APPENDIX 2

AIR INFILTRATION INTO HEATED BUILDINGS

by E. HARRISON

INTRODUCTION

The following note examines the question of the probable range of air change rates resulting from calculations based on infiltration through window cracks.

It is confined to buildings of the office type, of modern construction, and with single-glazed metal-framed windows of standard types.

In order to arrive at infiltration figures in terms of air change it is necessary to know or assume :—

the pressure across the window
the crack width
the air flow per unit length at that pressure
the length of crack per unit volume of room

The first of these variables, namely the pressure difference across a given window, is one of considerable complexity. In the present study the external pressure on the building has been assumed as the combination of wind pressure at a constant standard value (following Dick and Thomas [1]) and stack effect due to a temperature difference of 35 deg F between inside and outside; and the proportion of the total pressure difference from windward to leeward sides of the building which is the pressure difference across the windward window and has been calculated for a number of assumed arrangements of building.

The width of window cracks which occur in practice has been assumed from the data of Dick and Thomas and that given in the ASHRAE *Guide*. The air flow per unit length of crack used in these calculations is that given in the equation and nomogram by Dick and Thomas. The last variable, namely the length of crack per unit volume of room has been measured from architects' drawings of a number of recent office buildings and (in part) from manufacturers' data on steel-framed windows conforming to BS 990 : 1945 and to a manufacturer's own range in common use.

PRESSURE DROPS ACROSS WINDOWS IN BUILDINGS

External pressures

The external pressures on buildings are assumed to be as follows :—

(i) A stack effect of equal magnitude on all sides of the building, calculated from the expression given by Dick and Thomas :—

$$P = 2{\cdot}8 \times 10^{-5}h(\theta_i - \theta_o) \qquad \text{(A2.1)}$$

where P is the stack pressure, in. w.g.
h the height of the building, ft.
θ_i and θ_o the inside and outside temperatures, respectively, °F.

For each storey (10 ft high) of a building with a temperature difference between outside and inside of 35·7 deg F.

$\Delta P = 0{\cdot}01$ in. w.g.

Hence, in this note the stack effect is assumed to produce an external pressure of 0·01 in. w.g. at the windows of the top floor, increasing by 0·01 in. w.g. for each lower floor.

(ii) Wind Pressure. Dick and Thomas relate the exposure of buildings (in the sense of the IHVE *Guide*) to wind velocity in the following way :—

sheltered = wind velocity of 3 mile/h ; pressure 0·0045 in. w.g.
normal = wind velocity of 6 mile/h ; pressure 0·018 in. w.g.
severe = wind velocity of 9 mile/h ; pressure 0·040 in. w.g.

According to the *Guide*, ' sheltered ' includes the first two storeys above ground for buildings in towns; ' normal ' includes the third, fourth and fifth floors of such buildings and ' severe ' refers to the sixth and higher storeys.

It has been assumed in these calculations that the wind produces a positive pressure on the windward face of the building equal to half the dynamic head and a negative pressure of the same magnitude on the leeward side of the building.

The total pressure at the windows on each floor has been taken as approximately the sum of the wind pressure and the stack effect as defined in (i) and (ii) above.

TYPES OF BUILDINGS

Buildings have been classified according to the nature of the internal sealing against infiltration which modifies the pressure drop across individual windows and hence the rate of air change, thus

I. Buildings perfectly sealed against internal upward flow from storey to storey, *i.e.* without stairways or ducts. Four cases in this category were assumed :—

(*a*) A building with no internal partitioning but with similar windows to windward and leeward in which the pressure drop across each window is equal to half the total wind pressure difference across the building at each floor.

(*b*) A building with the same arrangement of windows but having also internal partitioning such that one-third of the wind pressure drop took place across each window.

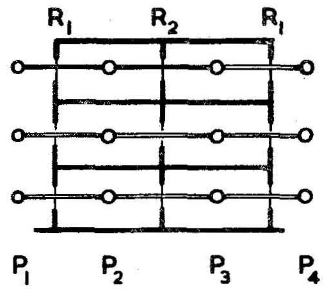
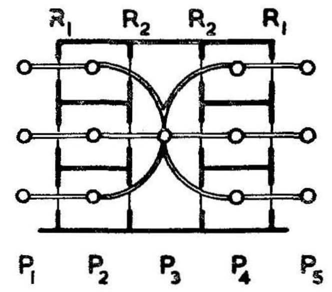
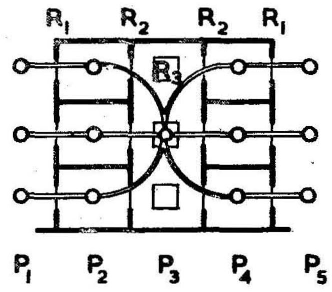
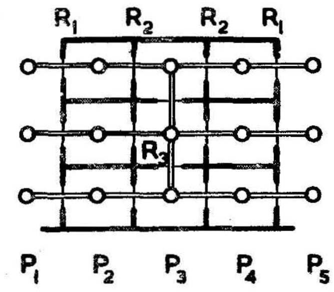
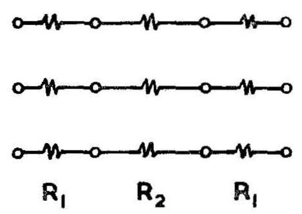
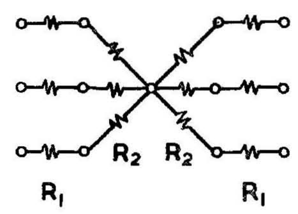
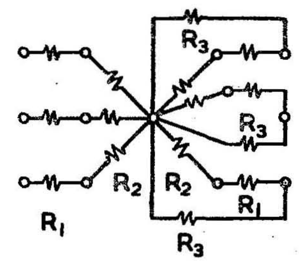
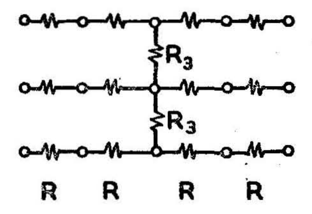
CATEGORY	I	II	III	IV
DIAGRAM OF BUILDING.				
ELECTRICAL ANALOGY				
RELATIVE RESISTANCES	A $R_2 = 0$ B $R_2 = R_1$ C $R_2 = 2R_1$ D $R_2 = 3R_1$	A $R_2 = R_1$ B $R_2 = 2R_1$ C $R_2 = 3R_1$ D $R_2 = 4R_1$	A $R_2 = R_1 = R_3$ B $R_2 = 2R_1 = 2R_3$ C $R_2 = 3R_1 = 3R_3$ D $R_2 = 4R_1 = 4R_3$	A $R_2 = R_1 = 2R_3$ B $R_2 = R_1 = 4R_3$ C $R_2 = 2R_1 = 4R_3$ D $R_2 = 3R_1 = 6R_3$ E $R_2 = 4R_1 = 8R_3$
ORIENTATION OF STAIRCASE WINDOWS	—	—	X TO WINDWARD Y TO LEEWARD	—
HEIGHT a	100 FT.	100 FT.	100 FT.	100 FT.
HEIGHT b	50 FT.	50 FT.	50 FT.	50 FT.

FIG. A2.1. DIAGRAM OF BUILDING TYPES

(*c*) As above but with partitioning such that the pressure drop across each window was reduced to one-quarter of the wind pressure difference.

(*d*) As above but with the pressure drop across each window equal to one-fifth of the wind pressure difference.

II. Buildings having an internal stairwell partially sealed from the rooms on each floor, but offering no resistance to upward flow from floor to floor. Cases in this category were considered as having sealing between the rooms and the stairwell offering a resistance:
  (a) equal to the resistance of a window
  (b) twice the resistance of a window
  (c) three times the resistance of a window
  (d) four times the resistance of a window

III. As II but with the stairwell itself considered to have windows either on the windward or the leeward side of the building.

IV. A fourth category of building, intermediate between I and II was also investigated. This was conceived as having a vertical duct or stairwell partially sealed at each floor to offer resistance to upward flow from floor to floor. The resistance from room to vertical duct was either equal to, twice, three times or four times the resistance of a window and the resistance of the vertical duct at each floor either twice or four times the window resistance.

In each of these building types two heights were investigated, namely 50 ft and 100 ft.

The diagram Fig. A2.1 summarises the kinds of building investigated.

The pressure drop across the windows on the windward side of these buildings was calculated for each case and the results are shown in Tables A2.1 and A2.2.

Discussion of resulting pressure differences

It is evident that the stack effect has a large influence on all buildings other than those in the first category which were assumed to be sealed completely at each floor. Hence, the pressure differences across all windows in the first fifty feet of height in a 100-ft high building are in most cases higher than those across any window in a 50-ft high building.

It seems necessary therefore to differentiate between low buildings and high buildings when attempting to select any design value of the pressure difference in order to calculate design values of infiltration rates. Taking the figures for 50-ft high buildings first, from Table A2.1 it will be seen that the whole range of pressure differences on the ground floor extends from $0{\cdot}2 \times 10^{-2}$ to $1{\cdot}5 \times 10^{-2}$ in. w.g. The four values of $1{\cdot}0 \times 10^{-2}$ and over are all for buildings in which the internal subdivision and sealing is lower than is likely to obtain in the majority of buildings in practice. Similarly on the top floor, whereas a negative pressure exists in some buildings (in which the stack effect predominates) the three high values of $1{\cdot}0 \times 10^{-2}$, and $2{\cdot}0 \times 10^{-2}$ occur in the case of the relatively poorly sealed buildings of category I, in which wind pressure alone operates.

If we disregard these maxima we may (not implausibly) suggest the following values for design minimum, mean and maximum pressure drops :—

design minimum pressure drop $0{\cdot}2 \times 10^{-2}$ in. w.g
design mean ,, $0{\cdot}4 \times 10^{-2}$ in. w.g.
design maximum ,, $0{\cdot}8 \times 10^{-2}$ in. w.g.

In the case of the 100-ft high buildings (Table A2.2) similar considerations suggest the following values :—

design minimum pressure drop $0{\cdot}3 \times 10^{-2}$ in. w.g.
design mean ,, $0{\cdot}6 \times 10^{-2}$ in. w.g.
design maximum ,, $1{\cdot}4 \times 10^{-2}$ in. w.g.

WINDOW CRACKS

Widths of cracks

The extreme range of face clearances of both wooden and metal framed windows tested by Dick and Thomas was from 0·005 to 0·095 in. These authors do not quote any figures for the normal range which might be expected in practice.

A random check of a number of steel framed windows in an office building in London (built in 1956) showed that an 0·025-in. feeler gauge could be inserted in the clearance at nearly all points in most windows, but that one of 0·05-in. thickness could only be inserted in some of the clearances of a few of the windows tested.

In the American data for steel framed windows, air infiltration rates are quoted for windows having cracks from $\frac{1}{64}$ in. (0·0156 in.) to $\frac{1}{16}$ in. (0·0625 in.). For two types of window $\frac{1}{32}$ in. (0·0312 in.) is said to represent average practice and, for another type, $\frac{3}{64}$ in. (0·0469 in.).

In the light of these data it is assumed that the design values of clearance may be taken as :—

minimum design clearance 0·03 in.
mean ,, ,, 0.04 in.
maximum ,, ,, 0·05 in.

Lengths of cracks in typical windows

For a range of B.S. metal windows with heights from 3 ft to 5 ft and widths from 4 ft 10½ in. to 6 ft 6 in. it was found that the ratio of crack length (*i.e.* perimeter of opening lights) to total window area ranged from 0·7 for the largest window to 1·6 for the smallest. For all the windows 4 ft high or greater the minimum value was 1·4 ft of crack per ft² of window. Almost exactly the same figures were obtained for another range of standard windows with a variety of arrangements of opening lights.

Relation of window area and crack length to floor area or room volume in typical buildings

From a scrutiny of typical plans of several multi-storey office buildings of recent design it was found that the ratio of window area to floor area was usually between 25 and 40 per cent. In some few rooms in two or three of such buildings, very small subdivided offices had window/floor area ratios in excess of 40 per cent.

All these buildings had floor to ceiling heights between 8 ft 10 in. and 10 ft 3 in.

The range of window area to room volume for these buildings (disregarding the few small offices which had abnormally high window/floor ratios) extended from 0·028 to 0·042 ft² of window per ft³ of room.

Table A2.1

PRESSURE DROP ACROSS WINDOWS ON WINDWARD SIDE OF 50-FT HIGH BUILDING

FLOOR	PRESSURE DROP (in.w.g. × 100)																				
	CLASS I				CLASS II				CLASS III								CLASS IV				
	a	b	c	d	a	b	c	d	a		b		c		d		a	b	c	d	e
									x	y	x	y	x	y	x	y					
1 (ground)	0·5	0·3	0·25	0·2	1·25	0·83	0·63	0·5	1·0	1·5	0·63	1·03	0·46	0·80	0·36	0·64	0·45	0·58	0·37	0·29	0·27
2	0·5	0·3	0·25	0·2	0·75	0·5	0·38	0·3	0·50	1·0	0·3	0·7	0·21	0·54	0·16	0·44	0·18	0·26	0·16	0·13	0·10
3	1·0	0·6	0·5	0·4	0·5	0·33	0·25	0·2	0·25	0·75	0·13	0·53	0·08	0·42	0·06	0·34	0·50	0·50	0·33	0·25	0·20
4	1.0	0·6	0·5	0·4	0·0	0·0	0·0	0·0	−0·25	0·25	−0·2	0·2	−0·17	0·17	−0·14	0·14	0·32	0·24	0·18	0·22	0·08
5	2·0	1·3	1·0	0·8	0·0	0·0	0·0	0·0	−0·25	0·25	−0·2	0·2	−0·17	0·17	−0·14	0·14	0·54	0·42	0·30	0·21	0·13

Table A2.2

PRESSURE DROPS ACROSS WINDOWS ON WINDWARD SIDE OF 100-FT HIGH BUILDING

FLOOR	PRESSURE DROP (*in.w.g.* × 100)																				
	CLASS I				CLASS II				CLASS III								CLASS IV				
	a	b	c	d	a	b	c	d	a		b		c		d		a	b	c	d	e
									x	y	x	y	x	y	x	y					
1 (ground)	0·5	0·3	0·25	0·2	2·5	1·67	1·25	1·0	2·13	2·9	1·4	2·0	1·0	1·5	0·8	1·2	0·50	0·76	0·43	0·38	0·34
2	0·5	0·3	0·25	0·2	2·0	1·33	1·0	0·8	1·63	2·3	1·0	1·6	0·8	1·2	0·6	1·0	0·25	0·40	0·24	0·20	0·21
2	1.0	0·6	0·5	0·4	1·25	1·17	0·88	0·7	1·38	2·1	0·9	1·5	0·6	1·1	0·5	0·9	0·67	0·76	0·46	0·38	0·33
4	1·0	0·6	0·5	0·4	1·25	0·83	0·62	0·5	0·88	1·6	0·5	1·1	0·4	0·9	0·3	0·7	0·56	0·64	0·40	0·32	0·27
5	2·0	1·3	1·0	0·8	1·25	0·83	0·62	0·5	0·88	1·6	0·5	1·1	0·4	0·9	0·3	0·7	1·02	1·04	0·69	0·52	0·41
6	2·0	1·3	1·0	0·8	0·25	0·5	0·38	0·3	0·38	1·1	0·2	0·8	0·1	0·6	0·1	0·5	0·99	0·96	0·65	0·48	0·38
7	2·0	1·3	1·0	0·8	0·25	0·17	0·12	0·1	−0·13	0·6	−0·1	0·5	−0·1	0·4	−0·1	0·3	0·95	0·87	0·60	0·43	0·33
8	2·0	1·3	1·0	0·8	−0·25	−0·17	−0·12	−0·1	−0·63	0·1	−0·5	0·1	−0·4	0·1	−0·3	0·1	0·88	0·74	0·53	0·37	0·27
9	2·0	1·3	1·0	0·8	−0·75	−0·50	−0·38	−0·3	−1·13	−0·4	−0·8	−0·2	−0·6	−0·1	−0·5	−0·1	0·76	0·54	0·42	0·27	0·18
10	2·0	1·3	1·0	0·8	−1·25	−0·83	−0·62	−0·5	−1·63	−0·9	−1·1	−0·5	−0·9	−0·4	−0·7	−0·3	0·62	0·24	0·23	0·12	0·06

If the ratio crack length/window area is taken as extending from 0·7 to 1·4 ft per ft², then the maximum and minimum values of the ratio crack length/volume of room would appear to be :—

maximum 0·042 × 1·4 = 0·059 ft/ft³

minimum 0·028 × 0·7 = 0·0196 ft/ft³

However, since large windows (rather than small floor areas) were, in the main, responsible for the window/floor ratios approaching 40 per cent, and the same large windows had crack length/area ratios of 0·9 to 0·7, it appears that the range could be narrowed to say :—

probable maximum 0·04} ft. run of window crack
probable minimum 0·03} per ft³ of room volume.

AIR CHANGE RATES IN BUILDINGS

We may now calculate the air change in the room of an average modern office building from the probable limits of the various parameters suggested in the foregoing sections.

Tables A2.3 and A2.4 show the results for 50-ft high and 100-ft high buildings respectively.

TABLE A2.3

LIMITS OF DESIGN VALUES OF AIR CHANGE RATES CALCULATED FROM PROBABLE RANGE OF ALL VARIABLES FOR 50-FT HIGH BUILDINGS

	Minimum	Mean	Maximum
Pressure drop across window, in. wg.	0·002	0·004	0·008
Crack width for steel-framed windows, in.	0·03	0·04	0·05
Infiltration rate per ft of crack, ft³/h	6	16	37
Crack length per unit volume of room in normal office buildings, ft/ft³	0·03	0·035	0·04
Air change rate /h	0·18	0·56	1·48

The infiltraton rate per foot of crack in this and the following table is based on the expression (equation (5)) given by Dick and Thomas. The equation has been replotted in Fig. A2.2 for a range of crack widths.

TABLE A2.4

LIMITS OF DESIGN VALUES OF AIR CHANGE RATES CALCULATED FROM PROBABLE RANGE OF ALL VARIABLES FOR 100-FT. HIGH BUILDINGS

	Minimum	Mean	Maximum
Pressure drop across window, in. wg.	0·003	0·006	0·014
Crack width for steel-framed windows, in.	0·03	0·04	0·05
Infiltration rate per ft. of crack, ft³/h	8	22	54
Crack length per unit volume of room in normal office buildings, ft/ft³	0·03	0·035	0·04
Air change rate /h	0·24	0·77	2·16

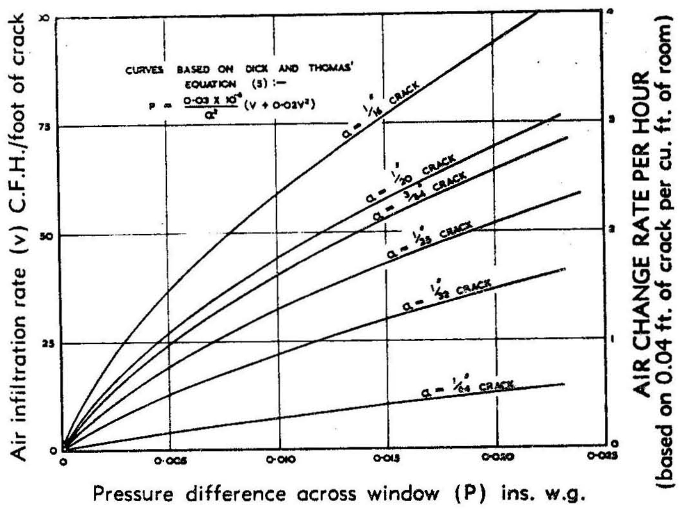


FIG. A2.2. AIR INFILTRATION THROUGH WINDOW CRACKS AT VARIOUS PRESSURE DIFFERENCES

COMPARISONS OF RESULTS WITH RECOMMENDED AIR CHANGE RATES GIVEN IN THE IHVE GUIDE

The rates recommended in the IHVE *Guide* for rooms of office type vary from 1½ to 2 air changes per hour for the category described as ' normal ' which includes the third, fourth and fifth storeys of buildings in the interior of towns ; the ' sheltered ' category, applying to the first two storeys of such buildings, has a recommended rate of 1¼ to 1¾ air changes per hour ; and ' severe ' exposure, applying to all storeys above the fifth, a rate of 2 to 2½ air changes per hour.

The results arrived at in the present calculations are at variance with these as being in general lower, but also inasmuch as the stack effect has been shown to produce an air change rate on the lower storeys of most buildings which is in many cases at least as great as any air change due to wind pressure alone. There is thus no warrant for assuming a greater rate of air change on the upper floors of tall buildings, except in the probably somewhat rare case of complete sealing from floor to floor.

The present results also demonstrate that there is a significant difference between the air change rates to be expected in buildings only 50 ft high as compared with those 100 ft high.

Finally it is evident from this work that (as was expected) a wide range of air change rates results from the extreme differences of pressure across an individual window which are obtained with different degrees and arrangements of internal sealing even when all the other variables, such as the wind pressure, stack effect and the crack width and length of the window itself are assumed constant.

RECOMMENDED VENTILATION RATES FOR OFF-PEAK ELECTRICALLY HEATED BUILDINGS

It is not easy to decide from the figures obtained, what values of ventilation rate or air change can be recommended for general adoption.

It is thought that a single rate for all cases would be too unrealistic and therefore it is provisionally suggested that :—

(*a*) Two rates should be recommended—one for low buildings (less than 50 ft high) and another, higher, rate for high buildings (more than 50 ft high).

(*b*) These should be again subdivided to give one rate for buildings with little or no internal partitioning, and another for buildings with internal full height partitioning with two or more partitions in series between windward and leeward windows and all staircases and lift lobbies fitted with self-closing doors. (This type of partitioning corresponds to that found in buildings with offices on each side of a central corridor.)

(*c*) These rates could possibly be again subdivided into day and night rates, on the assumption that internal and external doors remain shut at night thus improving the sealing of the building during the unoccupied hours.

These proposals lead to the following table of rates of air change by infiltration which are recommended for use in design when the number of occupants is not known. They are not proposed as necessarily fulfilling the ventilation requirements set out in Chapter 2.

TABLE A2.5

RECOMMENDED DESIGN VALUES OF RATES OF AIR CHANGE DUE TO INFILTRATION IN BUILDINGS HEATED BY OFF-PEAK ELECTRICITY

	Height of building			
	50 ft and under		over 50 ft	
	Infiltration rate (air change/h).			
	Day	Night	Day	Night
For buildings with little or no internal partitioning *i.e.* "open plan" buildings, or with partitions not of full height	$1\frac{1}{2}$	$\frac{3}{4}$	2	1
For buildings with internal full-height partitions (*i.e.* with rooms each side of a central corridor) without cross-ventilation and having self-closing doors to staircases, lift-lobbies etc.	$\frac{3}{4}$	$\frac{1}{3}$	1	$\frac{1}{2}$

REFERENCE

(1) DICK J. B. and THOMAS D. A. Air infiltration through gaps around windows. *Jl. Instn. Heat. Vent. Engrs.* 1953, vol. 21, pp. 85–97.