THE NATURAL VENTILATION OF UNHEATED 'CLOSED ROOMS'

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(With Plate 8 and 8 Figures in the Text)

'Ye men of Nottingham, listen to me....Air becomes unwholesome in a few hours if the windows are shut. Open those of your sleeping-rooms whenever you quit them to go to your workshops. Keep the windows of your workshops open whenever the weather is not insupportably cold....If you would not bring infection and disease upon yourselves, and to your wives and little ones, change the air you breathe, change it many times in a day, by opening your windows.'

Dr Erasmus Darwin, c. 1760.

INTRODUCTION

The provision of vents and openable windows in ancient dwellings is evidence that the desirability of ventilation has long been recognized. Considering the universal importance of the subject there are, however, comparatively little scientific data relating to the degree of natural ventilation which actually occurs in unheated rooms, and to the factors which control such ventilation.* The deficiency of precise information on this subject, so important to the health of the community, has been commented upon by an advisory committee of the Royal College of Physicians (1936).

The considerable lag of scientific investigation behind practice is attributable first to the ease with which it is possible to attain a more than adequate degree of ventilation in any normal living room under all but extreme climatic conditions, and secondly to the impossibility of controlling the main influences on which natural ventilation depends.

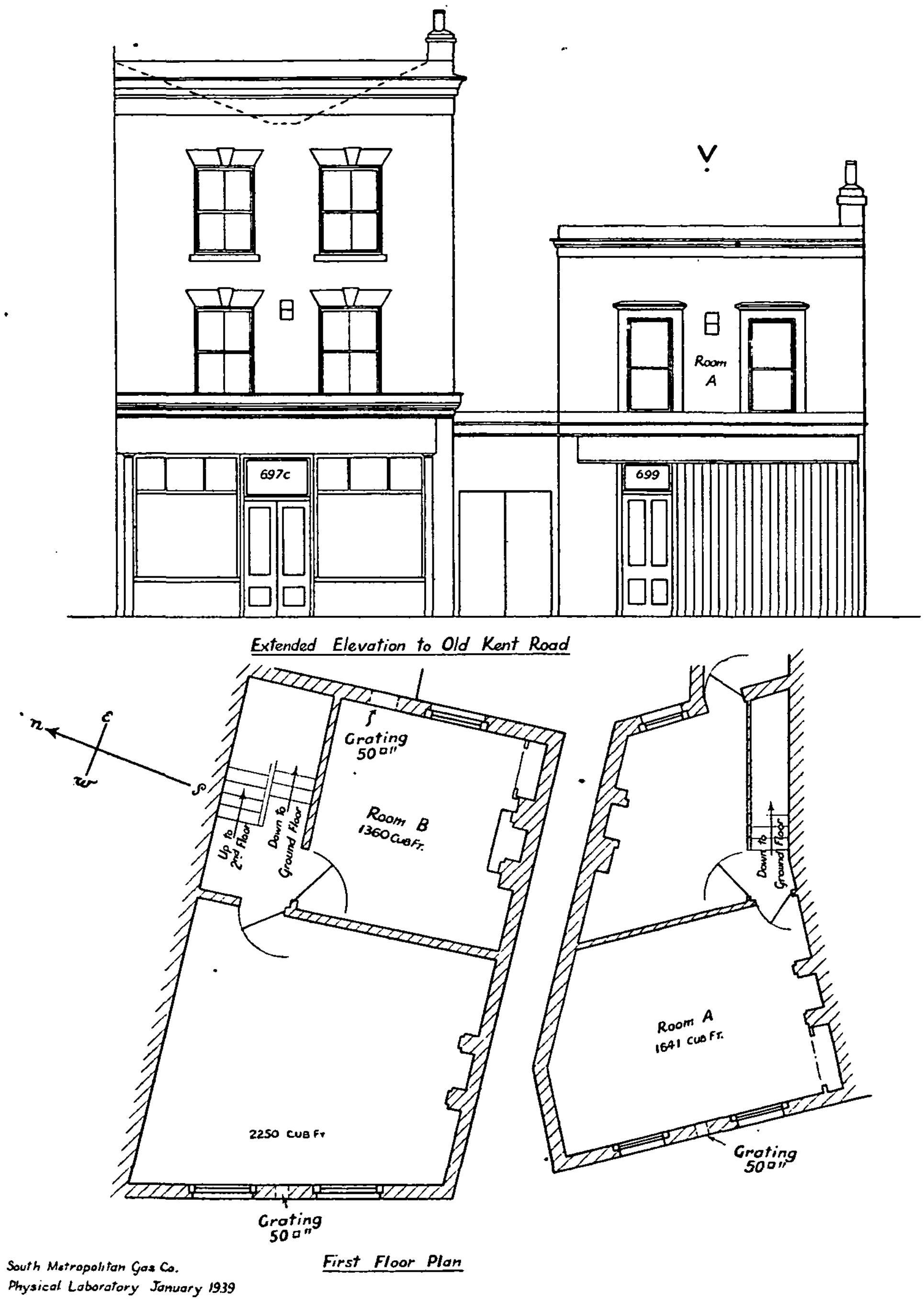
Scientific knowledge of the natural ventilation of living rooms has in recent years assumed an importance greater than hitherto, because of the reduction in the minimum degree of ventilation which has been brought about by modern design and construction of living quarters. In spite of discouragement by administrative and technical bodies living rooms are to-day frequently constructed without flues or air bricks, whilst modern building methods and materials have enabled the doors and windows of them to be made so well fitting that the rooms are in effect almost hermetically sealed.

* A comprehensive bibliography of literature on the subject to 1940 is given in the appendix to *Habitable Rooms and Natural Ventilation*, Radiation Ltd. 1942. A critical survey of work up to 1935 is contained in *Institution of Gas Engineers Publication*, no. 116, Masterman, C. A., Dunning, C. E. W. and Densham, A. B.

SCOPE

The investigation described in this paper was undertaken with the object of determining quantitatively the relative efficacy of a wall grating and a flue as means of facilitating the change of air in unheated 'closed rooms'. In this paper the term 'closed room' means a room in which windows and door are shut, but that either a wall grating or flue is open and that such fortuitous openings as usually exist in a normal house are present. The structural condition of the room under test was thus that conducive to the minimum air change likely to occur in a normal room under a given set of climatic conditions. An appreciable proportion of rooms are inhabited in this 'closed' condition, and it is considered that the majority of occupied bedrooms are normally so used. Since on an average more than one-third of the total lifetime of a person is spent in bedrooms, the ventilation rates studied correspond to a normal condition of use which is of considerable importance.

The first few experimental observations clearly indicated that the dominating factors on which such a comparison depended were the speed and direction of the prevailing wind. In view of the vagaries and the uncontrollability of these factors, it was clear that conclusions of a satisfactory nature could only be arrived at by consideration of results on a statistical basis. Approximately 350 determinations of natural air changes occurring mainly in two rooms having opposite aspects were made during the period November 1938–March 1939. The results of these have been analysed and an attempt has been made to correlate the general deductions made from the analysis with the flow forms of air streaming past grounded house models.



Text-fig. 1.

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THE BUILDINGS AND ROOMS USED FOR THE INVESTIGATION

In view of the dependence of the natural ventilation of a room on its structure, location and orientation, the following relevant details are important to the discussion of the subject.

The plan and elevation of the test room and buildings are seen in Text-fig. 1. The buildings were about 50 years old, the woodwork and the plaster were in good condition, and the doors and windows were good fitting. The structural condition was considered to be typical of that of the major proportion of dwellings existing in the country at the time the investigation was made.

The cubic content of room A was 1640 cu.ft. and of room B 1360 cu.ft.

Each fireplace was of the open-grate pattern. The flues were approximately 9 × 9 in. internal section, and that of room A 18 ft. high and of room B 26 ft. high. For test purposes the fireplace openings were covered with an iron sheet in which openings as required were made. The edges of the iron sheet were sealed with cement.

Each wall grating had a free area of 50 sq.in., and was fixed 7 ft. 6 in. above the floor level.

The walls of room A were papered (unvarnished), and those of room B distempered. The floor of each room was covered with linoleum.

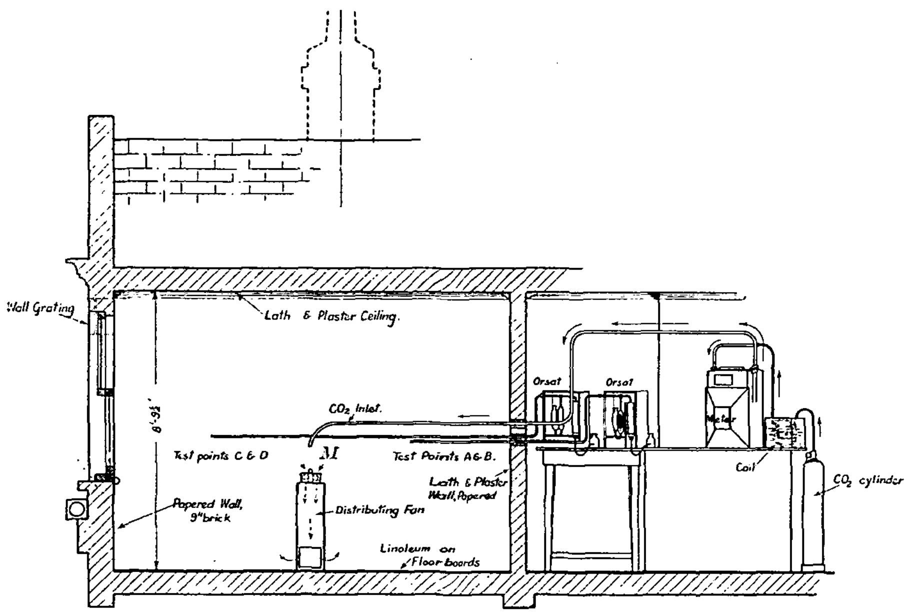
All windows were sash type and the wall grating in each room was fitted in the outer wall containing the window, which in room A faced approximately south-west, and in room B faced east.

The orientation and relative disposition of the rooms and containing buildings are shown in Text-fig. 1.

TEST METHOD

In all the tests quoted in this paper, the windows and door of the room under observation were shut throughout the test, and only the wall grating or the flue was open. No person was in the room during the test.

A suitable initial concentration of CO_2, of the order of 3 %, was created in the room by discharge of CO_2 at the centre of the room. In Text-fig. 2, which shows the arrangement of the apparatus in both the room under test and the adjoining room in which the CO_2 analysis and discharge apparatus were housed and operated, the point of discharge is indicated by M.



SECTIONAL ELEVATION AA

Text-fig. 2.

After leaving the cylinder and passing through a copper coil immersed in a tank of warm water, the CO_2 was metered in a dry gas meter before entering the test room. This measurement of the volume of the CO_2 discharged provided a check of the accuracy of the average CO_2 concentration in the room as determined by the analysis.

Even distribution of the CO_2 was effected by means of a fan near the point M and was proved to

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have been achieved by analysis of samples taken from points A, B, C and D immediately after discharge and fanning of the gas. Samples of the air at these four points were taken simultaneously at every 15 min. during the hour immediately following the discharge of the CO_2. The concentration of CO_2 in each sample was determined to an accuracy of 0·05 %, by a simple direct absorption apparatus designed for the purpose. During the test period the wind speed was frequently measured, using a vane anemometer and stopwatch, at the point V (Text-fig. 1) approximately 4 ft. above roof top. Wind direction was also observed at this point and again by a weather vane at approximately 50 yards distant mounted at about 60 ft. above ground-level on top of a tower. These dual observations of wind direction almost invariably agreed. The room and outdoor temperatures were noted during each test, and were found rarely to differ by more than 4° F.

Calculation of the influx rate during a period between sampling was calculated from the average CO_2 concentrations determined, using the formula

$$V_I = \frac{V_R}{T}\log_e\frac{(C_0)}{(C_T)},$$

where V_I = influx in cu.ft./hr., V_R = cubic content of room, in cu.ft., T = time in hours elapsed between initial and final sampling, C_0 = percentage CO_2 in initial sample, C_T = percentage CO_2 in final sample.

Table 1A. *Rates of air influx into Room A. Facing south-west. Analysis of results according to wind velocity*

Wind velocity group		Flue opening area				Wall grating
Direction	Speed m.p.h.	Nil cu.ft./hr.	13½ sq.in. cu.ft./hr.	17 sq.in. cu.ft./hr.	50 sq.in. cu.ft./hr.	50 sq.in. cu.ft./hr.
N.	0 – 3	510 (1)	—	—	540 (1)	1940 (1)
	3½– 6	1020 (1)	1270 (3)	2080 (4)	1610 (5)	1800 (1)
	6½– 9	820 (1)	2450 (2)	2750 (2)	—	1710 (2)
	12½–15	—	—	3900 (1)	4430 (1)	—
N.E.	0 – 3	—	1070 (2)	970 (4)	—	800 (7)
	3½– 6	580 (3)	1010 (3)	540 (3)	960 (5)	1060 (4)
	6½– 9	—	970 (2)	1110 (3)	2130 (1)	1530 (2)
	9½–12	950 (1)	1640 (1)	—	—	—
E.	0 – 3	710 (1)	—	—	2170 (1)	—
	3½– 6	480 (1)	1080 (2)	—	1330 (1)	820 (1)
	6½– 9	660 (1)	—	2100 (1)	2080 (1)	1200 (1)
	9½–12	—	—	2260 (1)	—	1240 (1)
S.E.	0 – 3	380 (1)	550 (2)	900 (1)	—	—
	3½– 6	—	970 (1)	—	—	990 (1)
	6½– 9	—	—	1630 (2)	1870 (1)	—
S.	3½– 6	—	—	1210 (1)	—	—
S.W.	0 – 3	430 (2)	800 (1)	—	1460 (2)	2590 (1)
	3½– 6	620 (2)	900 (2)	1110 (2)	920 (2)	1510 (2)
	6½– 9	1170 (2)	—	1780 (2)	2140 (3)	2780 (3)
	9½–12	—	1700 (2)	—	—	3810 (2)
	12½–15	—	—	2250 (2)	—	—
W.	0 – 3	510 (1)	560 (1)	—	660 (1)	890 (1)
	3½– 6	—	1190 (4)	1230 (2)	1520 (4)	1930 (7)
	6½– 9	840 (1)	1610 (4)	2440 (6)	2950 (1)	2710 (6)
	9½–12	—	2500 (2)	3760 (1)	2980 (2)	3610 (1)
	23 –24	4270 (1)	—	5410 (1)	—	—
N.W.	0 – 3	—	—	—	—	—
	3½– 6	—	2120 (1)	2260 (1)	—	2400 (1)
	6½– 9	—	—	1640 (1)	2520 (2)	—
	9½–12	1790 (1)	2890 (1)	—	3610 (1)	2670 (1)
	12½–15	—	—	3300 (2)	—	—
	15½–18	—	4610 (1)	6270 (1)	7280 (1)	6050 (1)

RESULTS OF OBSERVATIONS

In Tables 1A and 1B the measured air influx rates are set out against the wind velocity group, corresponding to the average wind velocity observed. Each velocity group covers a range of 3 m.p.h. and a 45° sector of the compass.

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Where more than one average hourly influx rate was obtained corresponding to a particular velocity group, the average value is given and the number of observations from which the average is derived is noted in brackets.

The ratio of the influx rate with each flue opening concerned, of a flue opening relative to that of the wall grating of 50 sq.in. free area is expressed as the ratio of the respective influx rates when the same wind velocity prevails for both devices. This ratio has been calculated for every size opening and wind velocity group for which data are provided in

Table 1B. *Rates of air influx into Room B. Facing east. Analysis of results according to wind velocity*

Wind velocity group		Flue opening area				Wall grating
Direction	Speed m.p.h.	Nil cu.ft./hr.	13½ sq.in. cu.ft./hr.	17 sq.in. cu.ft./hr.	50 sq.in. cu.ft./hr.	50 sq.in. cu.ft./hr.
N.	0 – 3	—	—	—	720 (1)	1080 (1)
	3½– 6	—	860 (2)	580 (1)	—	730 (1)
N.E.	0 – 3	640 (1)	1580 (1)	780 (1)	1250 (1)	—
	3½– 6	790 (1)	—	1700 (1)	1730 (5)	2230 (3)
	6½– 9	—	2040 (1)	1940 (2)	2460 (2)	2580 (1)
E.	0 – 3	—	—	3400 (1)	—	—
	3½– 6	—	2540 (2)	2610 (4)	2780 (2)	3810 (3)
	6½– 9	1225 (1)	—	4790 (1)	—	3440 (4)
	9½–12	—	—	3590 (1)	—	—
S.E.	0 – 3	870 (1)	—	—	—	—
	3½– 6	—	2040 (1)	—	—	2810 (2)
	6½– 9	—	—	4080 (1)	3470 (3)	3450 (2)
	9½–12	—	—	3830 (1)	—	—
S.	0 – 3	—	—	—	2580 (1)	—
	3½– 6	1060 (1)	—	2990 (1)	—	—
S.W.	0 – 3	—	—	—	—	1550 (2)
	3½– 6	530 (1)	560 (1)	670 (1)	1270 (3)	710 (1)
	6½– 9	410 (1)	—	1240 (2)	3400 (1)	3000 (2)
	9½–12	—	1510 (2)	2690 (1)	—	—
	12½–15	—	—	2830 (1)	—	1360 (1)
	15½–18	—	—	—	3430 (1)	—
W.	0 – 3	500 (1)	630 (1)	390 (2)	—	450 (1)
	3½– 6	330 (1)	520 (4)	—	470 (3)	470 (4)
	6½– 9	—	990 (1)	1250 (3)	950 (1)	1010 (3)
	9½–12	—	—	1770 (1)	—	1390 (1)
N.W.	0 – 3	—	—	—	—	—
	3½– 6	—	1100 (1)	—	—	730 (1)
	6½– 9	—	—	—	1270 (1)	860 (1)

Table 2. *Variation of influx rate with area of flue opening; rates expressed as proportion of rate with 50 sq.in. flue opening. Average ratios for all winds*

Room	Flue opening area: Nil	13½ sq.in.	17 sq.in.	50 sq.in.
A, facing S.W.	0·52 (12)	0·74 (11)	0·88 (14)	1·0 (19)
B, facing E.	0·4 (5)	0·91 (6)	0·82 (8)	1·0 (9)

(Figures in brackets denote number of calculated ratios from which the average ratio is derived.)

to that with a flue opening of 50 sq.in. for a wind velocity in the same group has been calculated for each size of flue opening used and for each velocity group for which data are given in Tables 1A and 1B. The averages of these ratios for each size of flue opening are given in Table 2.

The efficacy, so far as facilitating air change is Tables 1A and 1B, and the averages of the efficacy ratio for all wind velocities for each size of flue opening used are given in Table 3.

Magnitude of the air temperature-difference effect

On no occasion did a dead calm atmosphere persist long enough for measurement of influx rate

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under such conditions to be made. On three occasions, however, an average wind speed of less than 1 m.p.h. prevailed sufficiently, and the results obtained are set out in Table 4.

Although the accuracy of the measurements does not allow any conclusion to be drawn regarding the relation between air temperature difference and influx rate, comparison of the data in Tables 1A, 1B and 4 indicates that the effect of normal temperature differences is negligible compared with that due to normal winds.

The rapid changes in air flow through a grating or flue opening which occur under ordinary wind conditions, as revealed by the fluctuations in movement of a match flame held near them, support this conclusion.

Table 3. *Average efficacy ratios for all winds*

(Efficacy of 50 sq.in. Wall grating = 1·0)

Room	Flue opening area: Nil	13½ sq.in.	17 sq.in.	50 sq.in.	50 sq.in. wall grating
A, facing S.W.	0·46 (12)	0·80 (17)	1·03 (13)	0·99 (15)	1·0 (21)
B, facing E.	0·67 (6)	1·04 (9)	1·02 (12)	1·03 (10)	1·0 (17)

(Figures in brackets denote number of calculated ratios from which average ratio is derived.)

Table 4. *Influx rates for wind speeds of average of 0–1 m.p.h.*

Opening	Difference of room and outdoor temperatures ° F.	Influx rate cu.ft./hr.
Flue, 17 sq.in.	0	480
Flue, 50 sq.in.	3	790
Grating, 50 sq.in.	2	610

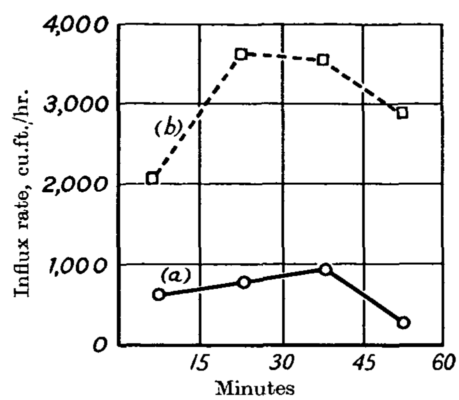
DISCUSSION OF RESULTS

Each influx rate stated is the average of the measured rates observed during quarter-hourly periods for 1 hr.

The graphs in Text-fig. 3, showing the measured quarter-hourly rates of two separate test periods, are indicative of the variation which occurs (*a*) when what is considered a steady wind prevails, and (*b*) when gusty conditions exist.

Automatic continuous records of wind velocity show that, except when dead calm prevails, both the speed and direction vary continuously. Examination of a portion of such a record, reproduced in Pl. 8, fig. 1, shows that in what would commonly be regarded as a steady north-east wind of 5 m.p.h., the direction varied by some 70° and the speed fluctuated from 2 to 10 m.p.h. Such variability does not permit a high degree of accuracy in the assessment of the true average values of the interdependent factors. It is considered, however, that the method of analysis employed, i.e. grouping observations according to velocity ranges covering 3 m.p.h. and subcardinal directions of the compass, assumes a degree of accuracy which is in consonance with that of the measurements.

Since the flow through a particular room is determined by air pressures which are developed at all the openings of a room and result from the shape and dimensions of the containing building and the wind stream engulfing the building, the velocity of the main wind stream appears to be both the practical and significant factor for correlation with influx rate. Comparison of the influence of the constructional features of a room on the influx rate



Text-fig. 3. Variation of influx rate during test period of one hour. Room A.

---□--- Grating, 50 sq.in. free area. Wind south-west, 0–14 m.p.h., gusty.

——○—— Grating, nil; flue, nil. Wind south-west, 4 m.p.h., steady.

requires the elimination of variations in wind velocity, and the analysis of the results, as given in Tables 2 and 3, has been made accordingly.

Relation of size of flue opening to influx rate

The data given in Table 2 are plotted in Text-fig. 4, and from the graphs it is evident that the influx rate increases but slowly with area after an

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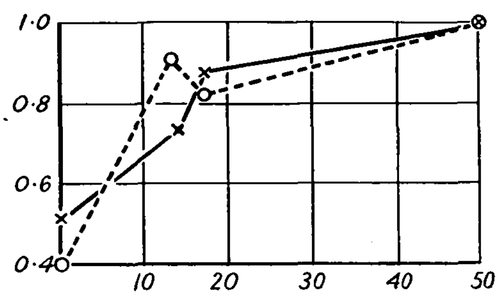
opening of 15–20 sq.in. has been provided at the base of the flue.

It seems reasonable to conclude that since the passage of air through a room requires the existence of both inlet and outlet apertures (that is, excepting contra flow through one opening), the effective area of the other openings in the rooms was of the order of 20 sq.in. in A and 15 sq.in. in B. Thus for flue openings having areas less than these values, the flue was the controlling resistance to flow, and for flue openings greater than these the 'other' openings were the dominant resistance. The 'other' openings, when a flue is used, consist of window, door and structure interstices, and porous wall material.



Text-fig. 4. Dependence of influx rate on area of opening at base of flue. (Averages for all observed wind velocities.)

Abscissa:

Area of opening at base of flue, square inches

Ordinate:

$$\text{Ratio: } \frac{\text{Influx rate. With base opening}}{\text{Influx rate. With 50 sq.in. base opening}}$$

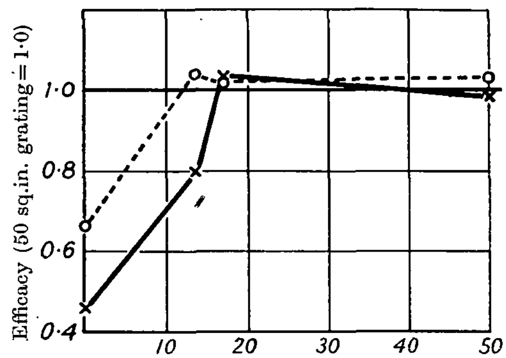
——×—— Room A. – – –O– – – Room B.

Relative efficacy of flue and wall grating

In the absence of sufficient determinations to allow the weighting of the results according to the natural prevalence of the various wind groups, it is considered that the averages of the ratios for each flue opening as given in Table 3 are the best available measure of the relative efficacies of the two devices. These average values are plotted in Text-fig. 5 from which it is concluded that in the rooms used a flue having a base opening of 15 sq.in. or more, is, on the average of all winds, as effective in allowing natural air change as a wall grating having 50 sq.in. free area.

The general problem

The complexity of the relation between the interdependent variables (wind velocity, openings in room, air influx rate), which is evident in the foregoing data, is due to the involved character of the aerodynamical conditions created by an obstruction at the boundary of an air stream. It appears to the author that the results of the foregoing analysis when considered in conjunction with the flow pattern of air streaming past grounded house models, due to Müller (1939) and reproduced in Pl. 8, figs. 2 and 3, enable deductions to be made of a general nature regarding the ventilation of unheated rooms. The polar curves in Text-figs. 6 and 7, showing the dependence of influx rate on wind direction, plotted from the data contained in Tables 1 A and 1 B, are, with the conclusions already stated, of value in this connexion.



Text-fig. 5. Efficacy of flue openings, relative to 50 sq.in. grating. (Averages for all observed wind velocities. See Table 3 and derivation.)

——×—— Room A, facing south-west.
– – –O– – – Room B, facing east.

The relation between influx rate and wind direction

In Text-figs. 6 and 7 the general features to be observed are:

Wall grating effect in both rooms

(1) At $3\frac{1}{2}$–6 m.p.h. the influx rate is a maximum when the wind blows in a direction approximately normal to the wall containing the grating, the rate decreasing steadily as the wind direction makes a greater angle with the normal. The minimum rate occurs when the wind blows normally away from the grating wall.

(2) At $6\frac{1}{2}$–9 m.p.h. there is no sharply defined maximum of the influx rate, the rate being approximately constant through an angle of 180°, corresponding roughly to 90° each side of the normal to the wall containing the grating, this constant rate being equal to the maximum rate with the wind speed of $3\frac{1}{2}$–6 m.p.h.

Throughout the leeward 180° the influx rate is relatively small.

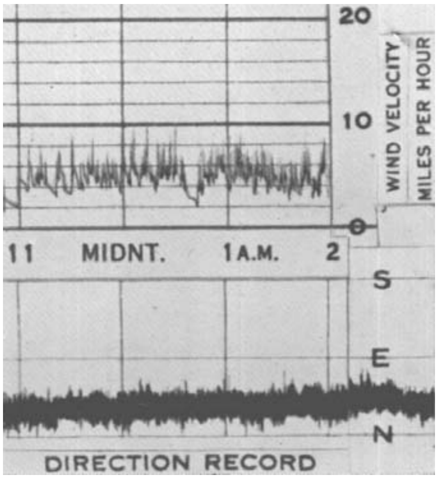


Fig. 1.

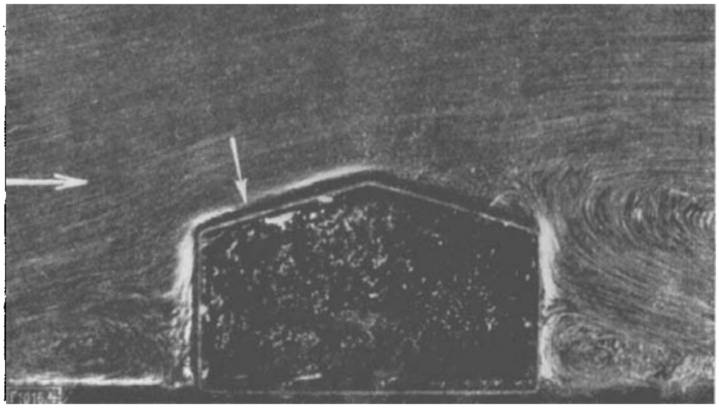


Fig. 2. Flow past model house with sloping roof.

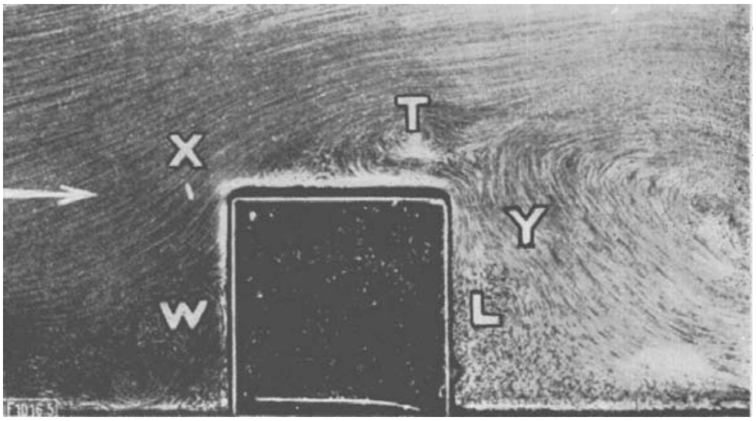


Fig. 3. Flow past model house with flat roof. Lettering on the photograph has been added by the author.

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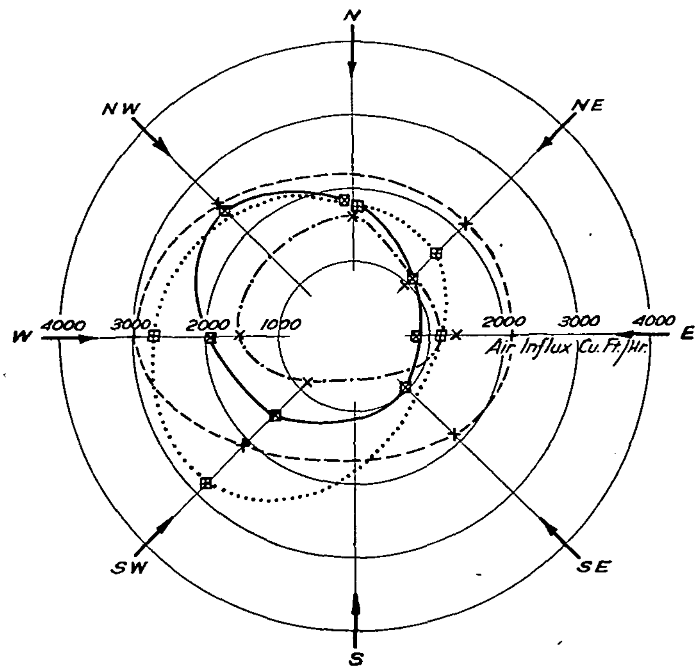
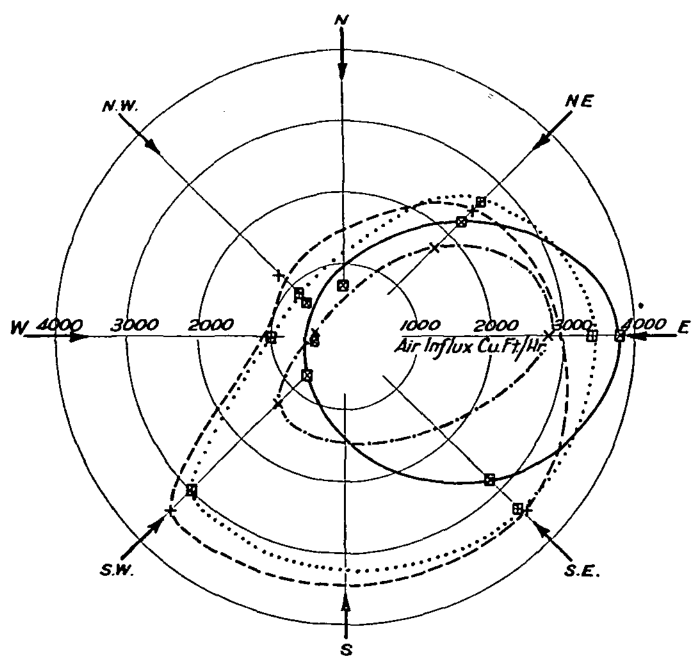


Text-fig. 6. Dependence of the rate of influx of air on the direction of wind. For speed groups 3½–6 m.p.h. and 6½–9 m.p.h. for 50 sq.in. flue and 50 sq.in. grating. Room A 1640 cu.ft. Wall containing grating and windows facing south-west.

—— ⊠ Grating 3½–6 m.p.h. –·–· × Flue 3½–6 m.p.h. ····· ⊞ Grating 6½–9 m.p.h. – – – + Flue 6½–9 m.p.h.



Text-fig. 7. Dependence of the rate of influx of air on the direction of wind. For speed groups 3½–6 m.p.h. and 6½–9 m.p.h. for 50 sq.in. flue and 50 sq.in. grating. Room B 1360 cu.ft. Wall containing grating and windows facing east.

—— ⊠ Grating 3½–6 m.p.h. –·–· × Flue 3½–6 m.p.h. ····· ⊞ Grating 6½–9 m.p.h. – – – + Flue 6½–9 m.p.h.

Flue effect

(3) In room A the influx rate for each speed range is approximately the same for all directions from which the wind blows, although it is somewhat greater when the wind blows toward the wall containing the grating.

(4) In room B the influx rates vary in an almost identical manner with wind direction as in the case of the grating.

Variation of influx rate with wind speed

The data from which the polar curves of Text-figs. 6 and 7 are derived appear to be the most complete which can be extracted for the purpose of this correlation. In this form they reveal broad relations which are supported by other results contained in Tables 1A and 1B.

Flue

With the flue only open, increase in wind speed causes increase in influx rate for all directions of the wind.

Grating

In the case of the grating, the relation between the influx rate and wind speed is complex, as it varies with the direction of the wind. With the wind blowing normal towards the wall containing the grating, increase in speed does not appreciably increase influx rate, but at the greater speed the maximum influx rate is approximately constant over a wider angle of incidence of the wind. Thus for oblique directions towards the wall containing the grating, influx rate increases with wind speed. The broadening of the maximum rate at the lower speed, which accompanies increase of speed, is a feature so apparent in the results of both rooms that this aspect of the interpretation is considered to be important.

The flow stream enveloping the building

The main features of the wind stream obstructed by a grounded model of a flat-roofed building observable in the photograph (Pl. 8, fig. 3) are:

(1) The high static pressure on the windward as compared with that on the leeward side of the model, as evidenced by the relative densities of the indicating medium in the regions marked *W* and *L*. Measurements of the wind pressure on isolated buildings (Richardson & Miller, 1932) confirm this observation.

(2) The concentration of steady flow lines in the regions *X* and *Y*.

(3) A region of high velocity gradient and instable flow at *T*, the confluence of the steady flow streams *X* and *Y*.

It appears justifiable to assume that these features would persist even if small openings were present in the containing walls of the model.

Correlation of experimental data and flow forms

The room under observation is one compartment of the many which constitute the building obstructing the air flow, and as such is but one branch in the flow circuit concerned. By analogy with an electrical circuit consisting of a network of resistances in series and parallel, or with a complex pipe circuit through which a fluid is flowing, the air flow through the room is determined by the combined resistance to air flow of the openings in the flow path and the pressure differences across these openings, the latter in turn depending on the pressures developed in the main flow stream about the house.

It is to be noted that, as in the analogous cases cited, the potential or pressure at any one point in the circuit is alone insufficient to determine the flow through any particular branch. Evidence of the dependence of the influx rate into the room on openings in other parts of the building was afforded by the increase in the measured rate which immediately occurred in the test room when a door on the ground floor and communicating with the open air was opened. These considerations and experiences indicate that correlation must be sought in the physical characteristics of the obstructed flow stream and the relevant flow resistances in the room and the containing house.

In Text-fig. 8 the house is represented diagrammatically with the main features of the flow form derived from Pl. 8, fig. 3 superimposed. *A*, *B*, *I*, *H* represents the room, the ventilation of which is under consideration, and the shaded area represents the remainder of the house. Openings into the room, other than the grating or flue, are represented by the gaps, denoted by *a*, *c*, *e* and *g*, into the well of the house at *I*; interstices round the windows which are near the grating are, when the grating is in use, reckoned as part of the grating; but when the flue is in use they are considered to be an additional opening. It is to be noted that at all times the flues of the rooms in the part of the building represented by the shaded area were open.

The wall grating

Wind direction

As already mentioned, the graphs of Text-fig. 4 indicate that in the case of room A the area of the openings represented at *I* is of the order of 20 sq.in.; thus with a grating of 50 sq.in. area, the flow through the room is determined mainly by the pressure drop across the opening at *I*.

Because the dominating resistance is at *I*, the pressure inside the room will be substantially that on the outside of AB, more or less, according to whether AB is the leeward or the windward side of the house. The pressure outside the room, in the well of the house, I, will depend on the relative and absolute 'tightness' of the sides BC and $EFGH$, and on the pressure developed by the wind stream at these surfaces. When AC is windward, a positive pressure prevails at BC, a negative pressure at EFG, and a negative pressure at the base of the flue in each room. Except in the case of BC, c, EFG and e and g, all being very open, the pressure at I will be negative and thus the pressure difference across, and the flow through, a will each be large. With EFG windward, pressure inside the room at a is negative, and the flue effect in each room and the negative pressure over BC will produce a negative pressure at I. The pressure on each side of a will be negative and the pressure difference and therefore the flow through a will be small.

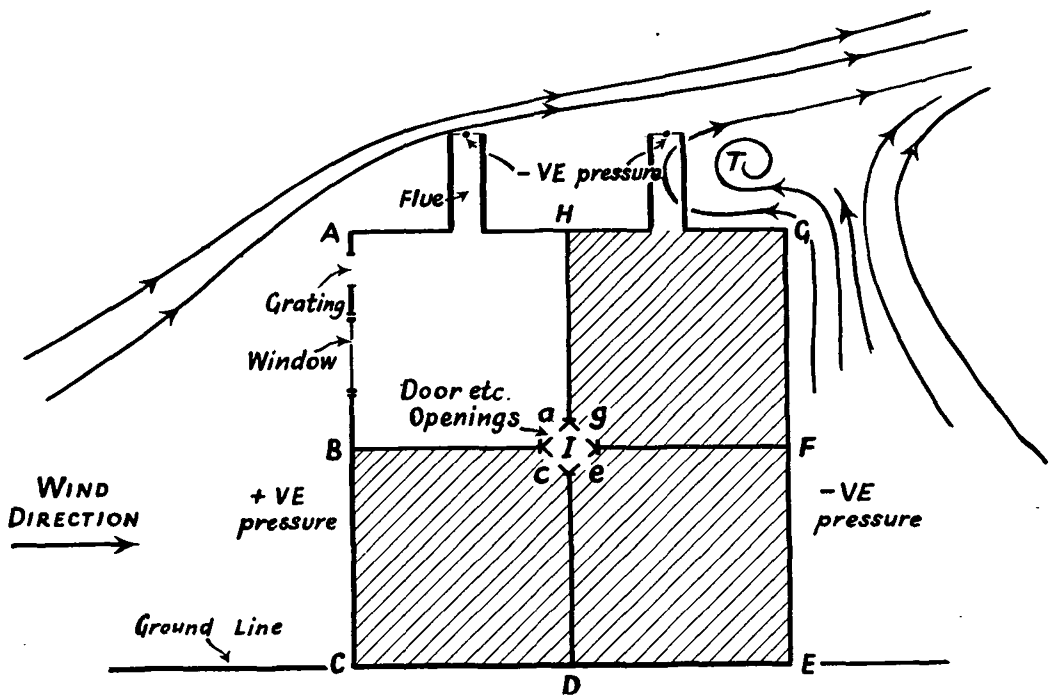
The lop-sided shape of the influx curves for the grating, shown in Text-figs. 6 and 7, are thus explained.

It follows that in order to equalize the influx rates for winds directed towards and away from the grating, it would be necessary to maintain a constant pressure at I, the mean between the pressures on the leeward and windward sides of the building. This could be effected by adequate air access from these two sides.

The somewhat greater influx rates for room A than for B when the grating was on the leeward side of the building indicates that to some extent this in fact was the case for the building containing room A and resulted from a loose structure of the building.

Wind speed

It is suggested that the approximate equality of the influx rates for the two wind speed groups, 3½–6 and 6½–9 m.p.h. for directions normal to the wall containing the grating, is due to a greater increase in pressure over the part BC than over the part AB of the windward wall with increase of wind speed, so that the pressure difference across a remains unaltered.



Text-fig. 8.

The flue

The existence in the room of two openings, i.e. flue and window-frame interstices, exposed to different parts of the wind stream, presents a set of flow conditions in the room which differ fundamentally from those governing the case of the grating, in which only one opening is exposed to the wind stream. Provided that the flue terminates outside the instable region T, a deficit of static pressure due to high dynamic pressure in the flow stream will always operate at the terminal and in general establish a negative pressure in the room.

The pressure at I will be the resultant of the negative pressure due to the flue effect in each of the other rooms, and the positive or negative pressure resulting from BC being windward or leeward. Similar considerations to those used in the case of the grating lead to an explanation of the shapes of the 'flue' curves in Text-figs. 6 and 7. The effect of maintaining a relatively constant pressure at I, on the equalization of the influx rate for all wind directions, is well shown by the symmetry of the 'flue' curves for room A, in Text-fig. 6, the constant pressure being due to a loose building structure already indicated by the proportions of the grating curves.

Throughout the development of the theory it has been tacitly assumed that the flow forms of the wind stream about the building concerned result entirely from the obstruction of a uniform stream by an isolated building. Apart from other buildings in the terrace of which those under test were part, no others were considered to be sufficiently close seriously to modify the pressure distribution assumed. The approximately 90° difference between the direction of maximum influx rate for the grating and the normal to the grating in the room of the lower building is probably due to interference of the wind stream resulting from the difference in heights of the two buildings containing the rooms used for test.

Comparison with published data on natural air change

Comparison of the results of this investigation with those of Warner (1940) and of Bedford, Warner & Chrenko (1943) shows close agreement on the lump averages of the influx rates. For instance, Warner (1940) found an average of 845 cu.ft./hr. for closed rooms with sealed flues in buildings described as pre-1914. Bedford *et al.* (1943) record an average of 810 cu.ft./hr. for similarly closed rooms in buildings 50 years old, whilst the corresponding average for this investigation is 800 cu.ft./hr.

Again the variation of average influx rate with the area of the flue base opening quoted by these authors is very similar to that recorded in Table 2 of this paper.

There appears, however, marked disagreement between the findings of this investigation and those of others regarding the effect of both wind speed and direction on influx rate. Warner (1940) states that in his observations little effect of wind direction on air change can be traced, and quotes Wellner as finding that a higher air change was accompanied by a higher wind speed, whatever its direction. The polar curves in Text-figs. 6 and 7 of this paper, however, show definite and considerable dependence of influx rate on wind direction, and that a higher wind speed does not necessarily effect a higher influx rate.

Warner (1940) and Masterman, Dunning & Densham (1935) report that on occasions the rate of air change observed appears out of all proportion to the value expected from the conditions ruling at the time. On the other hand, however, the data of Bedford *et al.* (1943) indicate a simple linear relation between influx rate and wind speed for all wind directions, and a regular increase of influx rate with increase of the angle of incidence of wind.

It is a main conclusion of this paper that the dependence of the influx rate on the speed and on the direction of the main wind stream is in each case both definite and complex.

Warner (1940) made his observations of wind speed using a kata-thermometer placed alongside the external wall of the room under investigation. It is here suggested that such an observation is of little significance since, as already pointed out, the influx rate for a given room is dependent on air pressures developed at all openings into the room, which are in turn dependent upon structural features of the whole building containing the room. The kata-thermometer indication at any point about a building is not a unique characteristic of a particular air-flow pattern and cannot, therefore, be considered a measure of a controlling factor in the problem. It is also suggested by the author that the main wind-stream velocity is the only unique property of a particular flow pattern about a given building, and thus any single subsidiary air speed or pressure feature is not a suitable factor for correlation. Bedford *et al.* (1943) in quoting wind speeds as being Meteorological Office figures do not explain the relation between these and the speed of the main wind near the building concerned. Since local wind speed and direction may both be peculiar to the topography of the locality and differ considerably from those in the neighbourhood of the Meteorological Observatory, the wind speeds quoted may not be significant. In view of the importance here attributed to the measurement of the main wind-stream velocity simultaneous with that of the influx rate, it is suggested that the anomalous results reported by Warner (1940) and Masterman *et al.* (1935) may be due to omission of such observations by these investigators.

In the investigations cited, the absence of observations on what are here considered fundamental factors in the problem, and also of a basis of analysis in which the controlling variables are separately considered, makes further comparison of the effect of these variables and the relative efficacy of flue and wall grating appear unwarranted.

Comparison with the treatment of the problem of natural ventilation by Shaw (1907) redirects attention to the physical principles involved as laid down by that author. The emphasis put by him on the role of all the pressure effects due to the wind, and the consequent necessity of taking account of not only the constructional features of the room under investigation but also those of other parts of the containing building, is well supported by the broad conclusions resulting from the correlation of the experimental evidence.

CONCLUSIONS

The degree of ventilation in existing dwellings

In a house considered to be of typical construction and condition, a chimney flue with a base opening of 15 sq.in. is on the average as efficacious as a wall grating having 50 sq.in. free area, in so far as facilitating natural air change when the room is unheated and the windows and door are closed.

If windows and doors are left open in other parts of the house, the ventilation in the room when the flue is used is approximately constant for all directions of the wind, but when the grating is used the ventilation is more when the grating is on the windward side of the house and considerably less when on the leeward side.

Provisions to ensure maximum natural ventilation in 'closed rooms'

From the broad theory of the relation between natural ventilation and wind velocity, which has been developed on the basis of the correlated data, it appears reasonable to suggest that in a building of tight construction attainment of a uniform degree of natural ventilation for winds from all directions requires provision of the following:

(1) A flue terminating outside the region of eddy motion in the wind stream.

(2) An opening between the room and the well of the building.

(3) An opening between the well of the building and the exterior of the building in each of two opposite walls of the building.

SUMMARY

The experimental method for, and analysis of, more than 300 determinations of air influx rates into two unheated 'closed rooms' of opposite aspects each fitted (*a*) with wall grating, or (*b*) with flue, are described. The average relative efficacy for all observed wind velocities of (*a*) of 50 sq.in. to (*b*) of 15 sq.in., so far as facilitating natural ventilation in the rooms used, is found to be 1·0. The analysis reveals definite and complex relations between influx rate and wind velocity. A correlation is made with data from other sources, principally photographs of the flow forms of air streaming past grounded house models, and a theory is advanced to explain the broad features of the observations. Comparison with similar published work is made, and the fundamental necessity of simultaneous measurement of the speed and direction of the main wind stream is stressed. The advantage of the flue and the importance of openings, other than those in the room concerned, are pointed out.

The author wishes to record that the investigation was commenced at the instigation of Mr Dean Chandler, to whom he is indebted for encouragement to publish the results of the further examination of the data obtained. He desires also to acknowledge the enthusiastic interest in the experimental work which his colleagues of the Physical Laboratory displayed throughout the investigation.

The measurements of the wind velocity, so essential to the completeness of the observations, frequently necessitated the scaling of roofs in snow, rain and gale, yet at no time were they neglected.

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