

height. For the specific case illustrated in Fig. 3(c), the pressure differences created by wind and those due to temperature difference acting singly can be added to determine the combined effect. Strictly speaking, however, this is not true in most instances since the effective areas of openings for inflow and outflow are not the same and further the ratio of these areas does not remain constant as the relative magnitudes of the pressure forces change. The inside pressure distribution must shift to maintain inflow equal to outflow and the pressure differences depend on this equality.

Information on the relative importance of wind and temperature difference forces based on actual observation is quite limited.⁸ In studies on tall buildings^{9,10} exfiltration from windward facing rooms in upper stories was noted at low outdoor temperatures even with relatively high winds. Pressures due to temperature difference during the heating season dominate at entrances to tall buildings⁹ in cold climates. Thus temperature difference forces must be taken into account in estimating air flow into tall buildings at various elevations. In low buildings the nature of the terrain and shielding provided by adjacent structures will have a major effect on wind velocity and therefore on the relative importance of wind and temperature difference. Air leakage studies on two houses¹¹ in an urban area indicated that temperature difference forces were at least as important as wind forces corresponding to weather station winds of 15 mph, when indoor-outdoor temperature differences were 70 F deg or greater in one instance, and 20 F deg or greater in another.

CALCULATION OF INFILTRATION

Air infiltration may account for a significant proportion of the heating or cooling requirements for buildings. It is therefore important to be able to make an adequate estimate of its contribution with respect to both design loads and seasonal energy requirements. Air infiltration is also an important factor in determining the relative humidity that will occur in buildings or, conversely, the amount of humidification or dehumidification required to maintain given humidities.

There are two methods of estimating air infiltration in buildings. In one case the estimate is based on measured leakage characteristics of the building components and selected pressure differences. This is known as the *crack method*, since cracks around windows and doors are usually the major source of air leakage. The other method is known as the *air change method* and consists of assuming a certain number of air changes per hour for each room, the number of changes assumed being dependent upon the type, use, and location of the room. The crack method is generally regarded as being more accurate, provided that leakage characteristics and pressure differences can be properly evaluated. Otherwise the air change method may be justified.

The air leakage due to opening and closing of doors in vestibules is sometimes based on the air change method, even though the air leakage estimates for other rooms are based on the crack method. Except for vestibules and reception halls, it is not advisable to attempt to apply the air change method to factories and industrial and commercial buildings, because of wide variations in the type and percentage of fenestration which is the principal source of leakage in such buildings. In refrigerated rooms or buildings, in which opening of doors provides the major source of air leakage, infiltration is usually based on estimated air changes.

The accuracy of estimating infiltration for design load calculations by the crack or component method is restricted both by the limitations in information on air leakage characteristics of components and by the difficulty of estimating the pressure differences under appropriate design conditions of

Table 1 Air Changes Taking Place under Average Conditions in Residences, Exclusive of Air Provided for Ventilation^a

Kind of Room or Building	Number of Air Changes Taking Place per Hour
Rooms with no windows or exterior doors.....	1/4
Rooms with windows or exterior doors on one side.....	1
Rooms with windows or exterior doors on two sides.....	1 1/4
Rooms with windows or exterior doors on three sides.....	2
Entrance halls.....	2

^a For rooms with weatherstripped windows or with storm sash, use 1/2 these values.

temperature and wind. The calculation of infiltration rates suitable for prediction of seasonal energy requirements is more difficult, since ideally the product of infiltration and indoor-outdoor temperature difference integrated over the season, is required. The measurement of air leakage characteristics of building components, such as walls, windows and doors, is quite straightforward and the principal problem here lies in the variety of components used in buildings for which specific air leakage data are not available, and the differences that develop between components as tested and as installed or constructed in the field. The major limitation, however, is in estimating the appropriate pressure differences. Further studies are required to determine practical relationships between the various factors affecting air change.

Air Change Method

There are few published data on the air change rates for different buildings. Experience and judgement are required to obtain satisfactory estimates by this method. The values in Table 1 may be used with reasonable precision for residences, and are the requirements for each room. Some engineers assume that the total infiltration allowance for the entire building is 1/4 the sum of the infiltration allowances of the individual rooms, since whatever air enters on the windward side generally leaves the building on the leeward side, and the infiltration requirements do not exist simultaneously on all sides or in all rooms. For residences, it is common practice to assume that the total infiltration allowance for the residence is equal to the sum of the infiltration allowances of the individual rooms.

Air Leakage Through Windows

Air leakage associated with closed windows occurs through cracks between the frame and surrounding construction and between sash and frame, the latter usually predominating. Air flow through window cracks can be expressed by an equation of the form:

$$Q = C \Delta p^n \quad (3)$$

where

Q = flow rate.

C = proportionality constant.

n = exponent of flow, between 1/4 and 1.

Δp = pressure difference across window.

Air leakage characteristics of windows are usually expressed as flow rate per foot of sash crack. The assumption that all cracks in a window arrangement are the same is not strictly correct, but usually is close enough for design purposes.

Infiltration rates for a number of window types at pressure differences corresponding to different wind velocities are given

Infiltration and Ventilation

Table 2 Infiltration Through Windows
Expressed in cubic feet per foot of crack per hour^a

Type of Window	Remarks	Wind Velocity, Miles per Hour					
		5	10	15	20	25	30
Double-Hung Wood Sash Windows (Unlocked)	Around frame in masonry wall—not calked ^b	3	8	14	20	27	35
	Around frame in masonry wall—calked ^b	1	2	3	4	5	6
	Around frame in wood frame construction ^b	2	6	11	17	23	30
	Total for average window, non-weatherstripped, 1/2-in. crack and 3/4-in. clearance. ^c Includes wood frame leakage ^d	7	21	39	59	80	104
	Ditto, weatherstripped ^d	4	13	24	36	49	63
	Total for poorly fitted window, non-weatherstripped, 1/2-in. crack and 3/4-in. clearance. ^c Includes wood frame leakage ^d	27	69	111	154	199	249
Double-Hung Metal Windows ^f	Ditto, weatherstripped ^d	6	19	34	51	71	92
	Non-weatherstripped, locked.....	20	45	70	96	125	154
	Non-weatherstripped, unlocked.....	20	47	74	104	137	170
Rolled Section Steel Sash Windows ^g	Weatherstripped, unlocked.....	6	19	32	46	60	76
	Industrial pivoted, 1/4-in. crack ^h	52	108	176	244	304	372
	Architectural projected, 1/4-in. crack ^h	15	36	62	86	112	139
	Architectural projected, 3/4-in. crack ^h	20	52	88	116	152	182
	Residential casement, 3/4-in. crack ^h	6	18	33	47	60	74
	Residential casement, 1/2-in. crack ^h	14	32	52	76	100	128
Hollow Metal, Vertically Pivoted Window ⁱ	Heavy casement section, projected, 3/4-in. crack ^h	3	10	18	26	36	48
	Heavy casement section, projected, 1/2-in. crack ^h	8	24	38	54	72	92
		30	88	145	186	221	242

^a The values given in this table, with the exception of those for double-hung and hollow metal windows are 20 percent less than test values to allow for building up of pressure in rooms, and are based on test data, reported in the papers listed in chapter footnotes.

^b The values given for frame leakages are per foot of sash perimeter, as determined for double-hung wood windows. Some of the frame leakages in masonry walls originate in the brick wall itself, and cannot be prevented by calking. For the additional reason that calking is not done perfectly and deteriorates with time, it is considered advisable to choose the masonry frame leakage values for calked frames as the average determined by the calked and non-calked tests.

^c The fit of the average double-hung wood window was determined as 1/2-in. crack and 3/4-in. clearance by measurements on approximately 800 windows under heating season conditions.

^d The values given are the totals for the window opening per foot of sash perimeter, and include frame leakage and so-called elsewhere leakage. The frame leakage values included are for wood frame construction, but apply as well to masonry construction assuming a 50 percent efficiency of frame calking.

^e A 3/4-in. crack and clearance represent a poorly fitted window, much poorer than average.

^f Windows tested in place in building, so that no reduction from test values is necessary, as mentioned in footnote a.

^g Industrial pivoted window generally used in industrial buildings. Ventilators horizontally pivoted at center or slightly above, lower part swinging out.

^h Architecturally projected made of same sections as industrial pivoted, except that outside framing member is heavier, and it has refinements in weathering and hardware. Used in semi-monumental buildings such as schools. Ventilators swing in or out and are balanced on side arms. 1/4-in. crack is obtainable in the best practice of manufacture and installation. 3/4-in. crack considered to represent average practice.

ⁱ Of same design and section shapes as so-called heavy section casement, but of lighter weight. 1/4-in. crack is obtainable in the best practice of manufacture and installation. 1/2-in. crack considered to represent average practice.

^j Made of heavy sections. Ventilators swing in or out and stay set at any degree of opening. 1/4-in. crack is obtainable in the best practice of manufacture and installation. 1/2-in. crack considered to represent average practice. Known as intermediate windows by steel window manufacturers.

^k With reasonable care in installation, leakage at contacts where windows are attached to steel framework and at mullions, is negligible. With 1/4-in. crack, representing poor installation, leakage at contact with steel framework is about one-third, and at mullions, about one-sixth of that given for industrial pivoted windows in the table.

in Table 2.¹² The values given in the table are 20 percent less than test values, which implies that the actual pressure difference across windward walls in a building is approximately 0.04 p_s, taking the exponent n in Equation 3 equal to 1/4. The wind velocity in Table 2 corresponding to pressure differences due to chimney effect can be found from Equation 2.

An alternative approach is to equate Equations 1 and 2, solve for V_w , and increase the leakage values found in Table 2 at this wind velocity by 20 percent.

There are a variety of designs of windows now in use in both residences and commercial buildings for which there are no published air leakage data. In some instances data may be available from the manufacturer. In large commercial buildings it is quite common for architects to specify minimum infiltration rates based on tests by independent laboratories. The specification¹³ of the Aluminum Window Manufacturers Association includes maximum air leakage rates for a variety of aluminum window types, based on a pressure difference during test of 0.301 in. of water.

The fit of double-hung wood windows is determined by crack and clearance. Crack thickness is equivalent to one-half the difference between the inside window frame dimension and the outside sash width. The difference between the width of the window frame guide and the sash thickness is considered as the clearance. The length of the perimeter opening or crack for a double-hung window is equal to three times the width, plus two times the height, or in other words, it is the outer sash perimeter length, plus the meeting rail length. All of the window crack in any given room is not necessarily used in estimating the infiltration heat loss by the crack method. The length of crack to be selected in any given case depends on the number of exposed sides, as explained in Chapter 26.

Values of leakage shown in Table 2 for the average double-hung wood window were determined by using, on nine windows tested in the laboratory, the average measured crack and clearance of a large number of windows found in a field survey. In addition the table gives figures for a