The effects of shelter on the natural ventilation and internal climates of simple animal houses.

by C.V. SMITH

1. Introduction

It has been suggested that on most occasions, the prime mover in the natural ventilation of farm buildings will be wind rather than stack pressure (1). The effect of variations of wind direction on the ventilation rate of buildings, as distinct from individual rooms, has been shown to be small, so that in general, our problem is reduced to a consideration of the effects of shelter on wind velocity and wind pressure.

Both the rate of exchange of air between the building and the outside atmosphere and the pattern of air flow within the building are of importance.

2. The analogy between ventilation and electrical networks

The relation between the electromotive force and current in a simple electrical circuit is given by Ohms law.

$$E = R\ I \qquad \text{(i)}$$

where E = the e.m.f.

I = current

R = a constant = the resistance of the circuit.

For a simple circuit of successive (series) conductors, continuity of current flow through the conductors is expressed by the relationship.

$$I = \text{constant} \qquad \text{(ii)}$$

Equations (i) and (ii) have been generalised by Kirschoff and for complex networks of conductors we may write,

(a) In any closed circuit

$$E = \Sigma\ R\ I$$

or the e.m.f. in the circuit is equal to the algebraic sum of the products of the resistance and current for each component of the circuit.

(b) At any point of a circuit

$$\Sigma I = 0$$

or the algebraic sum of the currents which meet at a point is zero.

The laws which govern the supply of air to a ventilation system have been indicated in a previous note (2).

The relation between the force or head moving the air and the flow or volume of air passing through the system in unit time is of the form

$$H = R\ V^2 \qquad \text{(iii)}$$

where H = the head

V = the flow

R = a constant characteristic of the ventilated system and known as its resistance.

If there may be no accummulation of air within the system i.e. outflow equals inflow, then continuity of flow may be approximated by the expression

$$V = \text{constant} \qquad \text{(iv)}$$

indicating that the volume of air passing in unit time is the same for all cross-sections of the system.

The generalisation of equations (iii) and (iv) and their application to a complex ventilation network is readily followed by analogy with the more familiar electrical systems and we may write

(a) In any closed ventilation circuit

$$H = \sum R\ V^2$$

or the head acting is equal to the algebraic sum of the products of the resistance and the square of the flow for each component of the circuit.

(b) At any point of a ventilation circuit

$$\sum V = 0$$

or the algebraic sum of the air flows which meet at a point is zero.

3. <u>The ventilation of isolated buildings.</u>

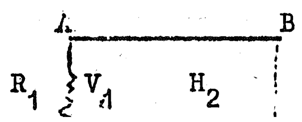
Let the resistance of the inlets on the windward walls of a ventilated building be r and the resistance of outlets in the remaining walls be R_1 and in the roof be R_2. The resistance of the intervening ventilated space is regarded as zero.

Let the head due to wind pressure across the vertical walls be H_1 and the head due to wind pressure on the roof be H_2.

Let the volume of air entering in unit time be V and the volumes leaving through the walls and roof be V_1 and V_2 respectively.

The analogy drawn between electrical and air flow circuits in the preceding section and enables us to set up the air flow diagram of figure 1.

Figure 1.



The generalisation of equations (iii) and (iv) enables us to write

for network A B C F $\qquad R_1V_1^{\,2} - R_2V_2^{\,2} = -H_2$

network F C D E $\qquad R_2V_2^{\,2} + r\,V^2 = H_2 + H_1$

network A B D E $\qquad r\,V^2 + R_1V_1^{\,2} = H_1$

at point F $\qquad V = V_1 + V_2$

We note that in general roof pressures are likely to be negative (for a pitch less than 35°) and H_2 will have the opposite sense to H_1.

The following cases are of interest.

<u>Case I.</u> $V_2 = 0,\ H_2 = 0$

i.e. cross ventilation with no flow through ducts in the roof.

Our expressions reduce to

$$V = V_1$$

$$r\,V^2 + R_1\,V_1^{\,2} = H_1$$

$$V = \left\{\frac{H_1}{r + R_1}\right\}^{\frac{1}{2}}$$

and if $r = R_1$

$$\boxed{V = .7\left(\frac{H_1}{r}\right)^{\frac{1}{2}}}$$

<u>Case II.</u> $V_2 \gg V_1$

i.e. the greater part of the outflow takes place through ducts in the roof, any out flow through the walls being fortuitous.

Our expressions reduce to $\quad V = V_2$

$$r\,V^2 + R_2\,V_2^{\,2} = H_1 + H_2$$

$$V = \left\{\frac{H_1 + H_2}{r + R_2}\right\}^{\frac{1}{2}}$$

and if $r = R$ and $H_1 = 2\,H_2$

$$\boxed{V = .87\left(\frac{H_1}{r}\right)^{\frac{1}{2}}}$$

Case III. Both V_1 and V_2 are significant.

For simplicity we assume $r = R_1 = R_2$ and $|H_1| = |2 H_2|$

Our expressions reduce to

$$V = V_1 + V_2$$

$$r V^2 + r V_2^2 = 3/2 H_1$$

$$r V_1^2 - r V_2^2 = -\tfrac{1}{2} H_1$$

and $V = .97 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$ or $.06 \left(H_1/_r\right)^{\frac{1}{2}}$

$$V_1 = .25\ V \quad , \quad V_2 = .75\ V$$

The two values for V arise from the solution of a quadratic for V^2. The larger value is accepted since it is reasonable to expect the ventilation rate to exceed that of Cases I and II.

4. Large scale processes

In general, the ventilation rate of a building will vary linearly with wind velocity since the velocity head has been shown proportional to the square of velocity.

The modification of the free wind imposed by topography and general surface roughness can be treated in broad terms. Measurements suggest that the wind speeds in suburban and built-up areas are approximately 2/3 and 1/3 of the wind speed observed in open country. The various categories of exposure adopted by the British Standards Institute (when the interest is in wind loading) are given in Table 1. The categories of exposure adopted by the Institute of Heating and Ventilating Engineers (when the interest is in conductance heat loss through the fabric of the building) are given in Table 2.

5. Local modification of the free wind

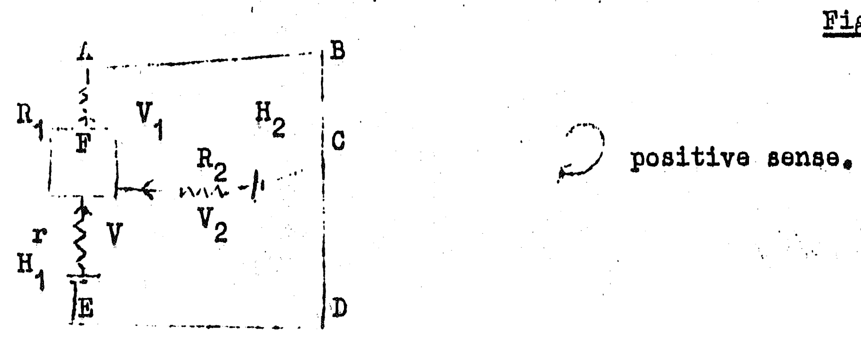
Obstacles having roughly the same height as buildings may be distinguished by their permeability to wind flow. The patterns of wind velocity established in association with shelter belts of varying degrees of permeability are now well documented (3). Of greater interest than the effect of a reduced wind velocity on ventilation rates is perhaps the effect of eddying flow (in the lee of shelter belts) on the pattern of air flow within a building. Because of inflow around the edges, the effectiveness of a barrier is likely to be slight for oblique incidence, unless the length of the barrier is greater than, say, 20 times its height.

(i) Permeable barriers

We suppose that the permeability is less than 50% i.e., we consider the case where downdraughts might normally be expected in the lee of the barrier.

The existence of a downdraught will reverse the normal negative wind pressure to be expected on the roof of an isolated building, and for a building under the lee of an obstacle to wind flow we may set up the flow diagram of figure 2, identical with that of figure 1, except that V_2 and H_2 are now reversed.

Figure 2



The conditions of flow are such that

for the network A B C D $\quad R_2 V_2^{\ 2} + R_1 V_1^{\ 2} = H_2$

network F C D E $\quad - R_2 V_2^{\ 2} + r V^2 = -H_2 + H_1$

for the point F $\quad V_1 = V + V_2$

for simplicity we again assume $r = R_1 = R_2$; $|H_1| = 2|H_2|$, and our expressions reduce to

$$V_1 = V + V_2$$

$$r V_1^{\ 2} + r V_2^{\ 2} = \tfrac{1}{2} H_1$$

$$r V^2 - r V_2^{\ 2} = \tfrac{1}{2} H_1$$

$$V_1^{\ 2} = .50 \left(\frac{H_1}{r}\right) \quad \text{or} \quad .44\left(\frac{H_1}{r}\right)$$

the two solutions arising from a quadratic for V^2.

<u>Case A</u> $V_1^{\ 2} = .50 \left(\frac{H_1}{r}\right)$

This solution implies $V_2 = 0$ and $\boxed{V_1 = V = .7 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}}$

<u>Case B</u> $V_1^{\ 2} = .44 \left(\frac{H_1}{r}\right)$ and $V_2^{\ 2} = .06 \left(\frac{H_1}{r}\right)$

Previously, the positive and negative signs to be associated with values of V, V_1, V_2 obtained from V^2, $V_1^{\ 2}$, $V_2^{\ 2}$ have been ignored, since they have simply reflected the symmetry of the circuits and implied that a reversal of the pressure heads simply reversed the direction of flow. This is not true in the present case, where the pressure heads act in parallel rather than in series.

If $V_1^{\ 2} = .44 \left(\frac{H_1}{r}\right)$ $\qquad$ then $V_1 = \pm .66 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$

$V_2^{\ 2} = .06 \left(\frac{H_1}{r}\right)$ $\qquad$ then $V_2 = \pm .24 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$

Now $V_1 = V + V1/_2$

Taking like signs for V_1 and V_2 we have

$$.66 \left(\frac{H_1}{r}\right)^{\frac{1}{2}} = V + .24 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$$

$$\text{and } V = .42 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$$

The ventilation rate is given by $\boxed{V = .66 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}}$ for $V_1 > V > V_2$

/<u>Case C</u>

<u>Case C</u> Taking alternate signs for V_1 and V_2

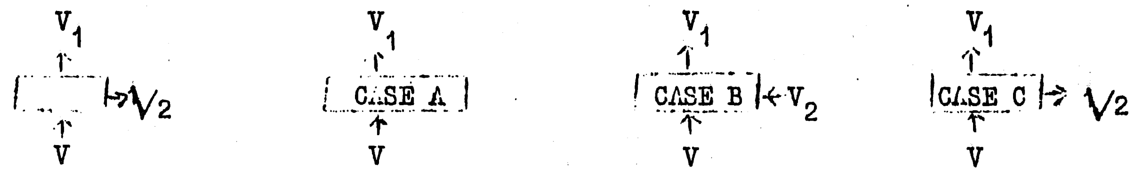
we have $V_1 = V + V_2$

$$.66 \left(\frac{H_1}{r}\right)^{\frac{1}{2}} = V - .24 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$$

$$\boxed{V = .90 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}}$$

The various alternatives are set out diagrammatically below and compared with the case where the wind pressure on the roof is negative.

<u>Roof Pressure Negative</u> <u>Roof pressure positive</u>



$V = .97 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$	$V = .70 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$	$V_1 = .66 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$	$V = .90 \left(\frac{H_1}{r}\right)^{\frac{1}{2}}$
$V_1 = .25\ V$	$V_1 = V$	$V = .64\ V_1$	$V_1 = .73\ V$
$V_2 = .75\ V$	$V_2 = 0$	$V_2 = .36\ V_1$	$V_2 = .27\ V$

This simple study suggests that whilst the overall ventilation rate may depend primarily on the velocity head, eddy motion may at times be important. The flow patterns established in the lee of shelter belts and bluff obstacles are unlikely to be stationary and if eddies break forward, and are superposed on the general airstream, then the pattern and magnitude of the air movements within buildings will change as the effectiveness of openings as inlets and outlets is modified by wind pressure.

A fluctuating wind direction will equally impose fluctuating pressure patterns on a building, again possibly causing openings to act alternately as inlets and outlets.

(ii) <u>Impermeable or slightly permeable barriers</u>

The work of Bailey and Vincent has been concerned with wind tunnel measurements of the wind pressure on buildings (of limited cross-wind length) standing alone and fully exposed, and also when sheltered by other buildings (4). The wind was at normal incidence to the models.

The pressure patterns observed are a function of building height and roof slope. For convenience the results in some simple cases are reproduced in figures 3 and 4.

We may comment on figure 3 that the flow of air through the sheltered building will be in the same sense as the wind (wind-ward wall pressure positive) until the separation is approximately 1.75 times the building width. If the separation is less than this, the flow within the building will have the opposite sense to that of the wind. Roof pressures are always negative. When the separation of the buildings is zero, the pressure experienced on the second leeward roof of a two bay building is approximately that experienced by a single bay building.

In figure 4 we see that the flow through the sheltered building has the same sense as the wind unless the separation is less that the width of the individual buildings. Eddy effects produce a positive pressure on the windward roof of the third building (at a separation of one to two B).

Measurements indicated that the wind pressures experienced by the central building of figure 4 were approximately those of the sheltered building in figure 3 that is, downstream features can in general be neglected.

6. Temperature and humidity changes within sheltered animal houses

The physical effects of shelter belts have been discussed by Gloyne. Shelter will change the overall ventilation rate and the conductance heat loss from a building.

If we assume conditions change sufficiently slowly inside and outside a building, we may write balance equations for the temperature and moisture conditions within the building.

Let h = the heat production /animal/ hour

h_s = supplementary space heating supplied/animal / hour

w = moisture produced /animal/hour

and if T = outside temperature

$T + \Delta T$ = inside temperature

M = moisture content of the outside air

$M + \Delta M$ = moisture content of the inside air

C = conductance heat loss through the fabric of the building/animal/ hour/degree F

V = volume of air supplied/animal/hour

ρ = air density

s = specific heat of air

For steady conditions within the house

Moisture produced = Moisture lost

$$w = V\rho . \Delta . M.$$

Heat produced = Heat lost

$$h + h_s = C . \Delta T + s . V \rho . \Delta T$$

The variable radiative heat loss from a building is compensated to some extent by a solar heat gain. The resultant variations of the external surface temperature will be attenuated at an internal surface and the influence on the internal heat balance is likely to be small, except for buildings of extremely light construction.

/The

The 'U value', the overall 'air to air' coefficient of heat transmission of a construction though usually quoted to two decimal places (suggesting considerable exactness) is nevertheless not a constant value. The transfer of heat from an external wall to the outside atmosphere will be dependent upon wind speed, evaporation and the emissivity of the surface and its surroundings. For the three categories of exposure adopted by the Institute of Heating and Ventilating Engineers the ratio of degree of exposure to U value is of the order,

Sheltered; normal; severe $= U_o; \; 1.1\,U_o; \; 1.2\,U_o$

for walls of normal construction

$= U_o; \; 1.2\,U_o; \; 1.4\,U_o$

for windows and roofs of normal construction.

Broadly, a reduction of exposure reduce the heat loss and increases the temperature lift.

A decrease in the ventilation rate increases the temperature difference of the internal and external atmosphores and simultaneously increases the moisture content within the building. The consequences, in terms of the resultant relative humidity or condensation can only be examined in specific cases. For the materials used in the construction of the building need to be known, whilst the basic heat and moisture output of animals varies with species and age.

Table 1

Exposure categories adopted in the British Standard Code of Practice.

C.P.3, Chapter V, 1952

Exposure A.

Exceptionally small exposure to wind as a result of natural protection to the building. This exposure hazard should be adopted only rarely, since often the shielding afforded by surrounding country of higher altitude is not effective for all directions of wind and in some directions a "funnel" effect may lead to a considerable increase of wind pressure.

Exposure B.

This grade should be used generally, except near the sea coast or estuaries or for altitudes over 500 ft. above sea level.

Exposure C.

This grade is applicable to open country generally, for altitudes up to about 800 ft. above sea level, but not near the sea coast or estuaries.

Exposure D.

This degree of exposure covers exposed sites within five miles of the coast or an estuary, or at an altitude of over 800 ft. above sea level.

Table 2

Definitions of exposure adopted by the Institute of Heating and Ventilating Engineers

Sheltered	-	includes the first two storeys above ground of buildings in the interior of towns
Normal	-	includes the third, fourth and fifth storeys of buildings in the interior of towns and most suburban and country premises
Severe	-	includes sixth and higher storeys in the interior of towns, and buildings exposed on hill sites, the coast, or riverside.

References

(1) Smith, C.V. — Observations of the natural ventilation of buildings M.O. Agricultural Memorandum XLIX

(2) Smith, C.V. — Fundamental relationships of natural ventilation M.O. Agricultural Memorandum XLV-III

(3) Gloyne, R.W. — Some effects of shelter belts and wind breaks Met. Mag. Vol. 84, 1955, pp. 272-281

(4) Bailey, A. and Vincent, N.D.G.: — Wind pressure on buildings including effects of adjacent buildings.

J. Inst. C.E. 1943, 20 (8), pp. 243-275.

Agricultural Memorandum L,
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FIGURE 3.

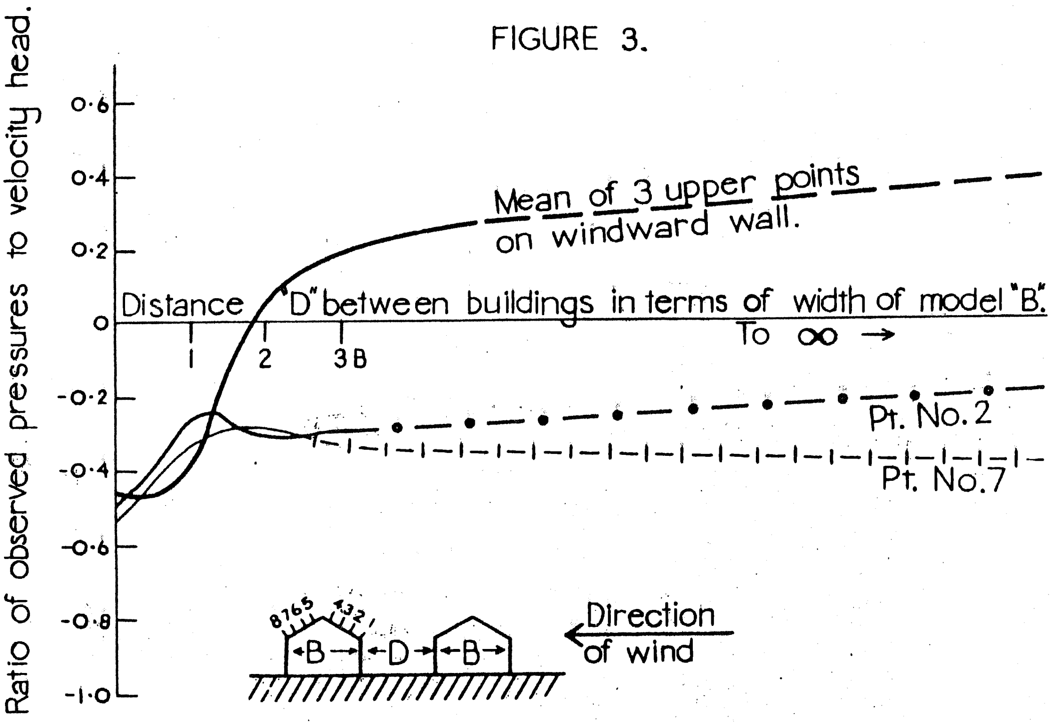
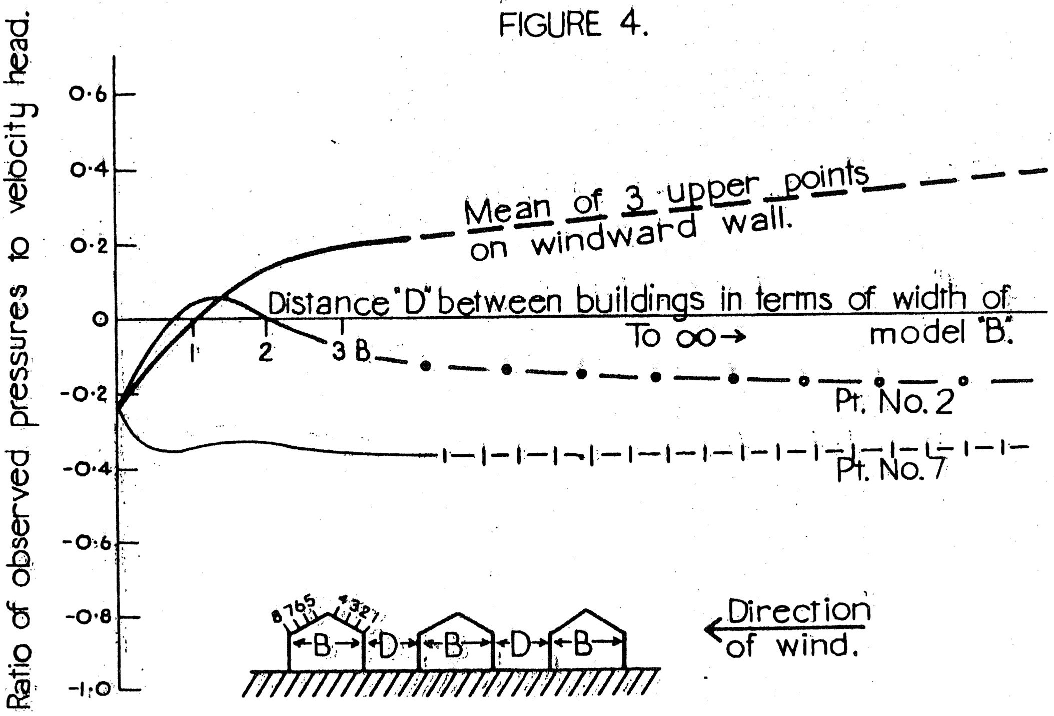


FIGURE 4.



Variation of pressure with dimension "D" in a model with roof scope 23½°.