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Summary Measurements have been carried out in an experimental roof rig, under steady-state temperature conditions, to determine the effect of air speed and direction on the thermal performance of glass fibre and mineral fibre loft insulation. The results show that when subjected to steady air speeds of up to 0.25 ms^{-1}, similar to those encountered in lofts, irrespective of direction of flow, the effective λ-value of the insulants is in close agreement with the values obtained in standard thermal conductivity tests. At higher air speeds the λ-value tended to increase significantly with increasing air speed and increasing angle of incidence. It was found that the λ-value can be predicted for transient air flow over the loft insulants by evaluating a 'mean integrated' speed for the air pulses and assuming this to be equivalent to a sustained air speed.

Loft insulants: Effect of air speed on thermal performance

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1 Introduction

In 1979[1] it was reported that thermal transmittance measurements made by the Agrément Board using a guarded hot box, indicated that the U-value of a roof containing a nominal 80 mm glass fibre quilt was 0.78 Wm^{-2}, K^{-1}, nearly twice the value of 0.4 Wm^{-2}, K^{-1} obtained from the usual calculation methods. These results implied that the effective thermal conductivity of the glass fibre *in situ* was much higher than that measured in a guarded hot-plate apparatus.

Anderson[2] reported similar results when the transmittance measurements were repeated, and that the mean air speed over the insulation was about 1 $m s^{-1}$. On the other hand, when the rig was operated with a minimal air flow over the surface of the insulation, the mean air speed was about 0.25 $m s^{-1}$ and the measured conductance fell appreciably; nevertheless it was still about 10% higher than that calculated using the thermal conductivity of the glass fibre measured on a sample taken from the same batch as that used for the conductance measurements. Anderson and Ward[3] have also reported detailed measurements of the air speed in the loft of an occupied house, indicating it to be less than 0.25 $m s^{-1}$. A BBA information leaflet[4] summarises the enhanced transmittance values measured on fibrous and loose fill loft insulations; velocity contours also published in the leaflet show a very non-uniform air flow over the test area with speeds varying from 0.25 to 1.75 $m s^{-1}$.

At the instigation of the Building Research Establishment experiments have been carried out to determine the effective thermal conductivity of fibrous insulation as a function of the speed of air flowing over its cold surface.

2 Test rig

Measurements were carried out in a roof laboratory consisting of an upper chamber in which realistic outdoor temperatures and wind speeds could be simulated together with a lower chamber providing indoor conditions of temperature and humidity. The overall test area between the two chambers was 4 × 2 m; half of this (2 × 2 m) was used to study the thermal performance of fibrous insulation laid over 12 mm plasterboard and between timber joists, 50 mm wide and 200 mm deep, with a centre-to-centre spacing of 400 mm.

Initially Pilkingtons' glass fibre 'Supawrap 100' loft insulation was tested after it had been unwrapped, allowed to expand freely for several days, and then installed in the roof rig. As the standard width of the Supawrap is 400 mm there was some lateral compression when it was inserted between the joists. Since the resulting surface was uneven, the insulation was carefully cut to fit between the joists so that the thickness could be measured accurately. Under these conditions the glass fibre had an average density of 10.5 $kg m^{-3}$ and average thickness of 84 mm at the testing zones. Rockwool rock fibre insulation from an 'Energy Saver' pack, nominally 100 mm thick, was also tested. When trimmed and inserted between the joists the insulation had a mean thickness of 101.3 mm and density 21.6 $kg m^{-3}$.

The heat flux through the insulation was measured with heat flow meters, 100 mm in diameter, placed between the plasterboard and the insulation. The temperature gradients were measured with a series of chromel/alumel thermocouples attached to the top of the heat flow meter, to the underside of the plasterboard and to the top of the glass fibre as shown in Figure 1. The thermocouples had small junctions about 0.005″ in diameter obtained by welding the wire in an argon arc. Care was taken to ensure good thermal contact between the thermocouple junction and the top surface of the insulation, a small metal disc being mounted over the junction to damp out the effects of air movement. The heat flow and temperature gradients were monitored at six positions, three equally spaced along two of the fibre strips of insulation as shown in Figure 2.

Four large fans were mounted side by side spanning the full width of the upper chamber, and the speed of each was continuously variable from 10% to 100% of maximum output, the latter producing an air speed of about 3 $m s^{-1}$. Six pitot static tube anemometers, one located above each

‡ Now retired.

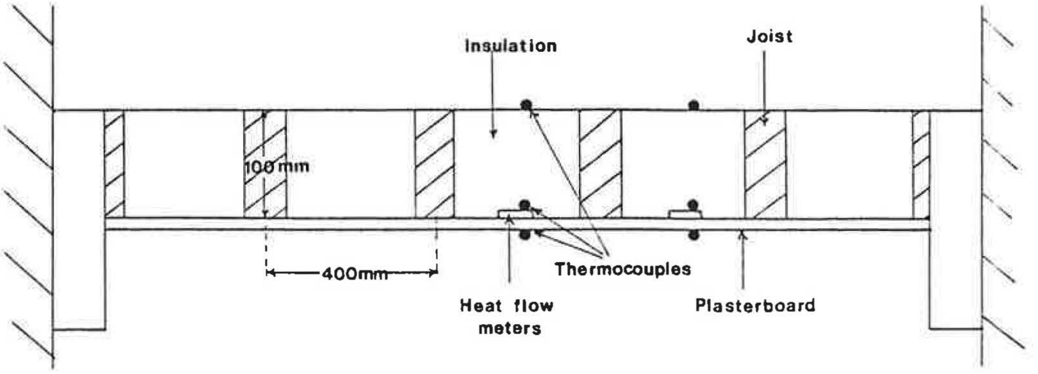

Figure 1 Cross section of test specimens showing the arrangement of heat flow meters and thermocouples

of the monitoring positions, were suspended from a plane sheet fixed parallel to the surface of the insulation, with their nozzles pointing directly into the air stream. The distance between the surface of the insulation and the plane sheet could be varied to provide a cavity from 150 to 300 mm deep. The cavity height of 150 mm was chosen since it resembled the dimensions of the test arrangement in the Agrément Board's guarded hot box. Voltages developed by the heat flow meters, thermocouples and pitot tube anemometers were all monitored by a data logging/computer system capable of scanning all the channels a few hundred times a minute to produce statistically averaged results. As well as the thermal conductance of the assembly, the effective thermal conductivity of the insulation could also be evaluated since its thickness was known.

Measurements were carried out with the upper chamber at -1 ± 0.3°C and with the lower chamber at 21 ± 0.3°C. Under still air the thermal conductivity obtained *in situ* at all monitoring positions agreed well with standard hotplate measurements. However, when air was blown directly over

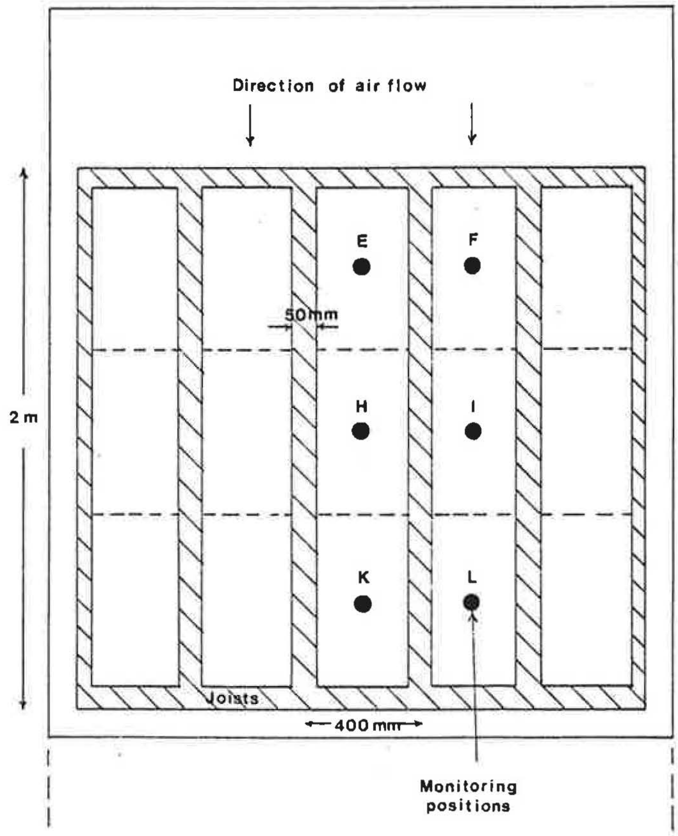

Figure 2 Monitoring positions on test specimens

the surface of the insulation the results became erratic as the air speed was increased. Consequently the fans were arranged as shown in Figure 3 so that air was sucked across the surface of the glass fibre using a similar arrangement to that found in wind tunnels. The air flow was directed from positions E, F to positions K, L. Air speed was measured as a function of distance above the surface by varying the height of the pitot tubes. The speed profiles were also checked with a 100 mm diameter vane anemometer and found to be in good agreement with those from the pitot tubes at speeds of up to 1.5 m s^{-1} where turbulence appeared to start. A precision hot wire anemometer was used to find whether or not the air flow was parallel to the surface of the glass fibre. It was concluded from all the measurements that over the central 1.2 m width of the test rig, which includes the monitoring positions E,F to K,L, the air flow up to 1.5 m s^{-1} was fairly laminar and parallel to the surface of the insulation and only results for this region are reported.

The effect on the λ-value of the glass fibre of an air flow impinging at an angle to its surface was also investigated. Two large plywood boards A and B were placed across the full width of the test rig as shown in Figure 4. A and B were parallel and 100 mm apart, and could be set at angles between 30° and 45° to the horizontal. In this way uniform air flow could be directed on to monitoring areas E and F. The separation of the deflector was sufficient to allow the vane anemometer to be held at the correct angle to monitor the air speed as it was found impracticable to use the pitot-static tubes in this situation.

Although it is unlikely that steady air speeds greater than 0.25 m s^{-1} occur in lofts, it is possible that much larger transients could occur, particularly over insulation near the eaves. Consequently tests were carried out with single and repeated pulses of air flow, both parallel and angled to the surface of the insulation, with maximum air speeds up to 2 m s^{-1}.

3 Experimental procedure

The thermal conductivity of the glass and rock fibre insulants was first determined under still air conditions, providing a base level for each monitoring position with which subsequent measurements could be compared.

With the temperature of the upper and lower chambers maintained at -1°C and 21°C respectively, the fan controls were set at some predetermined value and the test rig left for several hours to equilibrate. Control in each chamber was such that the temperature tended to cycle by not more than $\pm$ 0.3°C even at the highest air speeds. Several hundred scans of heat flow and temperature distribution were made

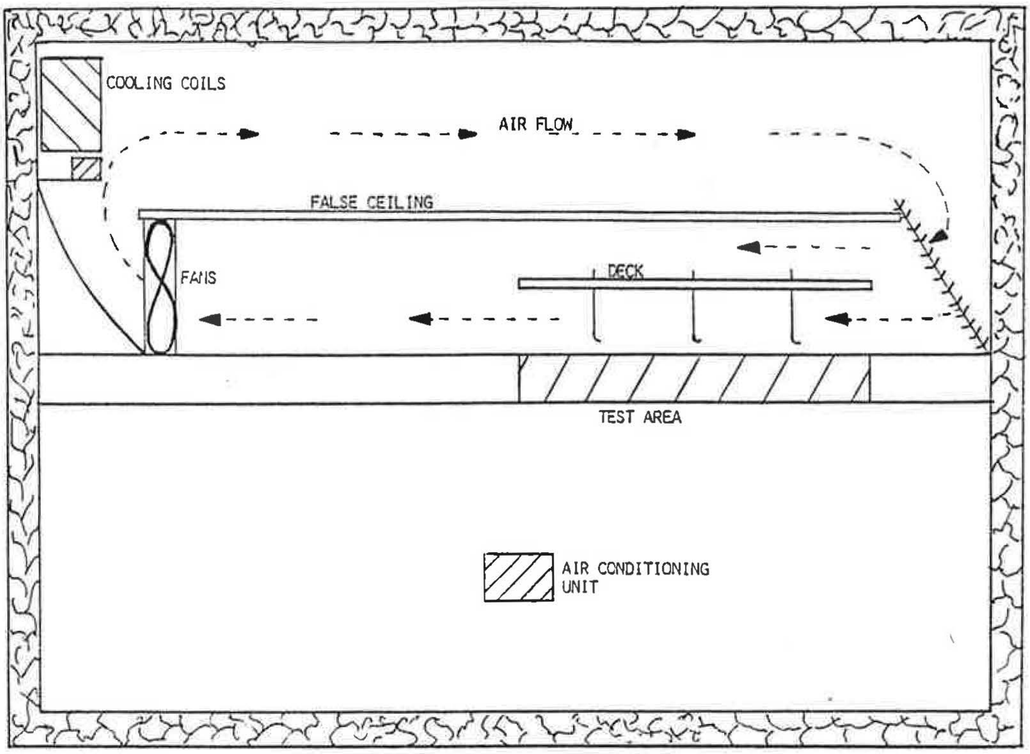

Figure 3 Schematic diagram of roof laboratory showing air flow path

at each monitoring position to determine mean λ-values. Measurements were carried out with a 300 mm and 150 mm air space between the upper surface of the glass fibre and the parallel plane to which the pitot tubes were attached. With the former spacing air speed was measured with the pitot tubes; speeds fluctuate considerably. Consequently at least 1000 scans of the output of each pitot tube were made to derive meaningful mean and standard deviation values. Even so the deviation was of the order of 60% of the mean. With the smaller air space the vane anemometer was used in the plane of the pitot tubes; with its larger diameter much smaller fluctuations about the mean were observed.

With the air flow angled at 30° and 40° to the surface of the glass fibre (this was 30° and 45° in the case of the mineral fibre) the λ-value at positions E and F, as a function of air speed, was also measured using the above procedure.

For transient air flow measurements the limited time available during each air pulse (~ 1 min) to scan the heat flow and temperature distribution across the insulation meant that it was necessary to restrict measurements to a single zone, E, to obtain realistic thermal conductivity data. Furthermore, due to time constraints on the project, only a limited range of pulses could be investigated in the 150 mm open cavity arrangement. The tests with a repeated series of pulses are reported in Tables 1 and 2. In addition the effect of single pulses of peak speed 1 and 2 $m\,s^{-1}$ were investigated for airflow parallel and at 40° to the surface of glass fibre, and parallel and at 30° to the surface of rock fibre.

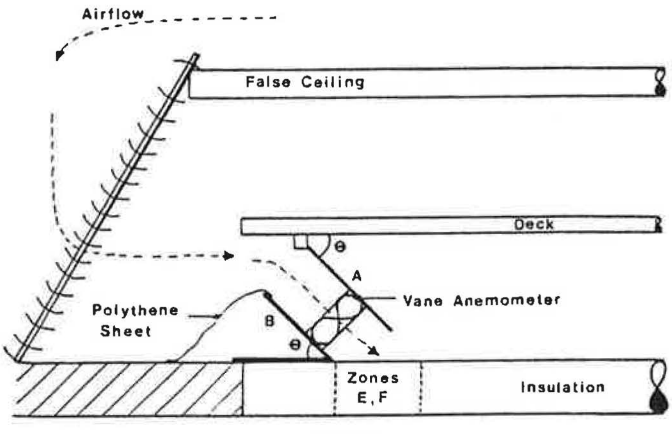

Figure 4 Angled air flow arrangement

The vane anenometer was used to measure air speed and was connected to a chart recorder so that the speed could be monitored continuously. Each pulse of air flow was generated by switching the fans on and off manually when the air speed had reached some predetermined value. Thus it was possible to control both the maximum and minimum values of the air speed and the repetition rate of the pulses. Initially, with the fans off, the thermal conductivity was measured under conditions of zero air flow. The insulants were then exposed to the airflow pulses until the measured thermal conductivity had reached an 'equilibrium' value.

4 Results

4.1 Static measurements on glass fibre

The thermal conductivity of the glass fibre under still air conditions (λ_0), measured in all six positions was found to be in the range $0.042 \pm 0.004\,W\,m^{-1}K^{-1}$ at a mean temperature of 10°C. This agrees well with a value of $0.044\,W\,m^{-1}K^{-1}$ obtained from guarded hot plate measurements on 50 mm thick samples from the same batch.

The thermal conductivity λ_s at speed s is compared with λ_0 in Figures 5 and 6 where λ_s/λ_0 is plotted as a function of the air speed. The results for all positions are included within the shaded envelopes, the upper and lower bounds representing either position E or position F.

For parallel air flow it can be seen that in general there are no really significant increases in the λ-value of the insulation up to speeds of 1.5 $m\,s^{-1}$, the greatest increase being 17%

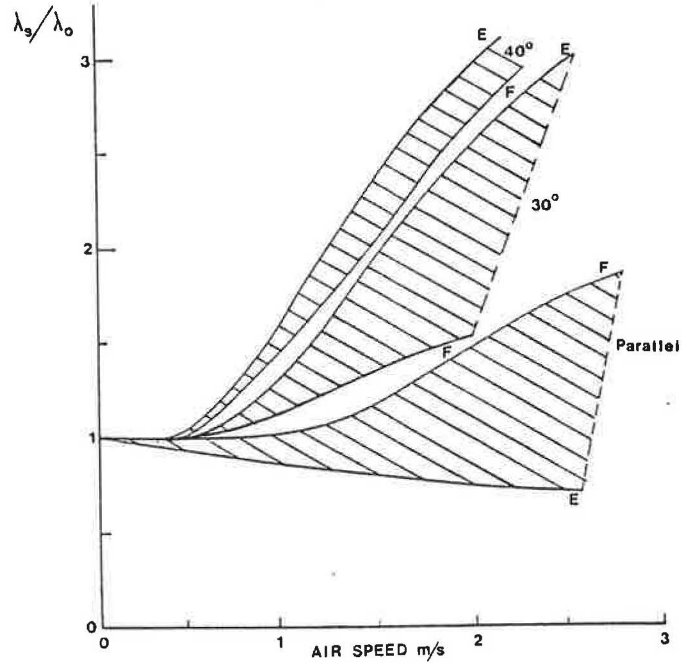

Figure 5 λ_s/λ_0 as a function of air speed and angle of impingement on 84 mm Supawrap 100 glass fibre insulation beneath a 150 mm cavity

in position E with the 150 mm cavity. It is curious to note that at speeds of less than 1 m s^{-1} there was a slight drop in λ-value with increasing air speed, in all positions. When measurements were repeated the results were always the same. The mechanism by which heat transfer through the glass fibre is reduced under these conditions is not yet understood, but it is thought to be due to air movement within the insulation. Crude pressure measurements using a nozzle attached to a manometer failed to detect any significant pressure changes within the glass fibre under the above conditions. At speeds above 1.5 m s^{-1} where it is suspected that air turbulence dominates, the λ-value tends to rise by up to 25% at 3.5 m s^{-1} in the 300 mm cavity and, even more dramatically, 80% at 2.5 m s^{-1} in the narrower cavity. It is also noticeable that the conductivity continues to decline in position F in both cavities to a value of between 70 and 90% of λ_0. The marked increase in λ-value and the large spread of results in the narrow cavity are thought to be due to increased air turbulence due to greater restriction to air flow at the entrance to the narrow cavity. It should also be noted that the maximum air speeds which could be achieved were much lower in the shallower cavity. From the above it would seem that a true laminar air flow parallel to the surface of the glass fibre produces relatively small increases in thermal conductivity, large changes being due to the effects of turbulence.

The effects of air flow impinging at angles of 30° and 40° to the surface of the glass fibre, at positions E and F, are also shown in Figures 5 and 6. The thermal conductivity remains virtually constant up to speeds of about 0.5 m s^{-1} and then increases rapidly. The rate of change increases with angle of air flow and is very similar for both types of cavity, although the scatter in the results is very large for an angle of impingement of 30° in the 150 mm cavity. At an air speed of 2 m s^{-1} the λ-value in both cavities increases by about 100% and 200% for angles of 30° and 40° respectively. The maximum air speed in the narrow cavity was limited to not much more than 2 m s^{-1}, whereas in the 300 m cavity at an angle of 30° a maximum speed of 3.5 m s^{-1} was achieved, with the λ-value increasing by 170%.

It is likely that still steeper angles would have produced even greater increases in thermal conductivity but it was not possible to prove this within the time available as it would have involved a major reorganisation of the fans and deflectors to provide a sufficiently efficient air flow.

In order to demonstrate the effect of angled air flow on

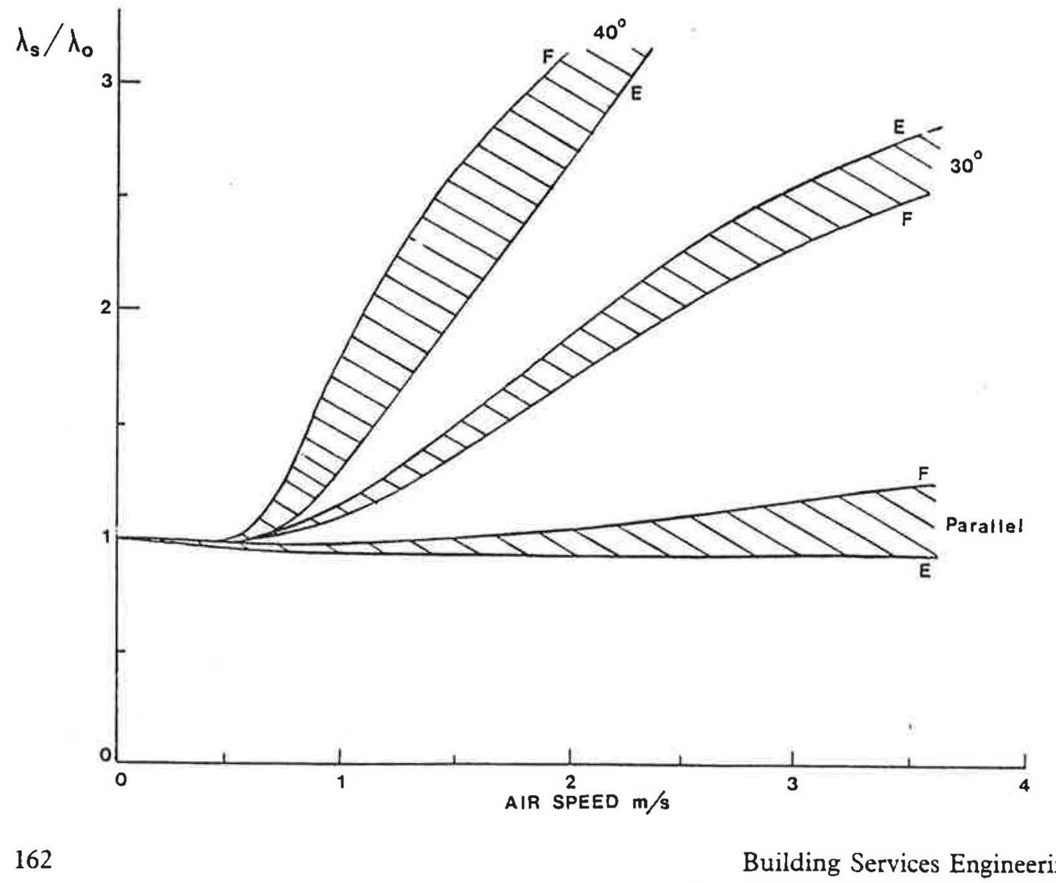

Figure 6 λ_s/λ_0 as a function of air speed and angle of impingement on 84 mm Supawrap 100 glass fibre insulation beneath a 300 mm cavity

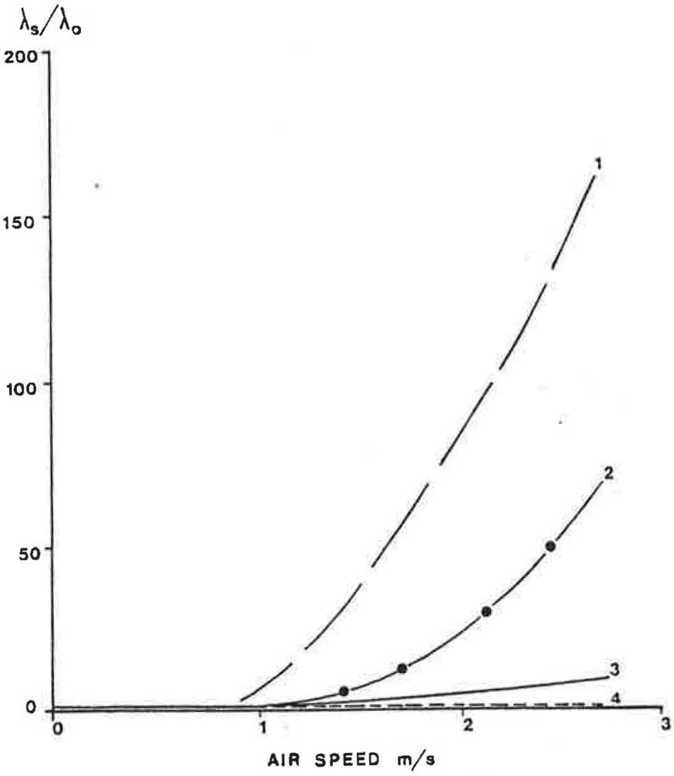

Figure 7 λ_s/λ_0 in each layer of glass fibre insulation (top layer = 1, bottom layer = 4 etc) as a function of air speed angled at 40° in the 300 mm cavity at position E

the heat transfer within the glass fibre, a special set of thermocouples were made. These were spaced 25 mm apart and pushed carefully into the insulation so that the thermocouple junctions were colinear with those monitoring the temperature of the lower and upper surfaces of the insulation. Although it was accepted that the distance between the thermocouples in the glass fibre would not be known precisely, leading to errors in the estimation of localised λ-values, such a system should indicate the relative changes in thermal conductivity of the various layers. The results obtained with the air flow angled at 40° in the 300 mm cavity are shown in Figure 7. As expected the results show enormous increases in λ in the top layer, becoming progressively less in the lower layers. This indicates that in thicker samples the overall effect on the λ-value as a whole would be less.

4.2 Static measurements on rock fibre insulation

The λ-value over the six positions of the Rockwool insulation was found to be in the range $0.040 \pm 0.003\ \mathrm{W\,m^{-1}\,K^{-1}}$ at zero air speed, which accords with a values of $0.040\ \mathrm{W\,m^{-1}\,K^{-1}}$ measured using a guarded hot plate apparatus. For parallel airflow in the 150 mm cavity, the thermal conductivity did not increase significantly for air speeds of up to $2\ \mathrm{m\,s^{-1}}$, as shown in Figure 8. At lower speeds the conductivity tended to be less than the value λ_0 obtained under still conditions. Although the changes in λ were very similar to those found for glass fibre, they were generally less marked, especially the spread in measurements. This is attributed to the greater density ($21.6\ \mathrm{kg\,m^{-3}}$) and thickness of the rock fibre, which would tend to damp air movement within the insulation. Similarly the effect of angling the air flow to the surface of the rock fibre was reduced as shown in Figure 8. At an angle of 30°, the thermal conductivity remains unchanged at speeds less than $0.5\ \mathrm{m\,s^{-1}}$ and then increases by 80% at $2\ \mathrm{m\,s^{-1}}$ and 180% at $3.5\ \mathrm{m\,s^{-1}}$. Measurements were also made with the air flow angled at 45°, so the results are not exactly comparable with those obtained with glass fibre when the flow was angled at 40° to the surface. However the increase in λ-value with increasing air speed is very similar to the increased λ-value of glass fibre with the flow angled at 40°, as can be

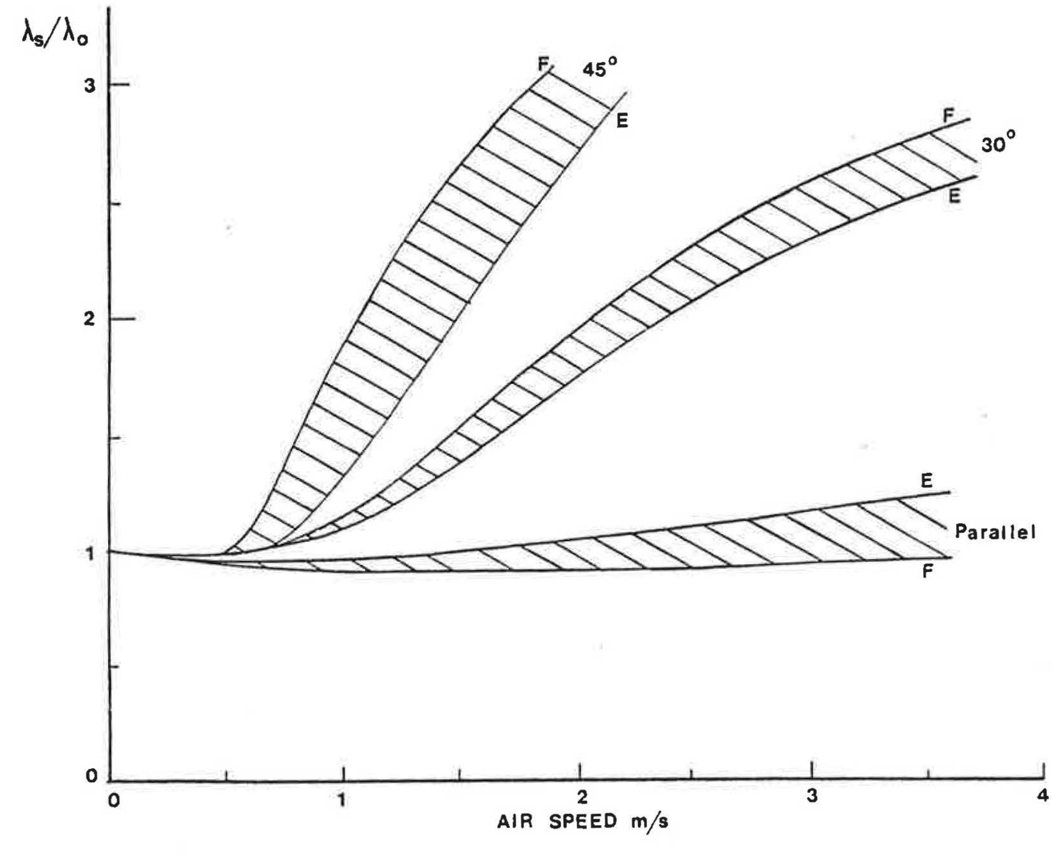

Figure 8 λ_s/λ_0 as a function of air speed and angle of impingement on 100 mm rock fibre insulation beneath a 150 mm cavity

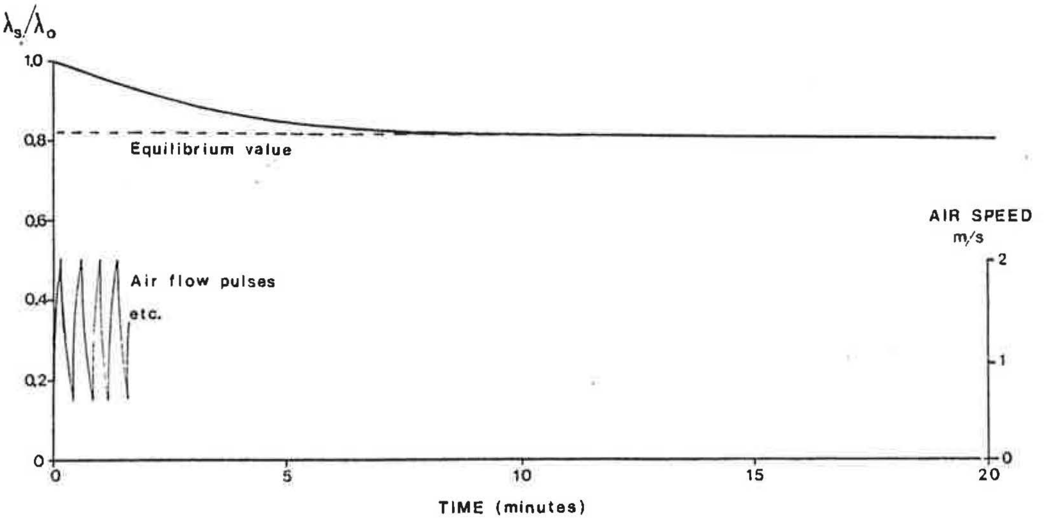

Figure 9 λ_s/λ_0 as a function of time for glass fibre insulation beneath a 150 mm cavity exposed to a repeated series of pulses of air flow parallel to the surface (Time period 23 s, maximum velocity 2 m s^{-1}, minimum velocity 0.6 m s^{-1} at position E)

seen by comparison of Figure 8 with Figure 5. This suggests that the increase in the thermal conductivity of rock fibre would be a little less than that found for glass fibre for the same angle of air flow.

4.3 Transient measurements on glass fibre

When subjected to a repeated series of pulses of air flow parallel to the surface of the insulation, beneath a 150 mm cavity, the mean λ-value was found to decrease gradually, reaching an equilibrium value. This is illustrated for example in Figure 9 for a series of pulses of period 23 s, peak speed 2 m s^{-1}, each pulse decaying to 0.6 m s^{-1}. It can be seen that after about 10 min exposure to the pulses the λ-value has fallen to an equilibrium value some 18% less than that under still conditions. The results for all four types of pulse series are summarised in Table 1. The period, minimum and maximum speed of each pulse are given as well as the 'mean' speed calculated from measurements of the area under the curve for air speed as a function of time. The 'equilibrium' λ-value λ_s divided by the value under still conditions λ_0 is also given. Equilibrium was achieved after 10 min at the most of repeated exposure to all types of pulses. It can be seen from Table 1 that there is a fall in the 'equilibrium' λ-value with increasing mean air speed, in accord with the behaviour of glass fibre under steady conditions. Assuming the mean speed to be equivalent to a sustained air speed, the values of λ_s/λ_0 from the static measurements have also been included in the table.

With the air flow angled at 40° to the surface, and pulses repeated periodically, the equilibrium λ-value rises markedly in accord with the behaviour under angled, steady air flow. The increase is greatest for repeated pulses with peak speeds of 2 m s^{-1}, for which measurements had to be continued for up to 20 min to enable equilibrium to be reached. The results are given in Table 1 including the 'mean' air speed, the equilibrium value of λ/λ_0 after pulsing as well as the value of λ/λ_0 at the equivalent sustained air speed for position E.

Measurements were also carried out with the glass fibre exposed to a single burst of air flow lasting about a minute, with a maximum speed of up to 2 m s^{-1}. This had a very small effect on the thermal conductivity when the flow was either parallel or angled at 40° to the insulation.

There is a fair degree of agreement between the values of λ/λ_0 obtained experimentally under repeated pulses of air flow with those measured under steady-state conditions, when a mean speed is assigned to the pulses in this way. The agreement is rather surprising in view of the dependence of thermal conductivity on air speed, but at least it implies that the thermal conductance of an insulated loft can be estimated for predicted variable air flows over the surface of the glass fibre.

4.4 Transient measurements on rock fibre

Single pulses of air flow had little effect on the λ-value of the rock fibre. From the results given in Table 2 it is

Table 1

Air flow direction	Pulsed air flow parameters				λ_s/λ_0	
	Period (s)	Peak speed (m s^{-1})	Minimum speed (m s^{-1})	Mean speed(s) (m s^{-1})	Equilibrium obtained under transient conditions	Interpolated from equivalent constant air speed
	60	1.1	0	0.36	0.97	0.96
Parallel	50	2	0	0.52	0.94	0.94
to surface	30	1	0.4	0.56	0.90	0.93
	23	2	0.6	1.1	0.82	0.85
	60	1.2	0	0.37	1.12	1.04
40° to	30	1.1	0.3	0.62	1.23	1.20
surface	35	2.1	0	0.68	1.46	1.23
	15	2.1	0.7	1.25	2.17	2.03

Table 2

Air flow direction	Pulsed air flow parameters				λ_v/λ_0	
	Period (s)	Peak speed ($m\,s^{-1}$)	Minimum speed ($m\,s^{-1}$)	Mean speed(s) ($m\,s^{-1}$)	Equilibrium obtained under transient conditions	Interpolated from equivalent constant air speed
Parallel to surface	60	1	0	0.35	0.99	0.97
	50	2	0	0.52	1.00	0.96
40° to surface	60	1	0	0.35	1.04	1.01
	50	2	0	0.52	1.03	1.01

clear that repeated bursts of air resulted in a slight reduction in the thermal conductivity of Rockwool below a 150 mm cavity, when the air flow is parallel to the surface.

For repeated fully decaying pulses directed at an angle of 30° to the surface, a small increase in the thermal conductivity of the insulation was observed. The integrated mean speed of these repeated pulses was, in each case, less than 1 $m\,s^{-1}$ and from the results obtained under steady air flow, little change would be predicted at these speeds as shown in Table 2. Unfortunately the results are not directly comparable with those for glass fibre because of the different angle of incidence, but the increase in the λ-value of glass fibre with repeated pulses at 40° to the surface was found to be much greater than the increase in λ-value of the rock fibre resulting from repeated pulses of similar magnitude, but angled at 30°.

5 Conclusion

This series of experiments has shown that the thermal conductivity of glass fibre (density 10.5 $kg\,m^{-3}$) and rock fibre (density 21.6 $kg\,m^{-3}$) loft insulation, subjected to a steady flow of air above the surface, depends on the speed and direction of air flow. Up to speeds of about 0.25 $m\,s^{-1}$, irrespective of direction of air flow the λ-value was found to be very similar to that obtained under steady-state conditions in a standard thermal conductivity test. Consequently air speeds of the magnitude normally encountered in the lofts of occupied buildings are unlikely to have any significant effect on the thermal conductance of roof structures lined with glass or rock fibre insulants.

For parallel air flow through cavities 150 mm and 300 mm in height above the surface of glass fibre there was a slight drop in λ-value with increasing air speeds, in all the areas monitored, up to a speed of 1 $m\,s^{-1}$. This curious behaviour was particularly noticeable in one monitoring position, the λ-value progressively decreasing with speed by some 10% and 30% up to 2.5 $m\,s^{-1}$ in the large and small cavities respectively. In general, however, there was little change until the speed exceeded 1.5 $m\,s^{-1}$, when the thermal conductivity tended to increase as the flow became turbulent. More dramatic changes in λ-value were found to occur at speeds above about 0.5 $m\,s^{-1}$ when the flow was angled to the surface, the effect becoming greater as the angle of flow was increased from 30° to 40°. At an air speed of 2 $m\,s^{-1}$ the λ-value increased by about 100% and 200% for angles of 30° and 40° respectively, in both types of cavity. Generally there was a much larger spread in all the measurements on glass fibre beneath a 150 mm cavity, suggesting greater air turbulence.

Measurements on the rock fibre showed the thermal conductivity to depend on the speed and direction of air flow in a similar fashion to glass fibre, tending to increase with increasing air speed and increasing angle of incidence. On the whole, the effect of air flow on the thermal conductivity of rock fibre is a little less than that on glass fibre, this being attributed partly to the greater thickness of the sample but mainly to its greater density.

Under conditions of nominally parallel air flow, the λ-value of both rock and glass fibre materials was found to decrease, at low air speeds, from the value obtained under 'static' air conditions or in a guarded hot plate apparatus. The effect was too large to be caused by uncertainties of measurement and was presumably caused by air movements within the insulation. However, there were no obvious differences between the particular monitoring positions to account for the variations in this effect. Unfortunately, time did not permit further investigation.

A single burst of air flow lasting about a minute, with a maximum speed up to 2 $m\,s^{-1}$, had very little effect on the thermal conductivity of the insulants when the flow was either parallel or angled to the surface. Bursts of air flow, repeated regularly at intervals of a minute or less had a significant effect on the λ-value of the glass fibre. The effect became more marked as the peak speed of the pulses was increased from 1 to 2 $m\,s^{-1}$. The change in λ-value of rock fibre exposed to repeated pulses of air flow was much smaller than in glass fibre.

It was found that the effect of repeated pulses could be roughly predicted by evaluating a 'mean integrated' speed for the pulses and assuming this to be equivalent to a sustained air speed, for which a thermal conductivity could be assigned from measurements made under conditions of steady air flow at the appropriate angle of incidence. This implies that thermal conductance of an insulated loft can be predicted for transient air flows over the surface of fibrous insulants, given the mean air velocity.

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