STATIC PRESSURE AND VENTILATION RATES IN ROOMS*

By FLORA W. BLACK, B.Sc., A.Inst.P.
Chief Scientific Adviser's Division, Ministry of Works

(With 6 Figures in the Text)

The *British Standard Code of Practice*, and other authoritative guides, recommend minimum rates of ventilation related to the size and use of rooms, and structural means for providing them. But the difficulty of measuring actual ventilation rates suggests that it is seldom done.

A standard way is to put into a room a known amount of some gas, measure the rate of decay of its concentration and hence infer the ventilation rate. (Renbourn, Angus & Ellison, 1949; Bedford, 1948; Lidwell & Lovelock, 1946). To estimate the ventilation rate by measuring the difference in static pressure between points inside and outside a room has been deemed impracticable (Carne, 1946). While investigating this conclusion, and, in the sequel, confirming it, observations on the relationship between air flow and static pressures, which may be of general interest, were made at the Ministry of Works Field Test Unit.

METHOD OF TEST

The investigation was made in a kitchen-living room forming one of three experimental rooms built inside a hut. This room (Fig. 1) has one external wall, but is otherwise within the hut and is thus similar to a room in an ordinary house. The

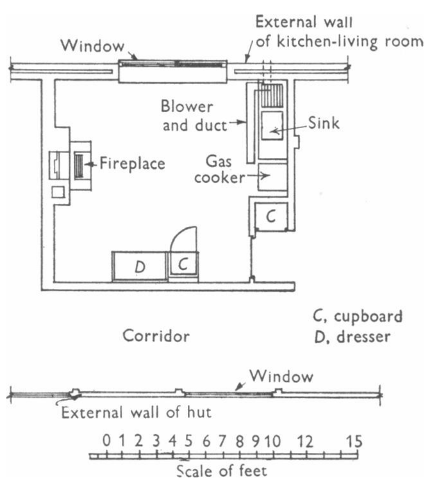

Fig. 1. Plan of experimental kitchen-living room.

fireplace was sealed, but various ventilation rates were produced by a variable-speed electrically driven blower, fitted to extract air from the room and pass it via a flowmeter, out through a pipe in the external wall. Provided the air pressure outside exceeded that inside the room, it was assumed that no air would escape from the room except through the flowmeter. Accordingly, the flowmeter was assumed to register the air flow through the room.

The meter was a tilted-gauge manometer connected across a $2\frac{1}{2}$ in. orifice plate in a pipe of $3\frac{1}{2}$ in. internal diameter. Its calibration with an accuracy of $\pm 2\frac{1}{2}$ % for air density 0·0756-lb./cu.ft. is

$$\text{Flow rate in cubic feet per minute (cu.ft./min.)} = 102{\cdot}5\sqrt{h},$$

where h in inches of water gauge is the static pressure across the orifice. With the tilted manometer filled with kerosene and set at $11\frac{1}{2}°$ to the horizontal the flow rate in cu.ft./min. $= 40{\cdot}6\sqrt{L}$, where L is the displacement in inches of kerosene in the tilted tube.

The pressure difference between the inside and the outside of the room was measured by a Chattock gauge, the smallest scale division of which represented a pressure difference of 0·6439 milli-inches of water gauge.

Rubber tubing, a hole in the partition wall and a metal pipe through the window frame enabled the gauge to be connected to any point in the room and inside or outside the hut.

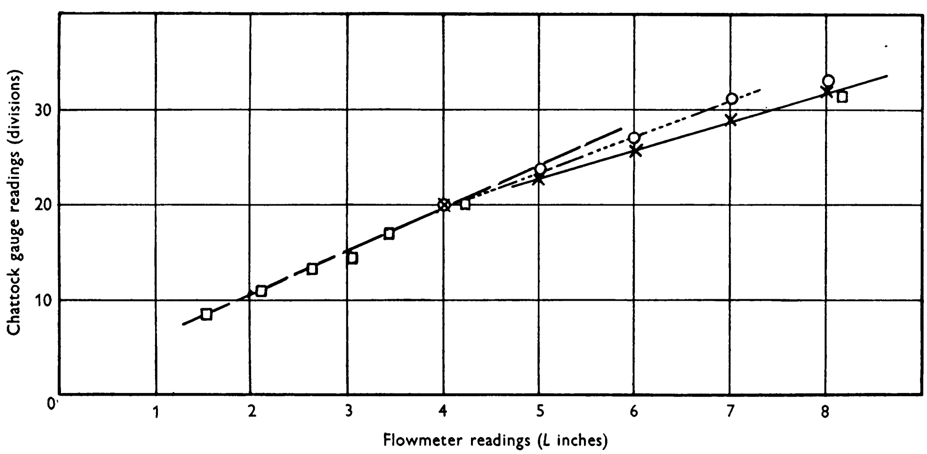

Fig. 2.

EXPERIMENTAL EVIDENCE

It was found, as expected, that whatever the rate of air flow through the room the static-pressure difference between points within the room was too small to be indicated by the Chattock gauge.

The static-pressure difference between the inside of the hut and the inside of the room, with doors and windows closed, was measured over a range of flowmeter readings. Three sets of readings were made—one in the morning and two by different observers in the afternoon. The readings of the Chattock gauge were then plotted against the readings of the flowmeter (Fig. 2). This appeared to show that the different groups of readings lay on different curves. A factor which might account for this was that for some readings the door of the room was locked with the key left in, for some locked with the key removed and for others unlocked.

Repeat observations were therefore made on the following day and the results for both days were plotted (Fig. 3). The presence or absence of the key was shown to

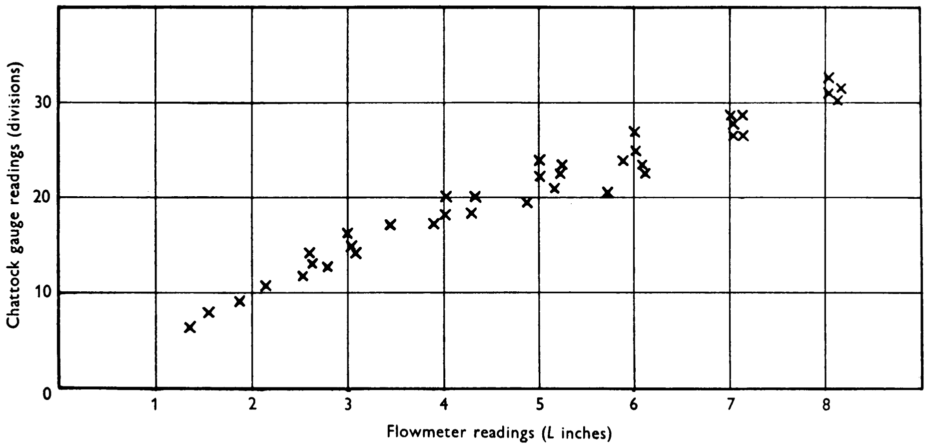

Fig. 3.

be not significant. From Fig. 3 it might be concluded—though this is shown later to be incorrect—that:

(i) the points lie about a smooth curve;

(ii) the scatter of the points about this curve is such that the rate of air flow through the room might be estimated from readings of the Chattock gauge with an accuracy within ± 10 %;

(iii) the apparently unique separate curves in Fig. 2 are fortuitous.

The law connecting the ventilation rate with static pressure difference might be expected to be of the form: flow $= Ap^n$, where $A =$ a constant for a given room with fixed openings, $p =$ static pressure difference between the inside of the room and the outside of the building, and $n =$ a constant frequently assumed to be 0·5. If this law were correct we could expect that flow $= A_1 p_1^n$ should apply for static pressure difference p_1 measured between the room and the interior of the hut. Plotting the logarithms of the readings of the flowmeter against those of the Chattock gauge for some of the data in Fig. 3, a value of n was determined as 0·66. It thus appeared that flow was not proportional to the square root of the pressure difference measured.

The next step was to measure the static pressure difference between the inside of the room and the outside of the building for different rates of flow. It was suggested that if the windows between the corridor and the outside of the hut were open the pressure difference between the room and the interior of the hut would be the same as that between the room and the outside of the building. For a given rate of air flow through the room the opening or closing of the corridor windows appeared to have little effect on the pressure difference between the room and the corridor. Although the doors and windows to the room were closed to the same extent as before, it was found that the pressure difference between the room and the interior of the hut, for a given flowmeter reading, was very much larger than would be expected from Fig. 3, and the readings were not as steady as previously.

Chattock gauge readings plotted against flowmeter readings appeared to show that the points lay about a very different curve (Fig. 4) from that suggested in Fig. 3. Similar results were obtained when the pressure difference was measured between the inside of the room and the outside of the building (Fig. 5). In Figs. 4

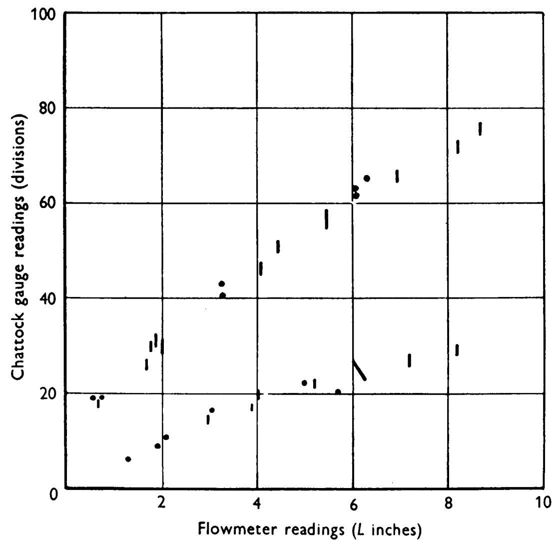

Fig. 4.

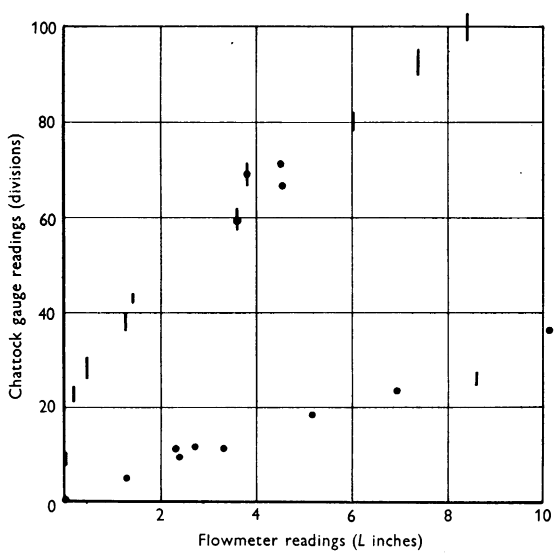

Fig. 5.

and 5 the upper curves relate to observations made on a day with wind from the north of 10–12 m.p.h., and lower curves relate to observations on a calm day.

These results necessitate a review of the conclusions which might have been drawn from Fig. 3.

Although over a period of time when external conditions are fairly steady the plots of Chattock gauge readings against flowmeter readings may lie about smooth curves, quite different curves may be obtained when external conditions alter, even though doors and windows are open to the same extent. The range of variation in external conditions covered by the data plotted in Figs. 4 and 5 is by no means extreme, but even in the range in which we might expect the difference between the flow through the blower and the total flow through the room to be tending to zero, Chattock gauge readings corresponding to identical flowmeter readings varied by as much as 3:1 in ratio. It must therefore be concluded that the rate of natural ventilation of a room cannot be estimated from a single measurement of static pressure difference.

The following inferences may be drawn from the various measurements:

(1) Between points inside the room there is no appreciable static pressure difference.

(2) Between points outside the building but adjacent to it there may be appreciable pressure differences, steady or fluctuating according to whether the wind is steady or gusty. Examples of the differences measured, with a north wind of 10–12 m.p.h., were:

(*a*) 40–50 milli-inches between the ridge of the roof and a point just outside the window approximately 3 ft. above the ground; and

(*b*) between the north and south sides of the building a pressure difference equal to that between the inside of the room and the outside on a calm day for an air flow equivalent to six air changes per hour.

(3) For the same rate of air flow through the room with doors and windows open to the same extents, different static pressure differences can be measured:

(*a*) at the same time between one point inside and different points outside; and

(*b*) at different times between one point inside and one fixed point outside.

(4) Alteration in the rate of flow through the blower does not, in general, affect the pressure difference between points outside the building.

(5) The pressure difference between the inside of the room and any point outside, for a given rate of air flow through the room, may be altered by varying the openings of the doors or windows through which air enters the room.

INTERPRETATION OF EXPERIMENTAL CURVES

The upper curves in Figs. 4 and 5 do not pass through the origin, thereby implying that pressure differences existed and that there was a flow of air through the room before the blower was switched on. Assuming that external conditions have remained fairly steady, we can interpret the curves thus. Initially air would be flowing into the room through certain channels which we will call group 1, outside of which the pressure is higher than the pressure in the room, and would be flowing out through other openings which we will call group 2, outside of which the pressure would be lower than the pressure in the room. (Which of the fixed ventilation channels in the room fall into either group will of course depend on factors such as wind direction, etc.). As the flow through the blower was gradually increased the pressure in the room would be gradually reduced so that (*a*) the pressure across all openings in group 1 would be gradually increased and more air therefore flow in through them, and (*b*) the pressure across the openings in group 2 would be gradually reduced to zero and then built up in the opposite direction. Outward flow of air through the group 2 openings would thus be gradually reduced to zero and be followed by gradually increasing inward flow. The flow through the blower is the difference between the inward flow through group 1 openings and the outward flow through group 2 openings. As it is increased the difference between it and the total flow through the room is gradually reduced to zero (when no air flows out through group 2 openings) and thereafter the two are equal (and equal the sum of the inflow through group 1 and group 2 openings). The flow rate for which this occurs and consequently the shape of the curve depend on the external pressure differences.

The lower curves of Figs. 4 and 5 pass through the origin and can be regarded as representing conditions on a still day when pressure differences between the inside and outside are fairly independent of the positions of measurement. It is interesting to examine whether these readings fit the law: flow $= Ap^n$. Plotting logarithms of flowmeter against Chattock gauge readings, values of n between 0·53 and 0·6 were deduced. An examination of published data on air flow through window crevices (Coleman & Heald, 1940) and shingle construction (*American Society of Heating and Ventilating Engineers Guide*), etc., showed that over the range of measurements reported the data fitted very well a power law, but the actual value of n varied between 0·5 and 1·0.

The rate of flow through a capillary is proportional to pressure difference, the rate through an orifice to the square root of the pressure difference and the rate through a pipe, according to recent American work (Heubscher, 1947), to the 0·542nd power of the pressure difference across it. For a network of capillaries, orifices and pipes, therefore, a logarithmic plot of flow against pressure difference would take the form of a curve of slope between 0·5 and 1·0. Results for the simple case of capillary and orifice, in series and in parallel, are shown in Fig. 6. Over a limited range of pressure the slope of any one curve appears to be approximately uniform, its actual value depending on the relative capillary and orifice dimension assumed, and over the range in question the rate of flow might well be assumed as proportional to the nth power of the pressure. It may be noted that the curve for the series arrangement is concave downwards and tends to resemble more closely that for an orifice as the pressure is increased, while the curve for the parallel arrangement is concave upwards and would tend to behave more like a capillary with increase in pressure. It is also clear that for more complicated arrangements the range over which the curve approximates to a straight line can be considerably extended.

From the above discussion it sems that a model network of capillaries and orifices could be constructed which would behave as do the actual crevices or leaks by which air enters a room, and that the index of the power law experimentally determined is not a fundamental physical property of all channels, but depends upon their distribution between orifice and capillary types and the pressure range over which the investigation is made.

When air flows through an opening, under quasi-static conditions, the pressure on the side from which the air flows must be higher than that on the other side. In natural ventilation air flows into and out from a room. It therefore follows that the pressure in the room must be lower than the pressure at some adjacent position outside and higher than that at some other position outside. Since the pressure outside is not uniform it is conceivable that many different pressures can co-exist across the several channels through which air flows to and from a room. Some idea of the directions and relative magnitudes of the pressures and suctions produced with winds from various directions, relative to a freely exposed building of simple shape, is given by the diagrams in the *British Standard Code of Practice on Structural Loading*. Most buildings have more complex outlines or exposures than those there listed, but even for those idealized cases it is clear that the number of ways in which the pressure at one point differs from that at another as the wind speed or direction alters is very great. In natural ventilation the only limiting factor is that

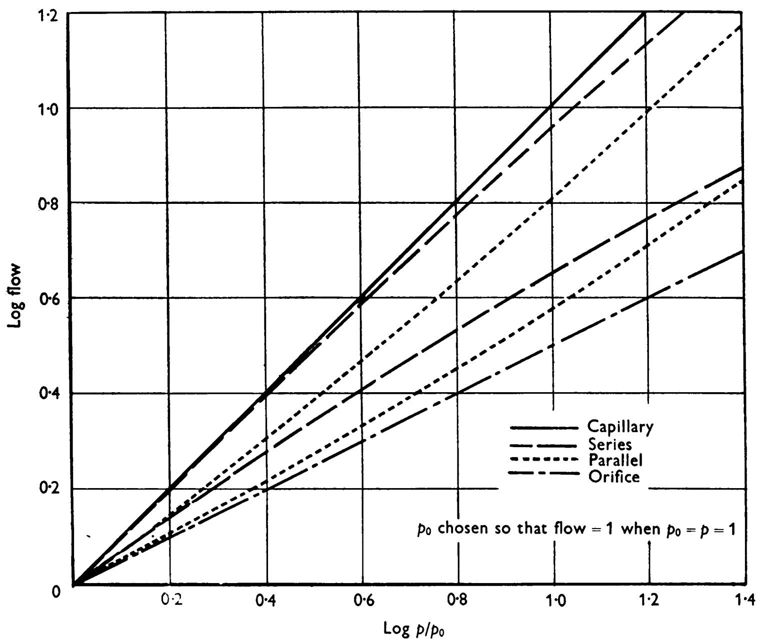

Fig. 6.

the average or total rate of flow into the room must equal the average or total rate out of the room, but the instantaneous rates need not be equal, and through any channel, at one time air may be flowing inwards, at another time outwards.

In principle, all individual channels can be calibrated so that the rate of flow through each may be uniquely determined by a knowledge of the pressure differences across it. A knowledge of the pressure difference across any one ventilation channel to a room will not, however, determine the pressure across nor the flow through each other channel. The vagaries of the wind, therefore, preclude the total rates of flow into the room being determined by a single measure of static pressure difference. This conclusion is in agreement with findings of previous investigations. Carne states that 'any single subsidiary air speed or pressure feature is not a suitable factor for correlation (with rate of air change)'. Masterman, Dunning & Densham (1935) state that 'Eddy currents will usually be caused by the shape of the building and of adjacent buildings and the pressure distribution on the whole external surfaces will be in detail almost unpredictable. The strength and direction of the wind will themselves rarely be constant for prolonged periods. The air movement through any one room could not even be derived directly from the uncertain pressure conditions....It is scarcely a matter for surprise that observations may fail to confirm any strict relation between air change in the room and the suction of the wind velocity.'

The foregoing discussion has been limited to the relationship between air flow and static pressure and the experimental investigation confined to periods of semi-steady conditions which rarely exist in practice. As, however, it has been shown that the relationship does not provide a useful method of estimating natural ventilation rates there is little to be gained by elaborating the further complications arising from consideration of temperature differences, the opening and closing of doors and windows or the behaviour of flues, and it is clearly impracticable to apply data derived from observations in one room to a similar but differently sited room.

CONCLUSIONS

1. For any one ventilation channel, or for a number of channels across which there is a uniform static pressure difference, the relationships between flow rate and static pressure difference, over a limited range of pressure variation, will fit a curve of the form: flow $= Ap^n$, where p is the pressure difference, A a constant for the channel(s), and n will lie between 0·5 and 1·0.

2. For a room with fixed boundary conditions, i.e. fixed degree of opening of doors, etc., there may sometimes—for quasi-steady external conditions—appear to be a definite relationship between the flow through the room and the pressure difference between one point inside and one point outside it, but this relationship will not be unique. At any instant there will usually be different pressures across the different ventilation channels and the differences between these pressures need not remain constant. A single measurement of static pressure difference cannot therefore form the basis of a method of measuring the natural ventilation rate.

3. It is impracticable to apply in detail data obtained from observations in one room, to the same room under different conditions or to other rooms differing in size or in siting or with different arrangements of doors and windows.

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