomington MI): I would like to congratulate Mr. Tamura for this fine paper in which he has quantified the relative importance of various components of infiltration losses in residential buildings. From reading the chapter on infiltration in the ASHRAE HANDBOOK OF FUNDAMENTALS and some of the quoted references (especially D.R. Bahnfleth et al., "Measurment of Infiltration in Two Residences", ASHRAE TRANSACTIONS 1957, Vol. 63), I got the impression that perhaps the chimney also contributes to house infiltration because (1) the neutral pressure zone (between indoor and outdoor pressure) is generally higher than at the mid-height point of the house, (2) decreasing outdoor temperature and increasing wind velocity tend to raise the position of the neutral zone even higher, and (3) this situation prevails in spite of major door cracks in the basement and/or the first floor. One could counter that poor seals of vents and chimney in the attic could also cause the observed effects; therefore, I wonder if you can offer further clarifications? A direct comparison of the total "equivalent" crack area of about 2 ft^2 with the chimney cross section is, of course, not quite fair since flow friction is larger for cracks than for round holes of equal total cross section.

TAMURA: The leakage openings represented by chimneys, not reported in the paper, were measured during the tests. The leakage openings of furnace, smoke pipe, and chimney combination varied from 0.076 to 0.340 sq ft. The test houses were equipped with a high pressure gun-type oil burner, 8-in. diameter smoke pipe, and a chimney with nominal 8-in. by 8-in. clay flue liner. The leakage openings of fireplaces with a closed damper and connected to a chimney with a nominal 8-in. by 12-in. clay flue liner varied from 0.053 to 0.083 sq ft.

The studies of air infiltration rates on two of the single-story test houses, Test House No. 1 and No. 3, reported by the author in a paper entitled "Air leakage and Pressure Measurements on Two Occupied Houses" (ASHRAE TRANSACTIONS 1964, Vol. 70, p. 110-119), indicated that the operation of a heating appliance with a flow of hot gases up the chimney, which represents a high level opening, has a significant influence on the overall infiltration rate. The neutral pressure levels of both test houses were located near the ceiling level. In the case of Test House No. 1, which was found to be relatively air tight, the measured rates of air infiltration were approximately equal to the measured rates of gas exhaust up the chimney. The direction of air flow was from the attic into the living space which indicated that the neutral pressure level for this test house was located above the ceiling level. When the chimney damper of the fireplace of Test House No. 3 was left open, there was a marked increase in the overall air infiltration rate.

A relatively air tight house can minimize air infiltration rate and, hence, effect fuel economy. It must be cautioned, however, that such a house can cause problems associated with improper venting of combustion gases as well as moisture condensation and odor.

PAUL R. ACHENBACH (National Bureau of Standards, Washington DC): The distribution of cracks and openings in a house affects the air infiltration rate measured by the tracer gas technique under actual heating and wind conditions because the pressure difference is not the same across all openings. Under the pressurized test, all openings function under the same pressure difference. The neutral zone in a house tends to be near the level with the largest openings. This means that the longest openings tend to have the lowest pressure difference across them under actual operating conditions.

TAMURA: The author agrees with Mr. Achenbach's statement. The pressure differences that occur across the house enclousre depend on the outside temperature, wind condition, the operation of fuel-fired heating appliances and exhaust fans, and the size and distribution of leakage openings in the house enclosure. At present, information on measured pressure differences is sparse. The leakage values obtained under a specified uniform pressure difference do provide a basis for comparing the leakage values of the major components of the house enclosure as well as overall leakage values of various houses. What is needed is more test data to provide a relationship between total air leakage opening related to enclosure construction and actual infiltration rate. This was done for two of the six test houses reported in the paper.

DR. C.M. HUNT (National Bureau of Standards, Washington DC): In the papers by Stricker and Tamura, fans have been used to produce measured pressure differences between the inside and outside of houses. Although the papers differ in important details, both base conclusions on measurements made at a single inside-outside pressure difference. ASTM Standard E283-73 on the rate of air leakage through windows, curtain walls, and doors also recommends measurements at a single pressure difference ($1.75\ lb_f/ft^2 = 75\ Pa \approx 0.3$ in. W.G. when not otherwise specified). While a 1-point measurement has the advantage of simplicity, the question is raised as to whether additional useful information might be obtained by measuring flow rate at a number of pressure differences so as to develop a Δp vs flow relationship over a wider range.

To illustrate, the following figure presents flow rate as a function of inside-outside pressure difference in a log-log plot when a 3600 ft^3 mobile home was depressurized with a fan. Two lines are shown in the figure, one obtained with, one without storm windows. In the example chosen the conclusions regarding the reduction of flow rates by storm windows would be different depending upon the pressure difference at which comparison is made. Is it possible that leakage rates through different components of a house relative to one another might be different depending upon the pressure difference at which the comparison is made? Also, is it legitimate to project that different components of a house might contribute greater or lesser fractions of the total leakage depending upon wind velocity?

To expand upon the dicussion of limitations of ELA measurements in Stricker's appendix A, the equation:

$$Q = C\Delta p^n \qquad (1)$$

may be evaluated from multipoint data and becomes:

$$Q = 3090\ p^{0.743} \quad \text{with storm windows in,}$$

and:

$$Q = 5170\ p^{0.929} \quad \text{with storm windows out.}$$

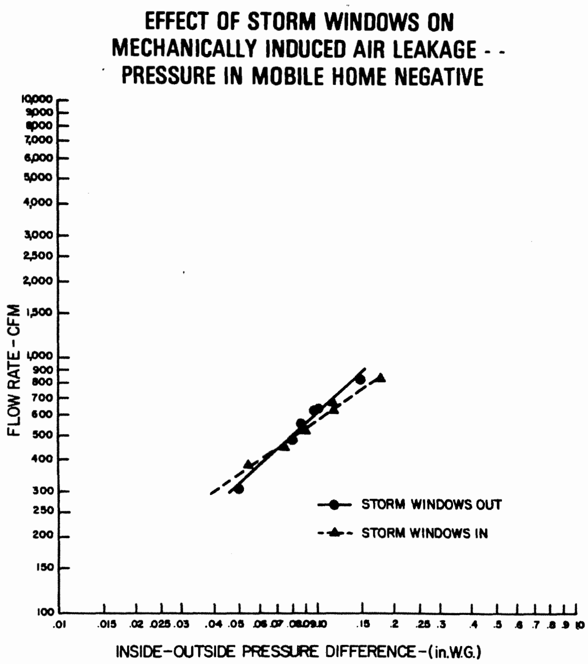
Equivalent areas may be calculated from these relationships as well as from the equation:

$$Q = 0.401 \times 10^4\ p^{1/2}\ AE \qquad (2)$$

which is Eq (3) in Stricker's Appendix A. Comparative equivalent areas calculated from Eq (1 and 2) are:

	Equivalent Area - ft^2	
Storm windows in	Eq (1)	Eq (2)
p = 0.15 in W.G.	1.28	0.81
p = 0.065 in W.G.	1.28	0.66
Storm windows out		
p = 0.15 in W.G	2.15	0.95
p = 0.065 in W.G.	2.15	0.66

While the use of p^n instead of $p^{1/2}$ eliminates the apparent change in area depending on the pressure at which the measurement is made, it also leads to an unrealistic estimate of the change in area due to installations of storm windows. As noted in Appendix A, the type of flow (ie, turbulent, laminar) may contribute the apparent area obtained from Q vs Δp data as well as the actual area itself, and the foregoing analysis would seem to bear this out.



TAMURA: It is likely that leakage rates through different components of a house relative to one another can vary depending upon the pressure difference. For the sake of simplicity, this aspect of the air leakage phenomena was not investigated. The author was aware of the possible effect of flow exponent n which can vary with house components. All tests, therefore, were conducted at a single pressure difference of 0.30 in. of water to permit valid comparison of the airtightness of test houses.

The effect of flow exponent n can be seen from the following equation:

$$A = A_x\left(\frac{\Delta P}{\Delta P_x}\right)^{n-1/2}$$

where:

A = equivalent orifice area

ΔP = pressure difference

A_x = equivalent orifice area at ΔP_x

n = flow exponent

The air leakage values (A_x) given in the paper are in terms of equivalent orifice area determined at a pressure difference (ΔP_x) of 0.30 in. of water. From the above equation, the value of A would be equal to A_x and independent of the pressure difference, if n is equal to 1/2. The value of n, however, can range from more than 1/2 to 1 for house enclosures and, hence, the value of A will vary with the pressure difference as described by the equation.

EDITOR'S NOTE: This same question was posed to Mr. Stricker, author of Technical Paper No. 2336.