Summary In situ measurements have been made of the heat loss through a roof insulated at ceiling level with glass fibre quilt. The results compare favourably with predicted values obtained from standard U-value calculations. An investigation of the dependence of the thermal resistance of the insulation on the air speed at its exposed upper surface showed that the performance of the insulation was not affected by air speed within the range 0 to 0.1 m/s. The air speeds within the loft space were only weakly correlated with external wind speed, and were mostly within the range 0 to 0.1 m/s, for external wind speeds up to 10 m/s.

Measurements of the heat loss through an insulated roof

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1 Introduction

The traditional calculation procedure for determining heat losses through roofs[1, 2] is based on thermal conductivity data obtained in standard laboratory tests and standardised values of air space and surface resistances, and was developed from measurements of U-value in the BRS roof laboratory[3, 4]. However the latter measurements were made between 1953 and 1957, mostly on uninsulated roofs; only one roof out of fourteen was insulated, and that with only 25 mm of mineral wool, as opposed to thicknesses of around 100 mm in common use today.

More recently conductance and transmittance tests, which can measure the heat flow through a building component, have been undertaken. Values for conductance of an insulated ceiling structure (not a complete roof) have been reported[5], which show a strong dependence of the measured value on the air flow at the upper surface of the insulation. In these tests the effect on the measured conductance of changing the air flow was dramatic, and indicated that there was at least a possibility that the calculation procedure was seriously in error.

This possibility arises essentially because of an important difference in boundary conditions between insulation in a laboratory thermal conductivity apparatus, and insulation installed in a roof space. In the thermal conductivity test the material is bounded by impermeable surfaces (the plates of the apparatus); whilst in the practical situation the upper surface is usually exposed. In the latter case there may additionally be convection across the surface which will have the effect of increasing the heat flow through the insulation. If there is air movement above the insulation it may be sufficient to cause forced convection, but even at very low air speeds there may be natural convection arising from the temperature difference across the insulation; this is most likely to occur with the lower density range of materials. There is however a lack of information about actual air velocities in lofts and on their possible effects on heat flow through insulation.

In this paper the results of measurements of heat flow through one roof under real weather conditions are reported. The experiment was designed to provide a comparison between the actual and predicted heat loss, and to investigate any dependence of actual heat loss on air speeds within the loft space.

2 Experimental details

The measurements were carried out in a two-storey terraced house, which faced approximately north/south. It had a pitched roof of 22° slope, consisting of tiles on battens above fibreboard sarking. The ceiling consisted of foil-backed plasterboard fixed to 100 mm joists at 600 mm centres. In half the roof, glass fibre quilt of nominal thickness 80 mm was placed between the joists; in the other half of the roof glass fibre quilt of nominal thickness 100 mm was used. The nominal width of the glass fibre was 600 mm so there was a slight lateral compression.

The heat flow through the ceiling was measured using circular heat flow discs 100 mm in diameter supplied by TNO Delft. The discs were calibrated in a guarded hot plate thermal conductivity apparatus at the University of Salford. Temperatures were measured using copper/constantan thermocouples.

Air speeds in the loft space were measured using thermistor anemometers. These had a small exposed thermostor bead and therefore gave a measure of the magnitude of the air speed, being relatively insensitive to direction. Readings were corrected for ambient air temperature in the loft space using calibration curves provided by the manufacturer. The external wind speed and direction were measured by a vane and cup anemometer mounted on a 10 m mast adjacent to the house (the height of the house to the apex of the roof was 7 m).

Thermocouples, a heat disc and an anemometer were arranged at certain points on the ceiling as depicted in Fig.

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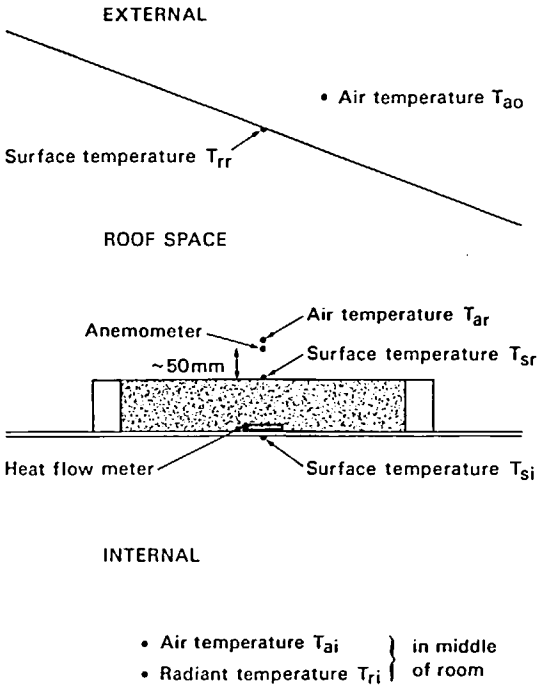

Fig. 1. Schematic diagram showing positions of thermocouples, heat flow meter, and anemometer.

1. In the roof space one thermocouple was mounted on the lower surface of the sarking board, one on the insulation surface (pushed under the top few fibres), and one together with an anemometer about 50 mm above the surface. Below the ceiling one thermocouple was taped to the surface and two more recorded the temperature in the room. One of these was within a matt black sphere of diameter 40 mm sensitive under approximately still air conditions to 52 per cent air temperature and 48 per cent radiant temperature[6]; the other was within a polished aluminium tube of diameter 20 mm and length 300 mm, sensitive to about 95 per cent air temperature and 5 per cent radiant temperature. From these two measurements the air temperature and the mean radiant temperature of the room, or any combination, may be derived. In addition the external air temperature was measured at the north side of the house, out of direct sunlight.

The house had a central heating system consisting of hot water radiators supplied by a gas boiler. During the tests the heating was operated continuously, controlled by a thermostat set at 20°C and located in one of the upstairs rooms.

The outputs from the two sets of heat discs, thermocouples and anemometers, were connected to a 24 channel data logger. A test run lasted seven to fourteen days during which time the data logger scanned every ten minutes. Thereafter the sensors were moved to a different part of the roof for repeat tests. Subsequent data reduction and analysis was carried out by computer. Readings on each channel were first averaged over one-hour periods, and these 'hourly averages' were used for the analysis. In addition some channels were duplicated on a multipoint chart recorder, which was used to maintain a check on the reliability and accuracy of the data collection system. The thickness of the insulation was measured using the 30 N/m^2 plate, probe and collar described in BS 2972:1975.

The systematic errors in the measurement of thermal resistance are estimated as: calibration of heat discs 3 per cent, thermocouples 2 per cent, calibration of data logger 0.2 per cent, giving a total of ± 5.2 per cent. The accuracy of the air speed measurements is estimated at ± 0.02 m/s.

Thermal conductivity tests were carried out by the University of Salford on samples of each of the two glass fibre quilts. The results, given in Table 1, may be used with the measured quilt thicknesses to give predicted vaules of thermal resistance, to an estimated accuracy of ± 5 per cent (thermal conductivity 3 per cent, measurement of thickness 2 per cent).

3 Results

3.1 Thermal resistance of insulation

Although the internal temperature was maintained at about 20°C, the temperature within the roof space varied considerably over the six weeks of measurement because of variations in external temperature. Indeed on occasions the solar radiation on the roof caused the roof space temperature to exceed 20°C so that the temperature difference across the ceiling was reversed, as was the direction of heat flow. The experiment was not therefore steady state. However effects due to phase differences between heat flow and temperature difference may very largely be eliminated, except insofar as they introduce scatter in the data, by carrying out the analysis over periods of time for which temperatures were the same at the beginning and at the end.

Thus we consider

$$Q_m = \frac{1}{R}\Delta T + E + e \qquad (1)$$

where Q_m is the measured heat flow per unit area, ΔT is the temperature difference across the ceiling ($= T_{si} - T_{sr}$ in Fig. 1), and R is the thermal resistance of the insulation plus that of the plasterboard and the heat disc. E is a small systematic error term arising from offsets in the dc amplifiers in the data loggers; the amplifiers were adjusted to reduce the offsets to a small value, but any errors arising from them can be eliminated from the measurement of R by using a regression of Q on ΔT. e represents departures of individual data points from a straight line relationship (i.e. random error).

Fig. 2 shows such a plot of Q_m versus ΔT for data taken on measurements of the nominal 100 mm glass fibre quilt, obtained from 275 hourly readings over a period of

Table 1. Thermal conductivity measurements on the glass fibre. Samples from the rolls used to insulate the loft were trimmed to 50 mm thickness for these tests.

	Nominal thickness 80 mm	Nominal thickness 100 mm	
Mean thickness during test	50	50	mm
Dry density	13.0	9.7	kg/m^3
Mean temperature	18.4	18.4	°C
Thermal conductivity	0.0424	0.0458	W/m°C

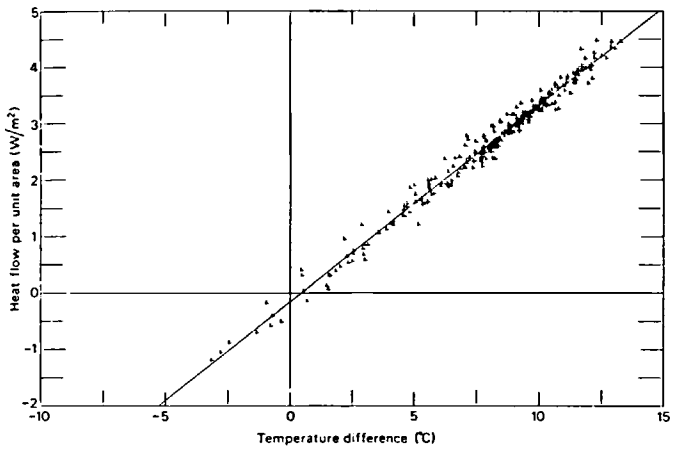

Fig. 2. Heat flow through ceiling plotted against the temperature difference across it (first example). The slope of the regression line drawn on the Figure gives the thermal resistance of the ceiling.

12 days (at location 3 of Fig. 6). The equation of the regression line drawn on Fig. 2 is

$$Q_1 = 0.367\ \Delta T - 0.17$$

The measured thermal resistance is therefore 1/0.367 = 2.72 m²°C/W. The standard error of the slope s_b is 2.90×10^{-3}, and so the confidence limits $ts_b \simeq 0.005$, taking t = 1.65 (95 per cent significance for 273 degrees of freedom), i.e. the statistical error of the slope is about 1.5 per cent. Including also the experimental error mentioned earlier this gives R = 2.72 ± 0.17 m² °C/W.

The predicted thermal resistance is obtained by applying the thermal conductivity of 0.0458 W/m°C to the test thickness, 116 mm, and adding the resistance of the plasterboard (0.078) and the heat disc (0.012), which yields 2.62 ± 0.13 m²°C/W. The predicted and measured values of thermal resistance are therefore in satisfactory agreement.

Similar measurements were made on the nominal 80 mm glass fibre, and were checked by repeating the measurements with both quilt thicknesses in other parts of the roof, including locations near to the eaves. The results are presented in Table 2 and show complete agreement after allowing for possible errors between predicted and measured values in all cases. A similar result has been reported recently for a test on 300 mm of mineral fibre[7].

3.2 Dependence of thermal resistance on air speed

The regression in Fig. 2 has a correlation coefficient of r = 0.996 implying that the simple model of Equation (1) gives a very good fit to the data, explaining 99.2 per cent (= r^2) of the variation. It is clear therefore that any effect of air speed during this test was small. Nevertheless a hypothesis that the thermal resistance is affected by air speed may be examined by multiple regression analysis.

An effect of air speed is likely to be complicated, but as a first approximation we shall consider a linear relation between effective thermal conductivity and air speed s, or

$\frac{1}{R} \propto (1 + As)$ where A is a constant. Allowing also for a variation with temperature, R may have the form

$$\frac{1}{R} = \frac{1}{R_o}(1 + As)(1 + B\Delta T)$$

We consider the equation

$$Q = b_o + b_1\Delta T + b_{2s}\Delta T + b_3(\Delta T)^2 + b_4 s(\Delta T)^2 + b_5 s + e \quad (2)$$

with the residuals represented by e as before, by substituting for R in Equation (1) and including a term $b_5 s$ although it does not have an obvious physical significance. Clearly the term in ΔT will be highly significant and the effect of including the other terms was examined by comparing the ratio of the reduction in

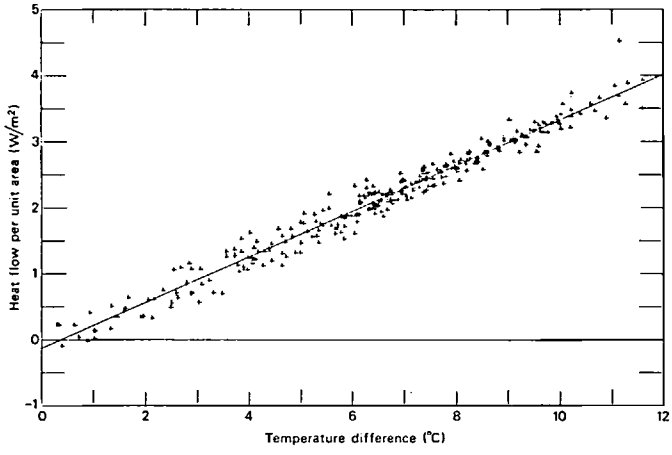

Fig. 3. Heat flow through ceiling plotted against the temperature difference across it (second example).

Table 2. Measurements of thermal resistance of ceiling.

Nominal Thickness mm	Actual Thickness mm	Density kg/m³	Location in roof space (as shown in Fig. 6)	Regression of Q on ΔT					Mean Temp glass fibre °C	Measured thermal resistance m²°C/W	Predicted thermal resistance m²°C/W
				Intercept W/m²	Slope W/m²°C	r	df	t			
80	82	12.5	25	−0.68	0.459	0.984	218	82.3	12.7	2.18 ± 0.16	2.02 ± 0.10
80	80	12.8	22	0.25	0.518	0.991	162	95.4	13.1	1.93 ± 0.13	1.98 ± 0.10
80	74	13.9	21	−0.30	0.513	0.980	162	62.3	13.3	1.95 ± 0.15	1.84 ± 0.10
80	77	13.3	21	−0.09	0.509	0.996	273	179.3	15.5	1.96 ± 0.12	1.91 ± 0.10
80	83	12.4	23	−0.10	0.466	0.967	301	66.2	16.2	2.15 ± 0.16	2.05 ± 0.10
100	111	10.2	12	−0.21	0.364	0.943	169	37.0	13.9	2.75 ± 0.27	2.51 ± 0.13
100	116	9.7	3	−0.17	0.367	0.992	273	126.0	15.0	2.72 ± 0.17	2.62 ± 0.13
100	115	9.8	3	−0.13	0.364	0.983	301	93.0	15.6	2.75 ± 0.19	2.60 ± 0.13

residual sum of squares to the residual mean square with the tabulated values of the F distribution.

For the data shown in Fig. 2 no additional terms of Equation (2) were significant, and the same result was obtained for a further four of the test runs of Table 2 (at locations 25, 21, 21 and 23). Thus the thermal resistance was not affected by air speed within the range of measurements (0 to 0.1 m/s).

In the other three runs the air speed s was apparently having an effect, although the interpretation is unclear. The analysis of each of these three gave very similar results; for example we consider the data shown in Fig. 3. With only the ΔT term included the regression equation was

$$Q = -0.13 + 0.364\ \Delta T \tag{3}$$

and adding the $s\Delta T$ term gave

$$Q = -0.15 + 0.376\ \Delta T - 0.371\ s\Delta T \tag{4}$$

with a variance ratio of F = 20.3. The additional term is statistically significant therefore, but its coefficient is negative indicating an increase in R with s if interpreted literally, and it is not clear what physical mechanism could cause such an effect. Moreover, including a term in s instead of $s\Delta T$ gave

$$Q = -0.09 + 0.366\ \Delta T - 2.70s \tag{5}$$

with F = 20.5, i.e. an equivalent result is obtained by including a term not dependent on ΔT, raising a further question about interpretation. Also, the multiple correlation coefficient increased only very slightly, from 0.983 for Equation (3) to 0.984 for Equations (4) and (5), so that either additional term had little practical effect in explaining the residual variance. There was some autocorrelation in these data, but allowing for this changed the results only very slightly. In fact the value of the coefficient of the ΔT is insensitive to the inclusion of additional terms, which gives confidence to the values of thermal resistance derived from the simple model of Equation (1).

As a definite statement we may say that the results show that there was no deterioration in the performance of the loft insulation caused by air speeds in the loft up to 0.1 m/s.

3.3 Surface resistances

In general a surface resistance may be written

$$R_s = \frac{1}{h_c + Eh_r} \tag{6}$$

where h_c is the convective coefficient, h_r is the radiation coefficient and E is the emissivity factor. Usually a reasonable estimate can be made for Eh_r, since $h_r = 4\sigma T_m^3$ where σ is Stefan's constant and T_m is the average of the surface temperature and the mean radiant temperature seen by the surface, and $E \simeq 0.9$ for most building materials at the thermal wavelengths concerned. In practice h_r will vary only slightly over a small range of temperature of a few degrees.

On the other hand h_c is less easily predicted. If we measure the surface temperature T_s, the air temperature T_a, the mean radiant temperature seen by the surface T_r', and the heat flow per unit area into the surface Q, we may write

$$Q = Eh_r(T_r' - T_s) + h_c\ (T_a - T_s)$$

in which h_c is unknown. Solving for h_c and substituting in equation (6) leads to

$$R_s = \frac{T_a - T_s}{Q - Eh_r(T_r' - T_a)} \tag{7}$$

This expression is valid for heat flow into or out of a surface provided the sign of Q is taken as positive if the heat flow is into the surface.

In the roof space the radiant temperature seen by the upper surface of the insulation will approximate to T_{rr} in Fig. 1, and assuming that the unshielded thermocouple T_{ar} responds to 85 per cent air temperature and 15 per cent mean radiant temperature, the air temperature may be calculated. A plot of $Q - Eh_r\ (T_r' - T_a)$ against $T_a - T_s$ will have a slope $1/R_s$. An example is shown in Fig. 4 (for which E was taken as 0.9). The equation of the regression line drawn on Fig. 4 is

$$Q - Eh_r\ (T_r' - T_a) = -1.24 + 8.07\ (T_a - T_s)$$

so that the surface resistance R_s is $1/8.07 = 0.13\ m^2°C/W$. A large part of the scatter on this graph probably arises because rather small temperature differences were being measured; the resolution of the recording apparatus was 0.25°C. Including the experimental and statistical error

$$h_c + Eh_r = 8.07 \pm 0.9\ W/m^2°C$$

Taking $Eh_r = 4.6$ corresponding to the 10°C mean temperature in the roof space over the period during which these data were collected,

$$h_c = 3.5 \pm 0.9\ W/m^2°C$$

This is consistent with the conventional value of 4.3 $W/m^2°C$ for upwards heat flow.

In principle a similar analysis could be performed at the internal surface. However for much of this experiment, the air temperature and the surface temperature were very similar, so that the convective heat transfer at the ceiling was much less than the radiation transfer and the former could not be estimated reliably. During part of the experiment when T_a and T_s differed sufficiently a plot similar to that in Fig. 4 yielded a value of $R_s = 0.08\ m^2°C/W$. This relates to measurement of the air temperature at the centre of the room; as there is likely to be a significant temperature gradient over the height of the room, the value of R_s will depend on where the air temperature is measured. This aspect was not investigated.

3.4 U-value of the roof

The standard U-value of a construction is defined by the equation

$$Q = U(T_{ei} - T_{ao}) \tag{8}$$

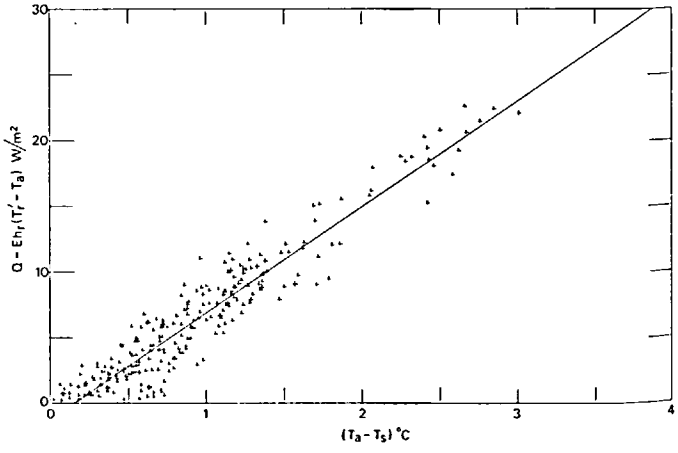

Fig. 4. Plot to determine surface resistance at upper surface of insulation (see text).

Table 3. U-values of roof. The calculated U-values are obtained from the nominal thickness and the thermal conductivity corresponding to a mean temperature of 10°C.

Nominal thickness of glass fibre mm	Calculated (predicted) U-value W/m²°C	Actual thickness of glass fibre mm	U-value from R in Table 2 W/m²°C	U-value from T_{ei} and T_{ao} W/m²°C
80	0.37	82	0.36	0.30
		80	0.39	0.33
		74	0.39	0.36
		77	0.39	0.32
		83	0.36	0.31
100	0.31	111	0.29	0.26
		116	0.30	0.22
		115	0.30	0.22

where Q is the heat flow per unit area, T_{ei} is the inside environmental temperature and T_{ao} is the external air temperature. However for many days during this experiment solar radiation on the roof surface caused additional heat input to the loft space, and the situation is further complicated by a ventilation heat loss from the loft space. These two factors mean that the heat flow through the roof surface will in general be different to that through the ceiling. These effects cannot be quantified precisely since the former was not measured. However we may add standard value of loft space resistance etc (total 0.62 m²°C/W) to the measured values of the thermal resistance of the insulation to obtain a U-value corresponding to each measurement. These are compared in Table 3 with the standardised U-value based on the nominal thickness of the glass fibre and the nominal thermal conductivity of 0.04 W/m°C.

Also shown in Table 3 are U-values obtained by dividing the heat flow through the ceiling by the measured temperature difference between inside environmental temperature and outside temperature. This gives a different result for the reasons stated above; in fact the values are lower indicating that the solar gain to the roof was more important than the ventilation loss. The actual heat loss was thus less than would be predicted from calculations based on the external air temperature. The use of sol-air temperature instead of air temperature and an allowance for ventilation loss would bring these figures more closely in line with those in the other columns of Table 3, but such a comparison cannot be made too closely in this instance because of the interaction of heat flows through the two halves of the ceiling having different thicknesses of insulation.

These U-values do not take account of joists in the ceiling construction, which bridge the insulation. Including joists in proportion to their relative area would increase the U-values by between 0.04 and 0.05 W/m²°C.

3.5 Ventilation rate of the loft space

Several measurements were made of the ventilation rate in the loft space, using a tracer gas technique. The loft was well ventilated, with air change rates up to 17 per hour being recorded. The ventilation rate n in air changes per hour is shown in Fig. 5 plotted against external wind speed W(m/s). The regression line drawn on the Figure has the equation

$$n = 2.29 + 2.19W$$

and there is a high correlation between n and W ($r = 0.97$).

3.6 Air speeds in the loft space

In the course of this experiment air speeds were recorded at a number of locations within the loft space. The roof

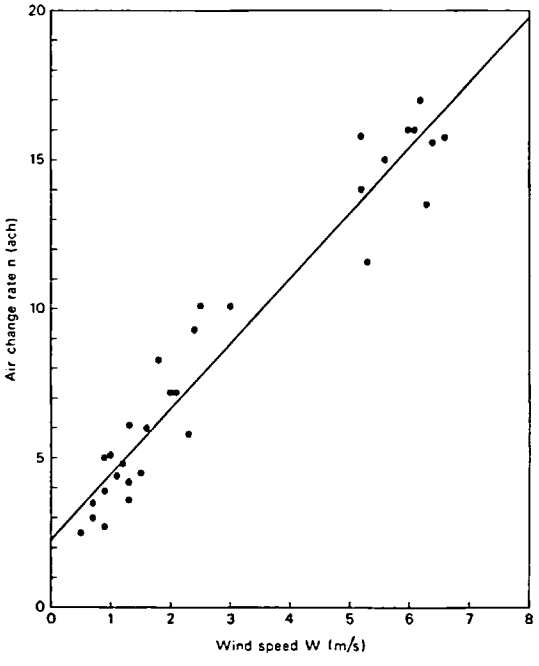

Fig. 5. Ventilation rate of the loft space plotted against external wind speed.

was ventilated by continuous openings about 20 mm wide in each soffit. Using a simple model that the air enters at one soffit and leaves at the other, and that the velocity is uniform across all vertical planes parallel to the eaves, one may obtain an indication, at least to within an order of magnitude, of what mean air velocities are to be expected if the ventilation rate is known. For a ventilation rate of n air changes per hour the volumetric flow into and out of the roof is n roof volumes per hour, or $n \times \frac{1}{2} lbh_m$ where l is the roof length, b is the breadth and h_m is the height at the apex. If at a point in the roof where the height is h the mean drift velocity is v, then

$$\frac{\frac{1}{2}nlbh_m}{3600} = vlh,$$

or

$$v = 1.35 \times 10^{-3}\, n/h \qquad (9)$$

since $h_m = 1.5$ m, $b = 6.5$ m. Expression (9) gives mean drift velocities ranging from 0.02 m/s at the apex to about 0.3 m/s at the edge of the insulation where h was about 0.1 m, for a mean wind speed of 10 m/s corresponding to 24 ac/h by extrapolation of the data in Fig. 5. (These figures would be reduced pro rata at lower ventilation rates.)

Table 4. Mean, maximum and standard deviations of external wind speeds and air speeds (m/ s) at each location indicated in Figure 6.

No. of Data Points	Wind Speed W			Air Speed s			't' statistic for regression of s on W	Location (c/f Fig. 6)
	Mean	Maximum	Standard deviation	Mean	Maximum	Standard deviation		
42	2.2	4.6	1.0	0.030	0.036	0.003	—7.0	13
131	2.3	5.8	1.3	0.045	0.073	0.007	3.3	7
				0.056	0.101	0.024	8.7	11
164	2.9	7.5	1.3	0.039	0.104	0.017	8.2	1
				0.045	0.077	0.010	3.4	28
378	3.0	10.4	2.1	0.035	0.097	0.020	6.2	2
				0.019	0.046	0.008	11.8	25
				0.048	0.152	0.045	1.3	5
69	3.0	5.8	1.1	0.028	0.039	0.004	0.0	6
				0.015	0.023	0.004	—4.6	8
				0.063	0.119	0.030	—5.1	17
283	3.1	6.3	1.4	0.031	0.081	0.013	8.5	18
				0.055	0.163	0.030	4.4	19
439	3.2	7.5	1.5	0.030	0.079	0.022	6.9	21
578	3.4	9.4	1.7	0.021	0.096	0.015	9.3	3
				0.021	0.063	0.010	11.4	22
303	3.5	9.4	1.8	0.020	0.067	0.010	7.9	23
178	3.6	10.4	2.7	0.059	0.166	0.027	5.5	9
				0.030	0.057	0.008	3.5	10
157	3.6	6.9	1.6	0.026	0.058	0.011	—3.7	14
				0.038	0.064	0.013	—6.2	15
363	3.6	9.8	1.9	0.045	0.105	0.018	12.5	16
				0.019	0.037	0.008	7.7	24
138	3.8	9.4	2.1	0.027	0.060	0.012	—0.6	26
				0.041	0.094	0.019	2.6	27
226	4.2	10.4	3.0	0.055	0.122	0.022	—0.7	12
42	5.9	9.8	3.0	0.118	0.221	0.059	15.7	4
				0.099	0.213	0.050	12.5	20

The Reynolds number for this flow, taking h as the dimensional factor, is $hv\rho/\mu$ or 888 n from Equation (9). For ventilation rates between 2 and 24 ac/h, the Reynolds number is in the range approx. 2,000 to 20,000, implying that the flow is turbulent. This view is reinforced by consideration of the non-uniform geometry of the roof space and the fact that the external wind is not constant but varies considerably in both speed and direction over short periods of time. Turbulent flow and the associated eddies imply relatively large variations in local velocities with time, including reversals of direction. As a result the output of the anemometers, which measured the instantaneous magnitude of the air flow, may not necessarily be closely related to the mean drift velocity, or to the mean external wind speed. Thus although one might anticipate that higher wind speeds will cause higher air speeds in the loft space, there will not necessarily be a high correlation between measured air speeds and wind speeds.

Over the duration of the test the air speed was monitored at the 28 locations shown in Fig. 6. The mean, standard deviation and maximum* values from the air speed and wind speed distributions are given in Table 4, along with the t statistic from the correlation of air speed with wind speed. When the magnitude of t is greater than 2 a significant relationship is suggested, and the sign of t indicates whether the slope of the regression line is positive or negative. There is considerable variation in these results, with the air speed at nineteen of the twenty-eight locations showing a positive correlation with wind speed, four no correlation and five negative

* As with the temperature and heat flow data, these figures are 'hourly averages', being mean values of six readings taken at 10 minute intervals. An examination of the original data indicated that the maximum instantaneous values of air speed were between 1.1 and 1.8 times the mean hourly values shown in the Table.

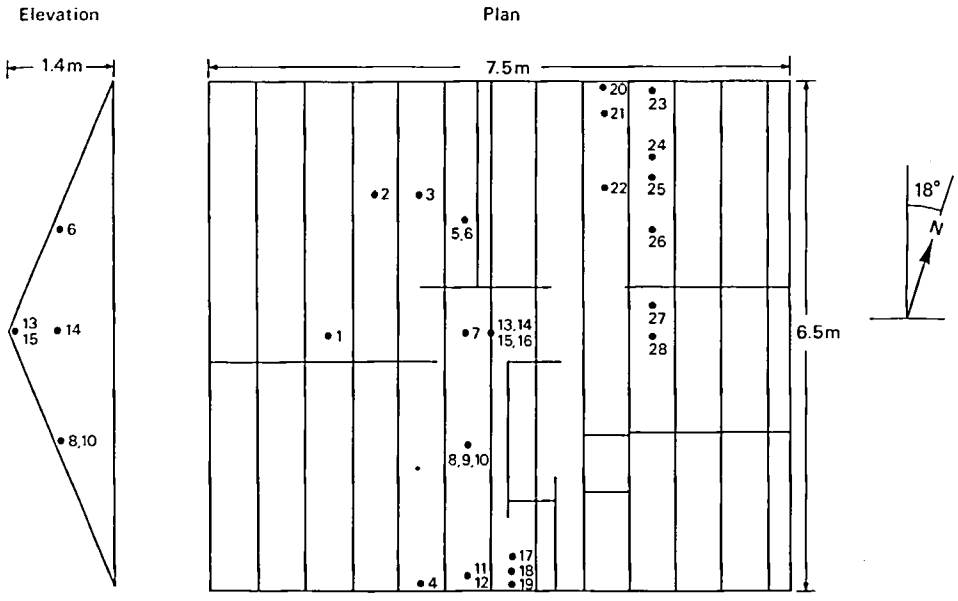

Fig. 6. Positions at which air speed measurements were made. Anemometers were placed 50 mm above the insulation surface except where shown otherwise under 'elevation'. Thermal resistance measurements were made at points 3, 12, 21, 22, 23 and 25.

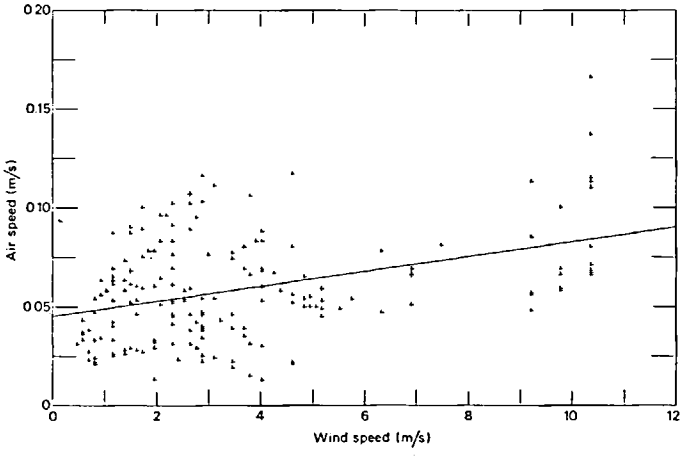

Fig. 7. Example of a plot of air speed against external wind speed.

correlation. Of the six locations which were away from the insulation surface five gave negative or no correlation, whilst of the remaining twenty-two locations (which were 50 mm above the insulation surface) twenty-one gave positive correlation. This would suggest that there may be a systematic difference between air flows near the ceiling and those near the rafters. Fig. 7 shows a typical example of a plot of air speed against wind speed, at a point midway between the eaves and the centre line of the roof (marked 25 in Fig. 6). Plotting against the component of wind speed perpendicular to the terrace gave higher correlation coefficients in some cases but lower in others. We conclude that in this loft the variability is too large to enable an accurate prediction of the air speed at a particular time to be made from the wind data.

However the measurements give information about the order of magnitude. The distribution of air speeds is illustrated in Fig. 8, which shows histograms for four locations (over the same time period), along with the corresponding distribution of external wind speed. In general air speeds within the loft space are two orders of magnitude less than the external wind speed.

Thus although the speeds exhibited considerable variability and were not consistently correlated with external wind speed, the important point is that within this well ventilated loft space, the air speeds were within a very restricted range throughout the six weeks of monitoring. A representative mean value over the roof as a whole and over the whole duration of the experiment would be approximately 0.03 m/s. Out of a total of 6,099 hourly air speeds 98 per cent were within the range 0 — 0.1 m/s; higher speeds up to 0.2 m/s were occasionally recorded at various locations. The air speed was higher very close to the eaves and the maximum instantaneous value obtained at any location was 0.3 m/s at location 22 at the south eaves.

4 Conclusions

In this experiment there was satisfactory agreement between measured and predicted heat loss, indicating that the standard calculation procedure gives a U-value which represents a realistic estimate of the actual performance of an insulated roof.

Over a six-week monitoring period during which time the mean hourly values of the external wind ranged up to 10.4 m/s the corresponding air speeds within the loft space were in the range 0 — 0.3 m/s, and the vast majority (98 per cent) were within the range 0 — 0.1 m/s. Within the latter range there was no evidence of air flow causing an increase in the heat flow through the insulation.

Thus the insulated roof of this house performed as predicted over a wide range of external temperature and wind conditions. To examine whether this result can be extended to all houses, further work is in hand to measure the effect of higher air velocities (including directional effects), and to measure air speeds in several types of loft space so as to obtain values representative of the housing stock.

Acknowledgements

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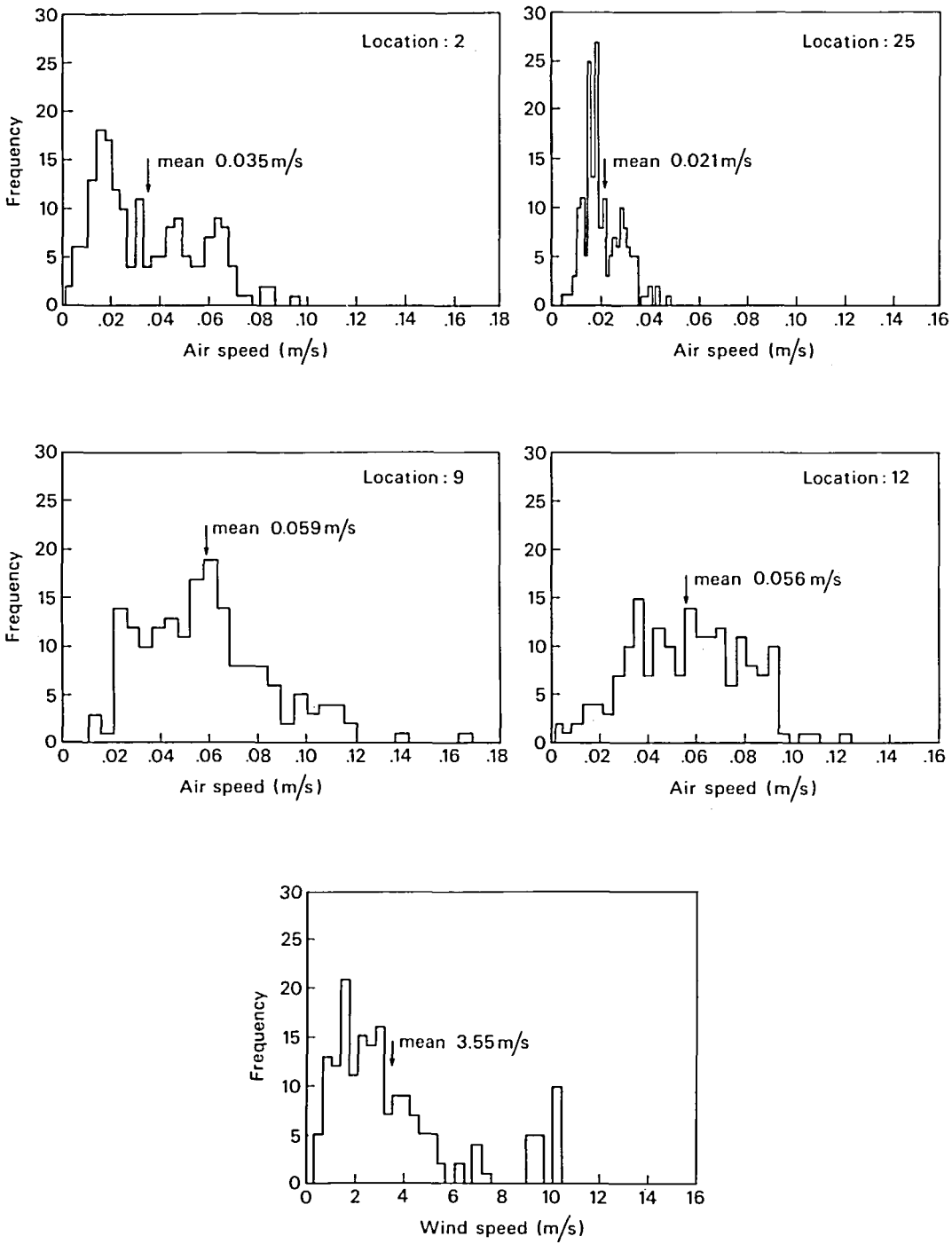

Fig. 8. Histograms of air speeds at four locations in the loft space, from data collected over an eight day period, and the corresponding histogram of external wind speed.

work described forms part of the research programme of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Director.

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