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THE FUNDAMENTALS OF NATURAL VENTILATION OF HOUSES*

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Synopsis.

The fundamentals of natural ventilation are discussed with particular reference to the ventilation of houses. The laws of flow are presented and typical values are suggested for the acting pressures and the apertures through which flow can occur. As an example of the application of the laws, the effect of wind and temperature difference on the ventilation of an exposed house is discussed, and the theoretical treatment is illustrated by experimental results.

Introduction.

When introducing a recent paper at a London meeting of the Institution,[1] the author outlined the general framework of ventilation laws within which he thought experimental studies of ventilation should be viewed. This framework is discussed below and is illustrated from the results of experimental studies of the ventilation of closed heated houses, which have been made at the Building Research Station. It should be noted that the approach is an approximate one, the aim being to show the relative importance of the factors affecting ventilation and the manner in which these combine.

PART I: THE LAWS OF NATURAL VENTILATION.

In 1903 Sir Napier Shaw gave a series of lectures at Cambridge University on air currents and the laws of ventilation.[2] The present paper is based on the laws enunciated by Shaw and relates them to the natural ventilation of heated houses with doors and windows shut; the laws are equally applicable to ventilation problems in other types of buildings.

The process of natural ventilation in a house is mainly due to the passage of air *through* the house, air entering at one point and leaving at a different point. With open windows, of course, air change can occur with air entering and leaving through the same window: on windy days this can be caused by turbulence induced by the wind and even on calm days there is some interchange of air by diffusion through an open window. In the closed house, however, it can be assumed that ventilation is produced by air passing through the house. This air does not necessarily mix completely with the air of the rooms through which it passes, but it was found that there was fairly complete mixing in the heated closed houses where the experimental studies referred to were made.

It has been found in laboratory tests that the rate of air flow through such openings as ventilators and the cracks around windows and doors is approximately proportional to the square root of the pressure difference acting across the component. There are conditions in which this law is not followed exactly, for instance, there may be an effect due to change in the appropriate Reynold's number,

Written discussion is invited.

or there may even be a physical movement of a window relative to its surround as the pressure across it changes ; but the assumption of the simple law is a fruitful one in understanding the main features of the ventilation processes. The simple law also applies to the flow through a thin plate orifice which for a coefficient of discharge of 0.65 is given by :

$$V = 1070 a\, H^{\frac{1}{2}} \qquad (1)$$

where V = rate of air flow in cubic feet per hour
a = area of orifice in square inches
H = pressure drop across the orifice in inches water.

Thus if the rate of air flow through a component is known for a given pressure across it, the area of the thin plate orifice to which the component can be regarded as equivalent may be calculated. This concept of equivalent area is a very useful one, as it makes readily apparent the importance of individual components.

As an example of this type of calculation the estimated rates of air flow through cracks around the windows of one of the experimental houses will be used. There the rate of infiltration was estimated to be 94 c.f.h. per foot crack of window when there was a pressure head of 0.03 in. w.g. across the windows. Substituting these values in equation (1), the equivalent area a is found to be 0.51 sq. in. So that for a typical window with total length of crack of 25 feet, the equivalent orifice would have an area of about 13 sq. in. ; in other words, the same amount of air would enter the room if the window were sealed and a hole of about 4 in. diameter were cut in the glass.

When there is a pressure difference (H) acting across the wall of a house there may be flow through a number of components in the wall, and using equation (1) the total rate of air flow will be given by :

$$V = 1070\; a_1\; H^{\frac{1}{2}} + 1070\; a_2\; H^{\frac{1}{2}} + \ldots$$

where $a_1, a_2 \ldots$ are the equivalent areas of the components. This may be written as :

$$V = 1070\; (a_1 + a_2 + \ldots)\; H^{\frac{1}{2}}$$

so that the equivalent area (a) of the components in this arrangement (in parallel as it is usually called) is the sum of the equivalent areas of the components. Thus with two components we have :

$$a = a_1 + a_2 \qquad (2)$$

Another arrangement of the components which is of interest is when they are in series so that the air traverses them in succession ; for instance, air may enter through the cracks around a window, then pass through an internal ventilator and finally leave through cracks around a second window. Taking the simplest case when two components of equivalent areas a_1 and a_2 are in series, the flow equations may be written :

$$V = 1070\; a_1\; H_1^{\frac{1}{2}}$$
$$V = 1070\; a_2\; H_2^{\frac{1}{2}}$$

where H_1 and H_2 are the pressure drops across the respective components, so that $H_1 + H_2 = H$, the total pressure drop. Expressing the rate of air flow in terms of H the equation is :—

$$V = 1070 \frac{a_1 a_2}{(a_1^2 + a_2^2)^{\frac{1}{2}}} H^{\frac{1}{2}}$$

Comparing this with equation (1), the equivalent area (a) of the two components in series is given by the relationship :

$$\frac{1}{a^2} = \frac{1}{a_1^2} + \frac{1}{a_2^2} \quad \ldots\ldots\ldots\ldots (3)$$

The effective equivalent area is, therefore, always less than either of the two separate areas. If the two areas are equal, the effective equivalent area is 70 per cent. of that of each, and if one area is large compared with the other then the effective equivalent area is approximately that of the smaller. Thus when there are two components in series the resultant effective area lies between 0.7 and 1.0 times the equivalent area of the smaller aperture. This incidentally demonstrates the importance of the remainder of the air circuit when considering the ventilation induced by a flue or an air-brick.

In Shaw's original discussion, equation (1) was presented in the form :

$$H = RV^2 \quad \ldots\ldots\ldots\ldots (4)$$

where R represents the resistance to air flow. Comparing this with equation (1) shows :

$$R = \left(\frac{1}{1070a}\right)^2$$

so that an alternative way of expressing equation (3) is :

$$R = R_1 + R_2 \quad \ldots\ldots\ldots\ldots (5)$$

The above laws can be applied to many problems of interest in ventilation, but before giving one or two examples the probable values of the pressure heads and the equivalent areas of components in houses will be examined ; with a knowledge of these, the rates of flow may be calculated.

PART 2 : THE ACTING PRESSURES.

The sources of the pressures which promote ventilation of houses are given in Table I, which also shows the magnitudes which are suggested as typical. These sources will be discussed in turn.

Table I.—Typical Acting Pressures.

Agency	Pressure Head (in. w.g.)	Assumptions
Wind—exposed area ..	0.04	Velocity head at 8.5 m.p.h.
built up area ..	0.004	Effective wind speed reduced by a factor of 3
Heated flues..	0.07	Flue 27 feet high with temperature excess 100° F.
Stack effect..	0.01	Height 15 feet with temperature excess 20° F.
Fire-beds	0.015	Fire-bed 1 foot deep

Wind—Exposed Areas.

Wind is one of the most important factors which produce pressures. The effect of wind on a building is shown in Fig. 1, which gives the results of pressure surveys on model buildings by Irminger and Nøkkentved.[3] They found that the pressures produced were approximately proportional to the square of the wind speed, so that from

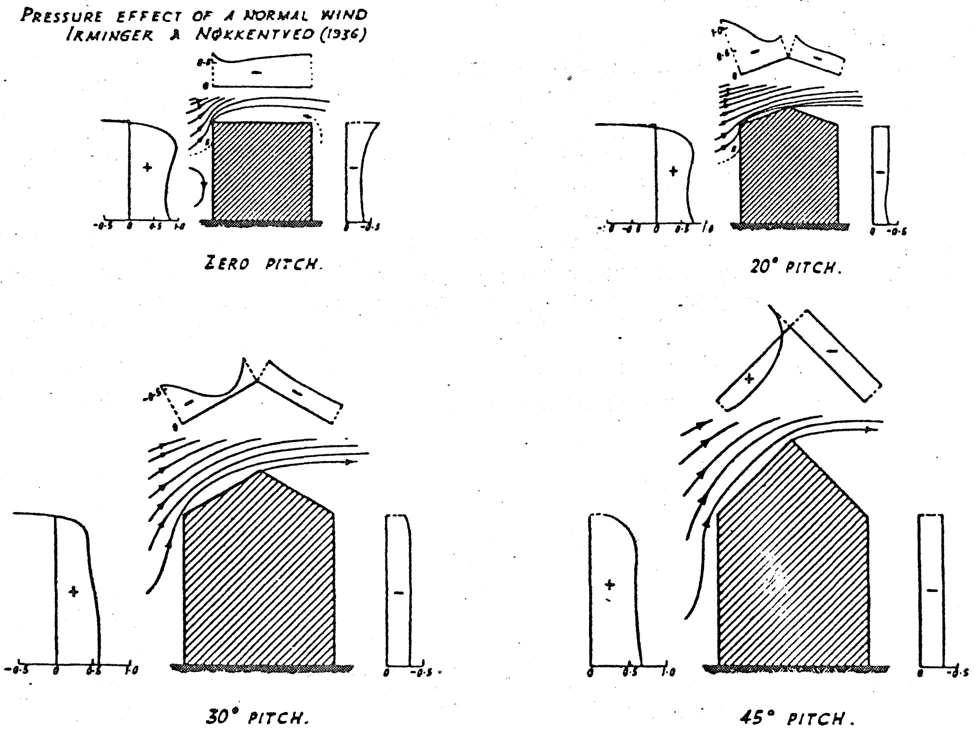


Fig. 1.—The Pressures Produced by a Wind Blowing Normal to a Building (Irminger and Nøkkentved, 1936).

equation (1) the flow through an aperture due to wind alone will be approximately proportional to the wind speed. In the figure the pressures have been expressed as fractions of the corresponding velocity head (which is given by 0.00051 v^2 in. w.g., where v is in m.p.h.), and it will be seen that the pressure on the windward side of the building is about 0.5 to 0.6 times the velocity head, and that the leeward suction is about 0.3 times the velocity head. So the pressure acting across an exposed house (when the wind is normal to it) is approximately equal to the velocity head and at the assumed average wind speed of 8½ m.p.h. this has a value of 0.04 in. w.g. A change of direction of wind alters the pressure pattern, but it has been found in practice that although the air-change rates of some rooms are affected by this, the effect in many rooms is small; it is thought that this is due to the realignment of apertures as inlets and outlets as the direction of the wind changes.

There may also be local effects of wind at the terminals of chimneys and vertical ventilation shafts. Here the suction produced can be of the order of the velocity head of the wind: the fraction in any particular case will depend on the design of the terminal and its location relative to the building contour.

Wind—Built-up Areas.

In built-up areas there is a shielding effect which reduces the pressures on buildings due to wind. Bedford, Warner and Chrenko, for instance, in their series of ventilation measurements in London,[4] found that the wind speeds at street level were of the order of one-third of the free wind speeds, so in Table I the wind pressures on buildings in built-up areas have been taken as being of the order of one-ninth of the pressures in exposed areas.

Flues.

The next source of pressure difference in the table is the heated flue, the pressure being caused by the difference in weight between the column of flue gases and a similar column of external air. The temperature at the inlet to the flue depends on the appliance which it serves, and the rate of decay of temperature with height up the flue depends on the mass flow of gas and the thermal properties of the flue and its surrounds. In the table an open fire is shown as an example, where a typical figure for the mean excess temperature is 100° F. It will be seen that the order of this pressure is comparable to that of wind on an exposed site.

Stack Effect.

Stack effect due to temperature difference between external air and the air in a house also plays a part in ventilation, but in the normal two-storeyed house it is unlikely to be large and will only become important when the effective wind speeds are low. The general equation for calculating the pressure due to stack effect is:

$$H = 7.6\, h \left[\frac{1}{T_e + 460} - \frac{1}{T_i + 460}\right]$$

where H = pressure (in. w.g.)
h = height of effective column (ft.)
T_e = external temperature (°F.)
T_i = internal temperature (°F.)

When the temperatures are not very different from 60° F. this approximates to:

$$H = 2.8 \times 10^{-5}\, h\, (T_i - T_e) \qquad (6)$$

The value of 0.01 in. w.g. given in the table is for a temperature difference of 20° F. with a vertical height of 15 feet, which are fairly typical values for winter conditions.

Fire-beds.

One further source of pressure is in the high temperature of the fire-bed in appliances such as domestic boilers. This will vary according to the appliance but there is a definite upper limit to its value, for if the fire-bed is one foot deep, the pressure cannot be greater than one foot of air or 0.015 in. w.g., no matter how high the temperature is.

PART 3 : TYPICAL EQUIVALENT AREAS.

Table II showing typical equivalent areas of the components in houses has been constructed using where possible measured flow characteristics ; where such measurements are not available the free areas have been used unless otherwise indicated.

Windows.

The equivalent area shown for windows is that already calculated in Part 1 ; it will, of course, vary considerably with the construction. Weather-stripping reduces this area and that shown in the table is based on results in a number of laboratory tests at the Building Research Station. Another crack associated with windows is that between the frame and the surround and the area taken for this is based on published American data.

Doors.

The equivalent areas given for cracks around doors are also calculated from American data. In experiments at the Building Research Station the reduction in air infiltration due to weather-stripping external doors was found to be even greater than indicated here. The improvement achieved does, of course, depend on the size of the original gap as well as the effectiveness of the weather-stripping.

Walls.

It will be seen from the equivalent areas given that with a modern hard plaster finish the infiltration through a normal wall is negligible.

Air-bricks.

The area given is the free area of a typical air-brick. Some by-laws require these to have a free area of 50 sq. in. but there are many installed which have a smaller free area going down to about 10 sq. in.

Floors.

The infiltration is negligible when there is a solid floor. With tongued and grooved boards in a ventilated floor the main gap will be where the boards meet the wall, a gap which may or may not be sealed by the skirting board ; assuming a gap of $\frac{1}{16}$ in. around the perimeter of a room 12 ft. square, the total free area is about 35 sq. in. With square boards in the same size of room and a gap of $\frac{1}{16}$ in. between adjacent boards, the total free area in an uncovered floor is about 200 sq. in., though in this case the area determining the flow is probably that of the ventilators in the external wall of the house. The latter may vary from 40–90 sq. in.

Flues.

The area given in Table II is for the throat of an open coal fire. There is also resistance to flow in the chimney pot and friction in the flue itself, and these probably reduce the equivalent area to about 25 sq. in. The areas given for gas-fire flues are those recommended by the Gas Council.

Table II.—Typical Equivalent Areas.

Component	Equivalent area (sq. in.)	Source
Windows—unweather-stripped	13	25 feet of crack—Building Research Station (B.R.S.) data
weather-stripped	3	
frame	1	Guide issued by American Society of Heating and Ventilating Engineers[5] (A.S.H.V.E.)
Doors—unweather-stripped..	13	18 feet of crack in poorly fitting door—A.S.H.V.E.[5]
weather-stripped ..	7	
Walls—unplastered	3	9 in. walls, 100 sq. ft.—A.S.H.V.E.[5]
plastered	0	
Air-bricks	10–50	
Floors—solid	0	
tongued and grooved boards	35	$\frac{1}{16}$ in. gap at skirting. Floor 12 ft. × 12 ft.
square boards ..	200	$\frac{1}{16}$ in. gap. Floor 12 ft. × 12 ft.
ventilators	40–90	Wall run of 60 ft.
Flues—open fire	50	
gas fire	20–50	
Heating appliances	large range	
Ventilators—fixed louvres ..	24	12 in. × 3 in. ventilator—B.R.S.
constant flow ..	13.5	At 2 m.p.h. B.R.S.
	3.5	At 20 m.p.h. B.R.S.

Heating Appliances.

In some solid-fuel appliances there is considerable resistance to air flow, for instance, the coke in the fire-bed of a domestic coke boiler presents a resistance and further resistance may be introduced by dampers. With an open fire only a fraction of the air passes through the fire-bed and the effective resistance of the latter is therefore small. The resistances and the corresponding equivalent areas for these components thus cover a wide range.

Ventilators.

Laboratory tests on a 12 in. × 3 in. ventilator (which is a fairly typical size for use in houses) showed the equivalent area to be 24 sq. in. The flow through this type of ventilator is approximately proportional to wind speed so that at high wind speeds the volume of air can become excessive. A constant-flow ventilator with self-adjusting vanes reduces this variation with wind speed as is shown from the experimental results in Fig. 2. In the upper graph the flow rates measured for various pressure drops across the ventilator, are plotted against the corresponding wind speed (assuming that the pressure is equal to the velocity head), and it will be seen that the rate of flow is fairly constant for wind speeds between 5 and 20 m.p.h. The two dotted lines show what the flow characteristic would have been if the area of the ventilator had remained constant during the measurements, at its fully opened and its fully closed positions.

The reduction of the effective area of the ventilator as the pressure increases is shown in the lower half of Fig. 2.

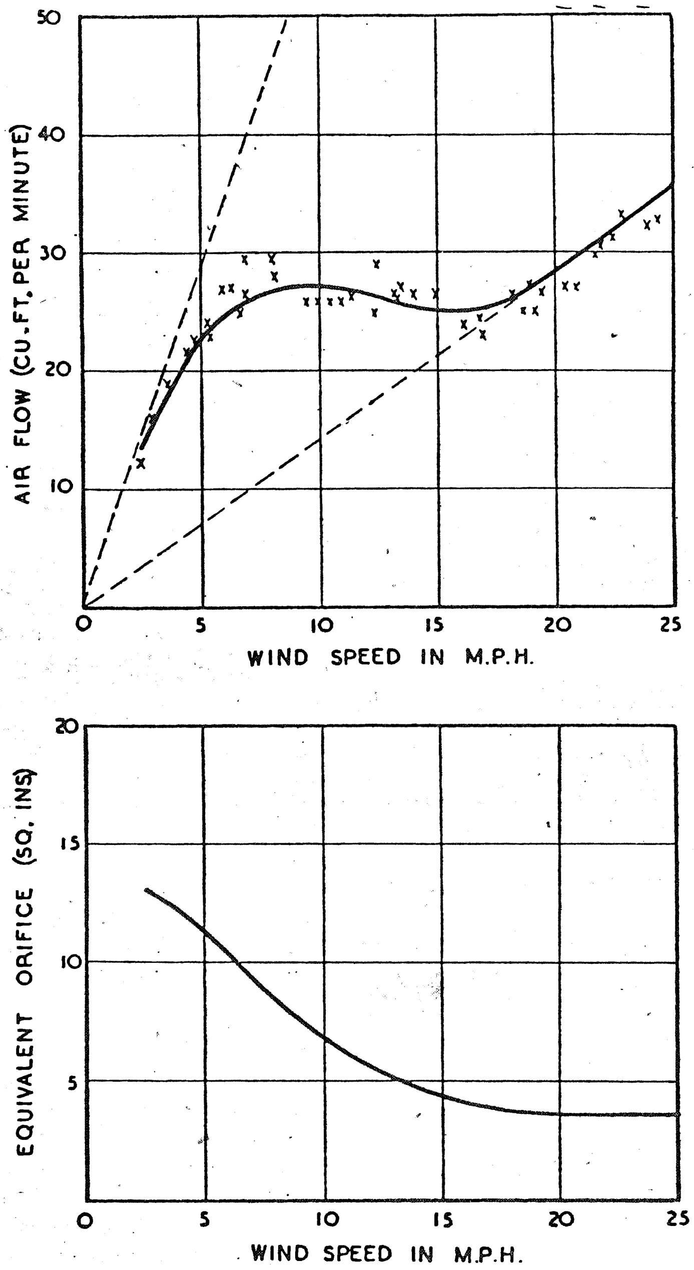
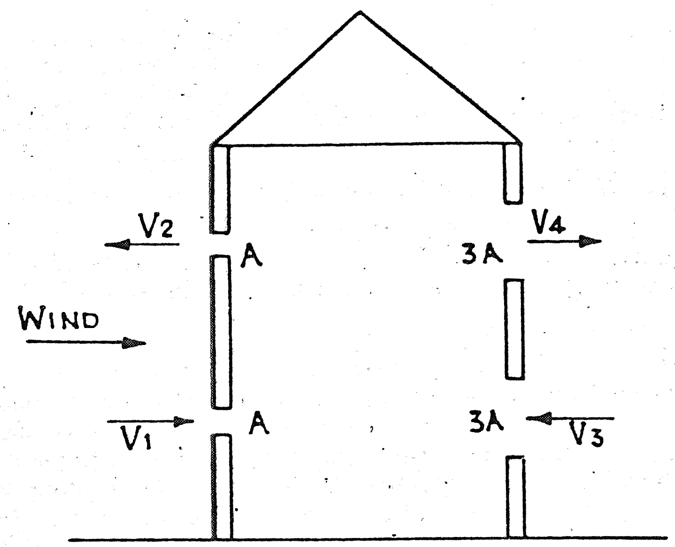


Fig. 2.—The Characteristics of Constant-Flow Ventilator.

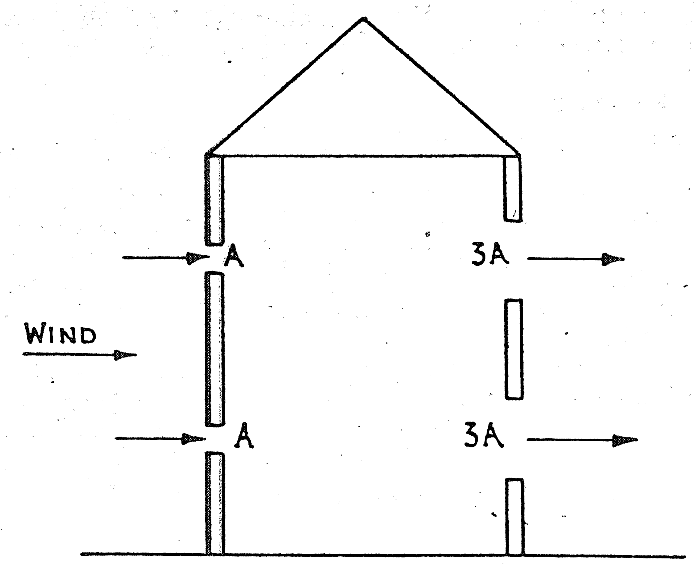
PART 4 : APPLICATIONS.

As an example of the application of the laws, consider the action of wind and temperature difference on the ventilation of an exposed detached two-storey house. For simplicity assume that in each wall upstairs and downstairs there are apertures whose equivalent areas are all equal to A sq. in ; that there is no resistance to air flow within the house ; and that when there is a wind normal to one of the walls, the outside surfaces of the other three walls will be at the same pressure.

When there is little wind and stack effect predominates, air will enter through the apertures on the ground floor and leave through the apertures on the first floor. The apertures in the three walls at



(a) STACK EFFECT PREDOMINANT.



(b) WIND PRESSURE PREDOMINANT.

Fig. 3.—Patterns of Air Flow in a House.

the same pressure are effectively in parallel and thus equivalent to apertures of area $3A$, so that the flow diagram is as shown in Fig. 3 (a) where the Vs represent the volume rates of flow. As the wind increases there will be a value at which the flow V_2 reverses, and as it increases still further V_3 will reverse giving the flow diagram in Fig. 3 (b). The rates of volume flow may be calculated for these types of flow by equating the acting pressure in any circuit to the pressure drop across the components in that circuit. Such calculations become rather complicated and here only the two extreme cases will be considered in detail, but the general results will be indicated.

When there is no wind, the acting pressure due to temperature difference is given by equation (6) :

$$\text{i.e. } H = 2.8 \times 10^{-5}\ h\ (T_i - T_e)$$

where h is the height between the apertures in a wall.

Considering the apertures in one wall, half this pressure will act across each aperture and using equation (1) the rate of air flow will be :

$$V = 4.0\ A\ [h\ (T_i - T_e)]^{\frac{1}{2}} \qquad (7)$$

This is a useful formula for general application ; it should be remembered that it assumes that the apertures have the same coefficient of discharge as a thin plate orifice, viz. 0.65. In this particular case the total rate of air flow through the apertures in the four walls into and out of the house will be four times this amount :

$$\text{i.e. } 16.0\ A\ [h\ (T_i - T_e)]^{\frac{1}{2}} \qquad (8)$$

When the wind is strong enough to swamp stack effect, the air flow will be as in Fig. 3 (b) and will occur through two apertures of areas $2A$ and $6A$ in series. From equation (3) the equivalent area of this arrangement will be $1.9A$, so using equation (1) the rate of flow is :

$$V = 2030\ A\ H^{\frac{1}{2}}$$

and substituting the pressure head of wind ($0.00051\ v^2$) this gives :

$$V = 46\ A\ v \qquad (9)$$

It may be shown from the general equations that the rate of air flow into the house is approximately that given by the larger estimate calculated from expressions (8) and (9) ; this approximation is independent of the ratio of the areas of the apertures in windward and leeward walls, which only affects the rates of flow calculated as above and, therefore, the critical wind speed. In the above example the speed above which wind takes control is given by equating the estimates of the air flow produced separately by wind and temperature difference.

$$\text{i.e. } 46\ A\ v = 16.0\ A\ [h\ (T_i - T_e)]^{\frac{1}{2}}$$

or :

$$v = 0.35\ [h\ (T_i - T_e)]^{\frac{1}{2}} \qquad (10)$$

Alternatively, this condition can be expressed in terms of the acting pressures, the relationship being that the velocity head must be greater than 2.2 times the stack pressure before wind predominates.

A series of measurements of air-change rates was recently made at the Building Research Station in an experimental house, which (although it has some ventilators to the roof) broadly corresponds to the case considered above. During these measurements the wind was fairly constant in direction. The height effective in producing stack pressure was probably about 10 feet, and at low wind speeds the house temperature was rarely less than 10° F. above the external temperature; with these values the critical wind speed calculated from equation (10) is about 3½ m.p.h. The measured rates of air change for wind speeds lower than 3½ m.p.h. are plotted against the square root of the temperature difference in Fig. 4; it will be seen

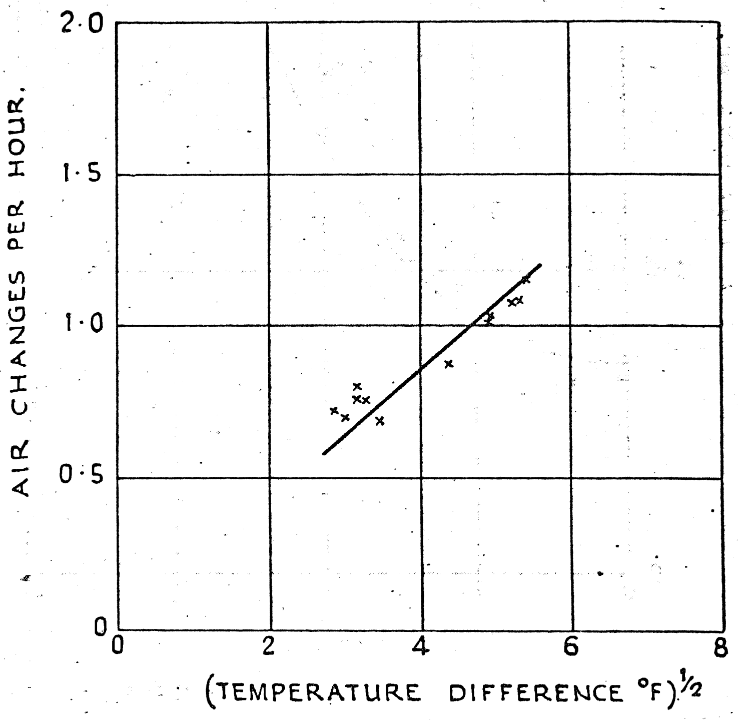


Fig. 4.—The Effect of Temperature Difference on Air-Change Rate at Low Wind Speeds.

that there is fairly good agreement with the proportionality predicted from equation (8). These readings have, therefore, been corrected to estimate the air-change rates for a temperature difference of 10° F. and are plotted with the other measured rates against wind speed in Fig. 5. When the wind was above 3½ m.p.h. the temperature difference was at most 12° F., so the theory would predict an approximately constant rate up to 3 or 4 m.p.h. and thereafter a rate proportional to wind speed. It will be seen that the observed rates agree fairly well with this prediction. Also from equations (8) and (9) the air-change rate at 15 m.p.h. is calculated to be 4.3 times the rate at zero wind speed; this may be compared with the observed ratio of about 3.5.

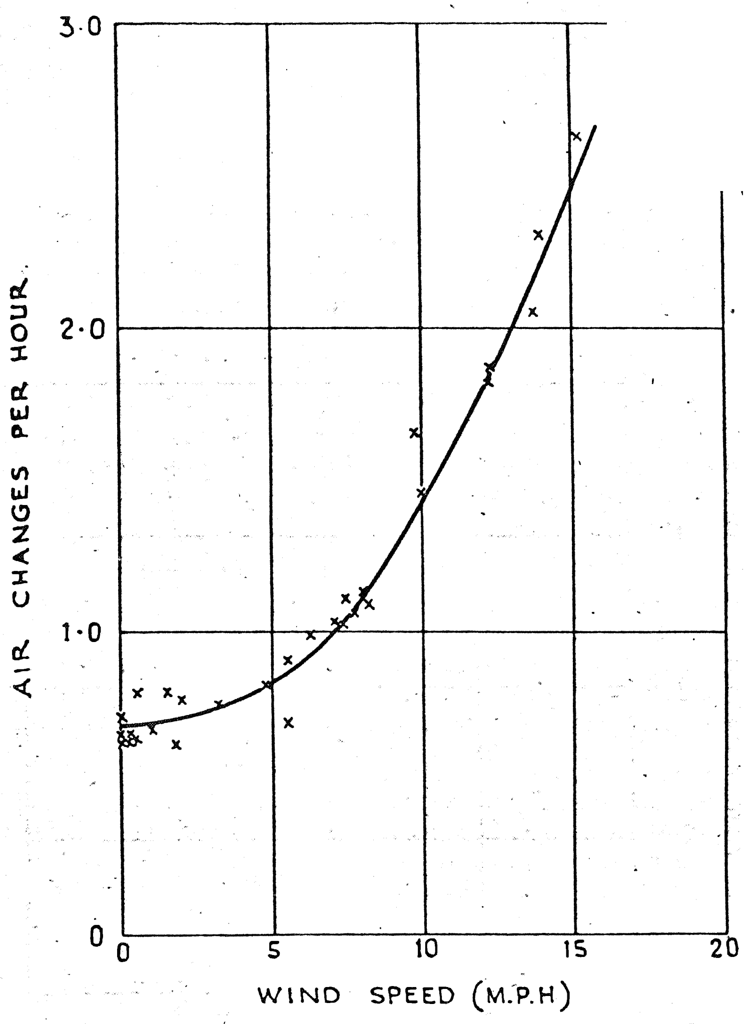


Fig. 5.—The Effect of Wind Speed on Air-Change Rate.

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