AIR INFILTRATION
THROUGH
GAPS AROUND WINDOWS*

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Summary.

The amount of air leakage through window gaps in buildings depends on the width and length of the gaps, the pressures across the buildings and the resistances in the air circuit. The ranges of these factors are reviewed for this country and results of measurements within these ranges are given for standard metal and wooden windows and for weather-stripped windows. The results have been analysed and two methods of estimating the air flow through gaps in complete windows are given : the first method based on measurements of flow through short, uniform lengths is accurate, but tedious, and the second method based on the best fitting equation, reproduced as a nomogram, provides a quick, but slightly less accurate estimate. Finally, it is shown how the air flow through windows in buildings may be estimated by the use of the nomogram.

I. GENERAL CONSIDERATIONS.

(1) Introduction.

Gaps occur around the fastened sash of all windows which have openable sections. In some windows the gaps are large, cause draughts and are a source of excessive heat loss from a building ; in others, gaps are small, well distributed, and are not an undesirable feature of window construction since they may provide part or all of the background ventilation of a room or building. The object of this report is to estimate the amount of air leakage through windows in buildings in this country for a normal range of gap sizes and under normal conditions of exposure. Windows in common use, which are the subject of this investigation, are of three main types ; the standard and " modified " standard wooden windows which are specified in B.S. 644/1945 and B.S. 644/1951 respectively, and the standard metal window specified in B.S. 990/1945.

A priori, the volume of air flow through the gaps around windows may be expected to depend on the width of the gaps, the shape and length of the air path, and the pressure across the gaps, and these factors are discussed more fully in succeeding sections.

(2) Gaps and Air Path.

A section through the gaps and the air paths for the three window types is shown in Fig. 1. The nomenclature used is as follows : when the openable sash (or side-hung casement) is bedded on the frame and fastened, the gaps between the sash and the frame consist of two exterior gaps on the outer and inner surfaces of the sash which are called " face clearances ", a (the external face clearance is a_e and the internal a_i), and an interior gap between the sash edge and the parallel inner surface of the frame which is called " edge clearance " e. This nomenclature is due to Coleman and Heald[1] : current American practice as in the A.S.H.V.E. Guide does not distinguish between the two face clearances and uses the term " clearance " to denote the sum of the external and internal face clearances and the term " crack " to denote edge clearance, but the former terminology has been preferred as being more precise.

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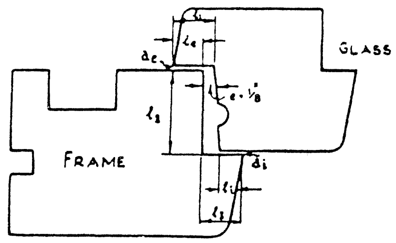
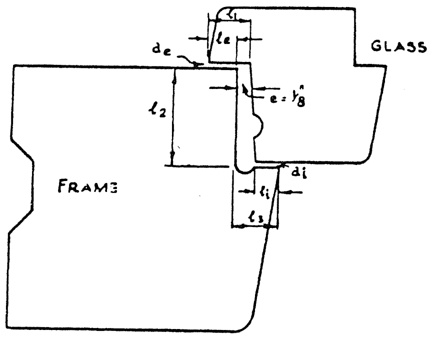
The range of clearances met with in windows is very wide ; along any length the external and internal face clearances and the edge clearance differ from each other, and at any point the external face clearance is not necessarily equal to the internal face clearance. The design basis is $e = \frac{1}{8}$ in. for wooden windows and $e = \frac{1}{3}$ in. for metal windows with a as small as possible. In practice e varies from 0.1 in. to 0.2 in. for wooden windows, but is occasionally less than 0.1 in., and from 0.2 in. to 0.4 in. for metal windows. The normal range of a is below 0.1 in., but individual gaps may be seen and have been measured which are above 0.1 in. The range of clearances tested in these experiments includes combinations of values of a below 0.1 in. and of e above 0.1 in. for all windows (which is considered the normal range) and of e below 0.1 in. for wooden windows.

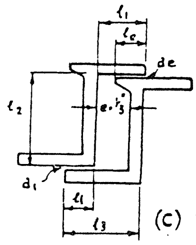
The average air path lengths l_1, l_2, l_3 are given in Fig. 1 for the three



(a) Standard wood (B.S. 644/1945)



(b) Modified standard wood (B.S. 644/1951)



Average dimensions (inches)

Window	e	l_1	l_2	l_3	l_e	l_i
Standard wood	0·13	0·40	0·85	0·42	0·27	0·23
Modified wood	0·13	0·40	1·0	0·42	0·27	0·22
Standard metal	0·35	0·48	1·0	0·62	0·22	0·23

(c) Standard metal (B.S. 990/1945)

Fig. 1.—Gap Sections of English Windows.

window types ; they are as designed by the manufacturers and differ only slightly from window to window. The effective air path lengths, however,

l_e and l_i associated with a_e and a_i vary considerably for different windows, depending on the value of e, and measured mean values are also given in Fig. 1.

(3) Pressures Across Windows.

The pressures across buildings which enable air to flow through components such as windows are caused by temperature differences and wind.

It may be shown that the pressure due to temperature differences (stack pressure) at normal temperatures is given by :

$$P = 2.8 \times 10^{-5}\ h\ (T_i - T_e) \qquad (1)$$

where P = Pressure (in. w.g.)
h = Height between inlet and outlet (ft.)
T_i = Internal temperature (°F.)
T_e = External temperature (°F.)

Typical stack pressures are as follows :

(*a*) Two-storey dwelling, $T_i - T_e = 20°$ F., $h = 10$ ft., $P = 0.0056$ in. w.g.
(*b*) Factory, $T_i - T_e = 20°$ F., $h = 40$ ft., $P = 0.022$ in. w.g.
(*c*) Heated flue, $T_i - T_e = 100°$ F., $h = 30$ ft., $P = 0.084$ in. w.g.

The pressure across an isolated building due to a wind blowing normal to one side is approximately equal to the velocity head of the wind as measured at the standard height of 10 metres in an open area ; if v is the free wind speed at this height, then the pressure is given by :

$$P = 0.0005\ v^2 \qquad (2)$$

Wind speed varies with height and for very high buildings v should be corrected, but this correction is small when compared with that due to exposure.

In inland, inhabited areas of the British Isles, the mean free wind is about 9 m.p.h., but on exposed coasts and hills the free wind may average 20 m.p.h. ; Bedford[2] has shown that the effective wind speeds in built-up areas are approximately a third of the free wind speed, i.e. $v = 3$ m.p.h., and in suburban areas an effective wind speed of 6 m.p.h. is suggested. The results of model experiments by Bailey and Vincent[3] on the effect of the height and distance of a screen on the pressure across a building have been examined with respect to the above criteria and these show that the exposure of buildings may be classified in the following way :

(*a*) *Sheltered :* ($v = 3$ m.p.h., $P = 0.0045$ in. w.g.).

For storeys below the height of the screen when the screen subtends an angle greater than 22° at the base of the building.

This includes the first two storeys above ground of buildings in the interior of towns or built-up areas, open courtyards.

(*b*) *Normal :* ($v = 6$ m.p.h., $P = 0.018$ in. w.g.).

For storeys below twice the height of the screen when the angle subtended by the screen is between 22° and 8°.

This includes houses in suburban areas or facing squares in towns, and the third and fourth storey in buildings in the interior of towns.

(*c*) *Exposed :* ($v = 9$ m.p.h., $P = 0.040$ in. w.g.).

For buildings in inland areas where there is no wind screen and for storeys above the fourth in towns.

(*d*) *Severe* : ($P = 0.0005\ v^2$).

For buildings on the coast or on hill sites, where the appropriate pressure is obtained from the prevailing wind.

This classification is the same as that given by the Institution of Heating and Ventilating Engineers[4] except that there is a subdivision of the " Normal " category into " Normal " and " Exposed " groups as given above for better definition.

If the normal pressure range across buildings is taken as 0 to 0.5 in. w.g., this will include all pressure differences due to temperature and pressure differences due to wind up to a mean speed of 30 m.p.h.

Two points to note are, firstly, that the air circuits in a building depend on the aeromotive forces acting ; e.g. in a semi-detached two-storeyed house with a window on each wall on each floor, when wind pressure is acting, the two windows on the windward wall will act as air inlets to the house, and the four windows on the leeward walls will act as outlets. On the other hand, if the motive force is stack pressure due to the house being heated, the air inlets will be the windows on the ground floor and the outlets the windows on the first floor. The second point is that when both stack pressure and wind pressure are acting, the effective motive force is the larger of the two pressures.

(4) Scope of Measurements.

The normal ranges of clearances and pressures are thus $a = 0$ to 0.1 in., $e > 0.1$ in., and $P = 0$ to 0.5 in. w.g.

Because the inherent variability of the gaps along a window made it difficult to assess the precise effect of a gap of given size on air flow, the experiments were carried out in two definite stages. In the first stage, the infiltration characteristics of a small uniform length (1 to 2 ft.) of each of the three window types were obtained for pre-set face and edge clearances which were closely controlled. In the second stage, the flow through the entire gap perimeter of complete windows was measured and compared with the flow predicted by the results from the first stage.

Finally, the characteristics of weather-stripped windows were obtained by measuring the flow through several such windows.

II. TESTS AND RESULTS.

(1) Short Uniform Window Lengths.

The experimental set-up is shown in Fig. 2. The window frame is hermetically sealed to the open side of a metal box. A pump of variable output (max. 800 c.f.h.) forces air through the gaps around the sash in either direction ; flow meters measure the volume of air flowing (6 c.f.h. to 1,000 c.f.h.), a water micromanometer (sensitive to 0.0005 in. w.g.) measures the pressure across the window, and feeler gauges (accuracy 0.001 in.) measure the face and edge clearances. Slots were cut into the overlapping length l_1 (Fig. 1) of the wooden windows so that feeler gauges could be inserted directly into the edge clearance, and the entire gap perimeter around the sash was sealed except for the uniform one or two foot length chosen. This length was carefully selected so that a_e was equal to a_i at any point and neither varied by more than 2 per cent. along the length. Shims* of varying thicknesses were used to vary a_e from

* Thin slip, usually of metal, used as a spacer.

0.005 to 0.10 in. and the sash was clamped to the frame to prevent any alteration of a_e during a test.

Over seventy tests were conducted on the three short, uniform lengths of standard, " modified " standard windows and standard metal windows for values of a and e within the normal range ; for wooden windows, it was also of interest to extend the range of e to cover some of the values

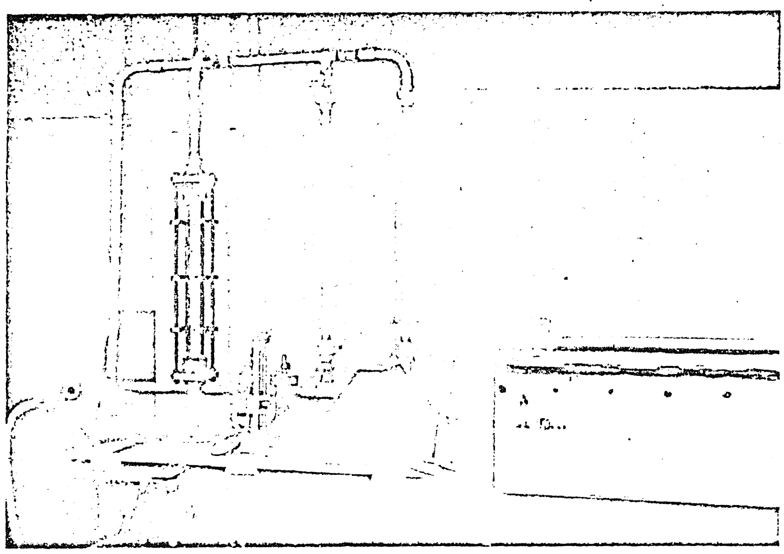


Fig. 2.—Experimental Arrangement for Measuring Infiltration through Window Gaps.

below 0.1 in. It was found that the volume flow V through the gaps was dependent on the applied pressure P (its magnitude but not its direction), on both a and e and the length of the air path : that the smaller of the two clearances was the more important factor influencing flow, while the larger clearance had a secondary influence which decreased as the disparity in size between a and e increased : further that the total length of the air path was not as significant a factor as the length of the air path associated with the minimum gap. Thus the observed flows through the standard and " modified " standard wooden windows were the same within the limits of experimental error when a was less than e, since the effective air path lengths associated with a, viz., l_e and l_i, are the same for both types. When e was less than a, however, there was less infiltration through the " modified " window than the standard for the same value of e, due presumably to the longer air path length l_2 associated with e in the " modified " window. The flow through gaps in metal windows is generally greater than that obtained for wooden windows with the same clearance ; this is due partly to the greater disparity in size between a and e, and partly to the shorter air path lengths l_e and l_i in metal windows.

The observed data have been summarised in Table I, which gives the measured flow through the gaps of the three window types tested for a normal range of clearances $e > 0.1$ in., $a = 0.005$ in. to 0.095 in. and for the normal pressure range $P = 0.005$ to 0.5 in. w.g.

(2) Complete Windows.

Five standard, two modified standard wooden windows (B.S. 240V) and six standard metal windows (B.S. NC 1) were obtained from the assembly lines of various manufacturers. The frames of each were sealed in turn to a metal box and air was forced through the gaps along the

Table I.—Infiltration through Metal Window Gaps (e = 0.3 in.).

Face clearance $a_e = a_i$ (inches)	Volume flow (c.f.h. per ft. crack of entry)						
	P (pressure in in. w.g.)						
	0.5	0.2	0.1	0.05	0.02	0.01	0.005
0.005	30	16	9.0	4.0	1.5	0.7	0.3
0.015	130	70	45	26	12	5.8	2.5
0.025	243	143	90	58	28	16	8
0.035	360	212	143	90	50	29	16
0.045	470	280	193	125	72	45	27
0.055	560	343	235	165	91	59	36
0.065	645	390	265	177	105	68	42
0.075	715	447	303	202	120	77	49
0.085	808	505	343	230	135	88	56
0.095	900	563	382	260	152	98	64

Infiltration through Wooden Window Gaps (e = 0.1 in.).

Face clearance $a_e = a_i$ (inches)	Volume flow (c.f.h. per ft. crack of entry)						
	P (pressure in in. w.g.)						
	0.5	0.2	0.1	0.05	0.02	0.01	0.005
0.005	15	8	4.0	2.5	1.5	0.8	0.4
0.015	95	44	26	14	7.5	4.1	1.9
0.025	190	100	62	38	19	12	5.5
0.035	285	160	103	66	35	22	11
0.045	385	220	145	95	53	33	18
0.055	485	280	185	124	71	46	27
0.065	585	340	225	153	89	60	37
0.075	685	400	265	182	107	74	47
0.085	785	460	305	212	125	89	57
0.095	885	520	345	242	143	103	67

perimeter (16 ft. for wooden and 9 ft. for metal windows). The air flow was measured at small increments of pressure to cover as large a range of volumes from 0.005 to 0.5 in. w.g. pressure for both directions of pressure. In three instances to increase the range of clearances, the experiments were repeated with shims inserted to increase the face clearances, although no attempt was made to equalise the face clearances along the window. In some of the windows with a large average gap, the maximum output of the pump was insufficient to obtain pressure differences above 0.1 in. w.g. across the window, and on the other hand, in the case of a metal window with a very small clearance, the flow was not measurable at pressures below 0.03 in. w.g.

Face clearances were measured at 2 in. intervals ; the mean face clearances were distributed from 0.002 to 0.047 in. for the sixteen sets of results, although in each window there was a considerable range of face clearances about the mean value. The edge clearances were also measured at two points along each side for each window ; in the wooden windows the range was 0.1 to 0.2 in. and in the metal windows the range was 0.2 to 0.4 in.

The mean volume flow-pressure curves were drawn for each set of results and the volume flow was obtained at the fixed pressure levels 0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5 in. w.g. ; this was divided by the perimeter length to give a mean volume flow in c.f.h. per ft. crack of entry at each pressure level.

It should be possible to predict the above rates of air flow for the whole windows from those measured on short uniform window lengths as given in Table I. There are, however, two main difficulties in prediction : the gap size varies with impressed pressure across the window and the clearances vary at any point and along the length of a complete window. The movement of the window or the variation of gap size with pressure was deliberately prevented by the use of clamps in the previous measurements, but a short investigation showed that the decrease (or increase) in face clearance a was 0.001 in. at 0.05 in. w.g. becoming 0.004 in. at 0.5 in. w.g. applied pressure and this effect is not likely to affect significantly the applicability of Table I in predicting the flow through unclamped complete windows provided that the window fasteners do pull the sash home.

To allow for the inherent variability of the clearances, the simplest approximation is to evaluate the flow from Table I for the minimum face clearance at each point (this is a good approximation only when a_e and a_i are of the same order) and integrate the flow over all the minimum gaps along the perimeter.

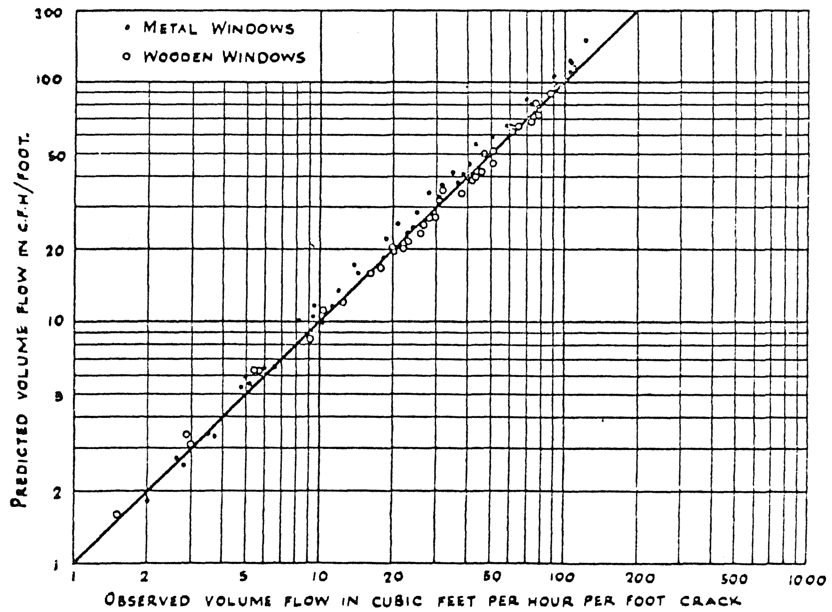


Fig. 3.—Comparison of Air Flow Predicted by Table I with Observed Flow through Gaps in Complete Windows.

From the sixteen sets of results on thirteen windows, comparison was possible for 79 values of the observed flow which were distributed along the pressure levels as follows : 15 at 0.005, 15 at 0.010, 15 at 0.020, 14 at 0.050, 10 at 0.10, 5 at 0.2 and 5 at 0.5 in. w.g. The predicted and observed values of the flow have been plotted in Fig. 3, and it will be seen that agreement is good (average percentage error 9 per cent.) for a range of observed flows 1.5 to 123 c.f.h. per ft. crack of entry. It should be observed here, since it is not apparent from the graph, that the errors are evenly distributed at each pressure level.

Table I may be used, therefore, to predict the air flow through metal and wooden windows for pressure levels to 0.5 in. w.g. with an average error of less than 10 per cent.

(3) Weather-stripped Wider Windows.

The prevalence of large gaps with their attendant draughts in present-day windows has encouraged the use of weather-stripping ; in some cases these are fitted by the window manufacturers or by the weather-strip agents, in others by the householders themselves.

An investigation was carried out on the effect of draught excluders on the air flow through windows. This may be reviewed in two sections ; expert weather-stripping or weather-strip fitted by skilled craftsmen and inexpert weather-stripping or that fitted by the average man. In the first category were three metal and two wooden windows, four fitted with phosphor-bronze and one with felt weather-strip by the agents, and in the second there were two wooden windows fitted with phosphor-bronze by an inexperienced workman.

The tests were conducted in the same way as described earlier for complete windows with each window fitted in turn to a metal box. The mean volume flows measured at pressures from 0.005 to 0.5 in. w.g. are given in Table II.

Table II.—Air Flow through Weather-stripped Windows.

Windows	Volume flow in c.f.h. per ft.						
	P in in. w.g.						
	0.5	0.2	0.1	0.05	0.02	0.01	0.005
Expert weather-stripping ..	32	17	10	6.3	3.0	1.7	1.0
Inexpert weather-stripping ..	57	32	20	13	6.6	3.6	2.0

The flow figures for inexpert weather-stripping correspond approximately to a window with an average clearance of 0.010 in., and for expert weather-stripping, to an average clearance of about 0.007 in.

III. ANALYSIS OF RESULTS.

All the observed flow-pressure curves may be written in the form :

$$P = AV + BV^2 \quad \ldots\ldots (3)$$

where A and B are constants uniquely determined for each curve or as :

$$P = A\left(V + \frac{B}{AV^2}\right) \quad \ldots\ldots (4)$$

where $\frac{B}{A}$ defines the shape of the curve, and A its level.

In the tests on short, uniform window lengths where the face clearances were equal, it was found that $\frac{B}{A}$ had a constant value for all three window types = 0.0143, and the value of A was given approximately by the equation $A = \frac{K}{a^2}$, where K, the coefficient of proportionality, differed only slightly for wooden and metal windows.

When the face clearances are not uniform, and this applies to the complete windows tested, the shape of the flow-pressure curve is dependent on the distribution of gap sizes about their mean and is not the same for all windows. Analysis of the sixteen tests here in the laboratory and of tests in Germany[5] and the U.S.A.[6] suggests that the mean value of $\frac{B}{A}$ is about 0.02 : variations from this value might be expected if the gaps are uniform or if the distribution of the gap sizes about their mean is abnormal. This value has been fitted to equation (4) and the level of A has been determined from the sixteen windows tested he.e. The formula obtained was :

$$P = \frac{0.30 \times 10^{-6}}{a^2} (V + 0.02V^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where a = mean face clearance in incnes.

The accuracy of prediction of this equation has been tested against the observed flow through standard, " modified " standard and metal windows at pressure levels 0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5 in. w.g. and this is shown in Fig. 4. The average error is 12 per cent. of the observed flows,

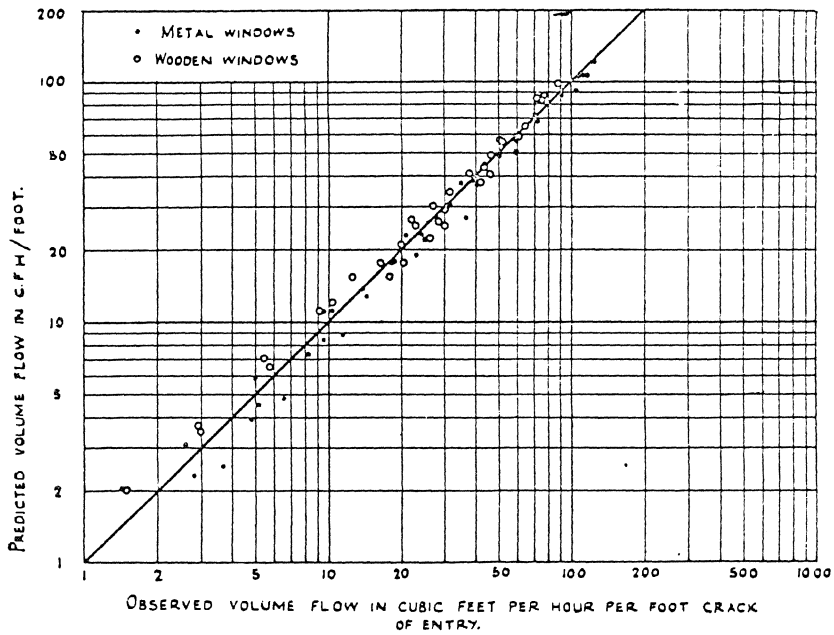


Fig. 4.—Comparison of Air Flow Predicted by Formula $P = \frac{0.30 \times 10^{-6}}{a^2} (V + 0.02\ V^2)$ with Observed Flow through Gaps in Complete Windows.

but it is worth noting that the errors are highest for low volume flows (less than 10 c.f.h. per ft.), and that the formula does not underestimate or overestimate significantly for metal or wooden windows.

IV. APPLICATIONS.

(1) Nomogram for Predicting Air Flow Through Complete Windows.

It will be realised that the evaluation of volume flow through metal and wooden windows by taking the minimum gap at each point, applying Table I and integrating over the entire length of a window is a tedious process and not to be recommended for obtaining a quick estimate of the flow through any particular window. The usefulness of an estimate depends not only on its accuracy, but also on the ease with which it is obtained, and for this reason it is suggested that a nomogram based on equation (5) could be used to predict the flow with rather less accuracy, but with considerably greater facility.

Fig. 5 indicates such a nomogram where the flow through windows with mean gaps from 0.007 in. to 0.090 in. may be predicted in c.f.h. per ft. for pressures from 0.003 to 0.5 in. w.g. with an accuracy of 12 per cent.

(2) Air Flow Across Windows in Series.

A further simplification that arises from the theoretical analysis is the distribution of pressures and volume flow across windows in series. If the motive pressure is temperature difference, this pressure will cause flow into and out of the house through half the window length on each wall of the building. If the motive force is wind, however, the distribution of pressures across each wall will depend on the wind direction, and the air resistances in the circuit from inlet to outlet. Thus if 1 ft. of window length on the windward wall is in series with n feet of window length on leeward walls, pressure P across the house divides into P_1 across the windward wall and P_2 across the leeward walls.

where $P_1 = AV + BV^2$

$$P_2 = \frac{AV}{n} + B\left(\frac{V}{n}\right)^2$$

and $P = P_1 + P_2 = AV\left(1 + \frac{1}{n}\right) + BV^2\left(1 + \frac{1}{n^2}\right)$

When $n = \infty$ all the pressure drop occurs across the windward window and $P = AV + BV^2$.

Provided $\frac{B}{A}$ is constant the actual flow V' may be evaluated for different values of n and V from the formula.

$$AV + BV^2 = AV'\left(1 + \frac{1}{n}\right) + BV'^2\left(1 + \frac{1}{n^2}\right) \qquad (6)$$

This evaluation has been carried out for $\frac{B}{A} = 0.0143$ and $\frac{B}{A} = 0.02$ and it was found that if V is the air flow through a window when all the pressure drop P occurs across this window the values of V' for $n = 1, 2, 3$ are approximately the same at the same V for both values of $\frac{B}{A}$.

Fig. 6 shows V' as a percentage of V for $n = 1, 2, 3$ for $\frac{B}{A} = 0.02$, which may be used in conjunction with the nomogram to predict the air flow through a window in a building.

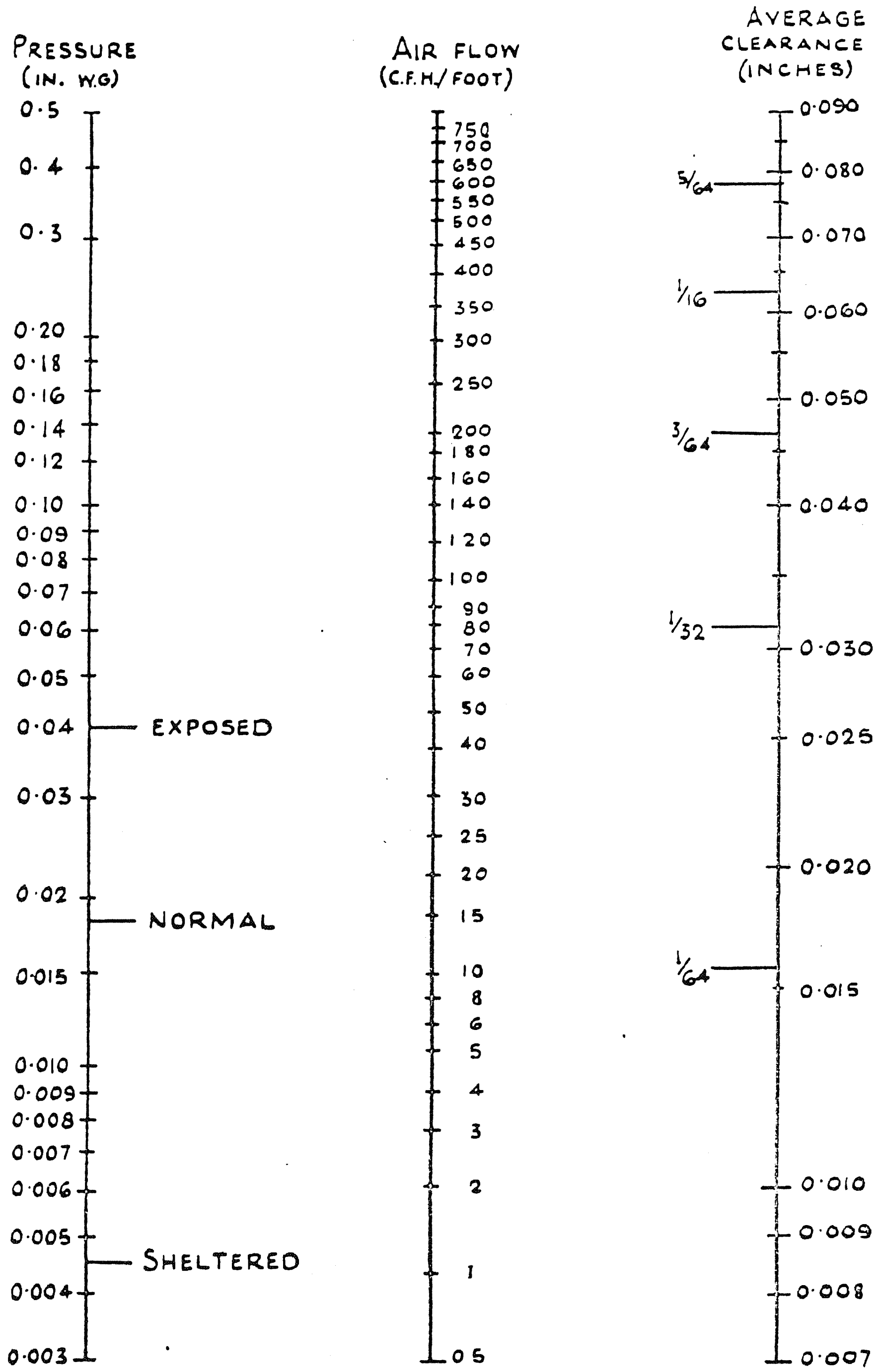


Fig. 5.—Nomogram for Predicting Air Flow through Windows.

(3) Examples.

The following examples indicate how Figs. 5 and 6 may be used to predict the air flow through windows in buildings.

(*a*) Small factory situated in a rural area, 4,000 ft. of window perimeter on each of four sides with an average clearance of $\frac{1}{64}$ in.

P (exposed) = 0.040 in. w.g., $a = \frac{1}{64}$ in.

V from nomogram = 23 c.f.h. per ft.

1 ft. of window is in series with 3 ft. of windows and for $n = 3$ and $V = 23$ c.f.h. per ft., percentage of air flow across windward window from Fig. 6 is 84.

Total volume flow through 4,000 ft. of window is, therefore,

$$\frac{84}{100} \times 23 \times 4,000 = 77,000 \text{ c.f.h.}$$

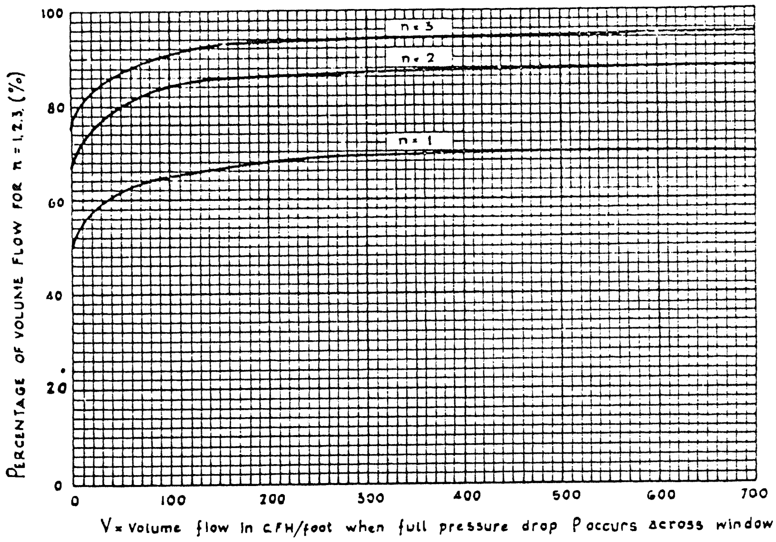


Fig. 6.—Volume Flow through Unit Length of a Window in series with n Lengths of a Window.

(*b*) Factory in a suburban area with 2,000 ft. of window perimeter on each of four sides with an average clearance of $\frac{1}{32}$ in. There is a ridge ventilator with a large outlet area ; the distance from windows to ridge is 40 ft. and the average temperature excess above outside air is 20° F.

P (wind pressure normal) = 0.018 in. w.g.

P (stack pressure) = 0.022 in. w.g.

hence stack pressure is acting and the inlets are 8,000 ft. of window perimeter.

For $P = 0.022$, $a = \frac{1}{32}$, $V = 40$ c.f.h. per ft.

Since 1 ft. of window length is in series with a much larger outlet $n = \infty$, and there is no correction for V.

Total volume flow is $8,000 \times 40 = 320,000$ c.f.h.

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