Heat transfer in a wet porous thermal insulation in a flat roof

Publisher's version / Version de l'éditeur:

Journal of Thermal Insulation, 11, pp. 165-188, 1988-01

National Research Council Canada

Conseil national de recherches Canada

Institute for Research in Construction

Institut de recherche en construction

Heat Transfer in a Wet Porous Thermal Insulation in a Flat Roof

by C.P. Hedlin

Reprinted from
Journal of Thermal Insulation
Volume 11, January 1988
p. 165 - 188
(IRC Paper No. 1552)

NRCC 29215

Canada

RÉSUMÉ

Des échantillons d'isolant de fibre de verre dont la teneur en eau variait entre 0 et 15 % en volume ont été placés sur le toit d'une installation d'essai extérieure. Des mesures de l'écoulement thermique ont été effectuées à l'aide de thermofluxmètres à toutes les saisons de l'année. Les températures extérieures allaient d'environ -40 à +35 °C.

Les conductances thermiques des isolants humides augmentent considérablement par temps chaud, alors que les variations de la température extérieure causent des inversions quotidiennes du gradient de température des isolants. Ce phénomène est attribué aux cycles évaporation-condensation, au cours desquels la vapeur d'eau effectue un va-et-vient dans l'isolant, transportant de la chaleur latente. Dans l'analyse, l'écoulement thermique a été considéré comme constitué de deux éléments : la chaleur sensible et la chaleur latente.

On a utilisé les résultats des mesures pour définir des relations faisant intervenir des coefficients de transfert et exprimant l'écoulement thermique en termes de température et de pressions de vapeur d'eau.

Les moyennes des écoulements thermiques quotidiens d'un échantillon sec et d'échantillons ayant u[illegible]ées pour une période estival[illegible]ême pour tous les échant[illegible] était environ trois fois s[illegible]

Heat Transfer in a Wet Porous Thermal Insulation in a Flat Roof

C. P. HEDLIN
Prairie Regional Station
Institute for Research in Construction
National Research Council of Canada
Saskatoon, Saskatchewan S7N 0W9

ABSTRACT

Glass fiber insulation specimens with moisture contents ranging from 0 to 15% by volume were placed on the roof of an outdoor test facility. Heat flow measurements were made, using heat flux transducers at all seasons of the year. Outdoor temperatures ranged from about −40° to +35°C.

Thermal conductances for the wet insulations increase sharply in warm weather when swings in outdoor temperature cause daily reversals in the temperature gradient in the insulations. This is attributed to evaporation-condensation cycles in which water vapor is transferred back and forth in the insulation, carrying latent heat. In the analysis, the heat flux was regarded as comprising two components—a sensible heat component and a latent heat component.

The results of the measurements were used to develop relationships, involving transfer coefficients, to express the heat flux in terms of temperature and water vapor pressures.

Daily average heat fluxes were found for a summer period for a dry insulation specimen and specimens containing 1, 9 and 15% moisture (volume). The difference in heat flux was substantially the same for all of the wet specimens. For each wet insulation, the heat flux was about three times as large as it was for the dry specimen.

KEY WORDS

Thermal insulation, moisture, heat flux, flat roof, thermal conductance, moisture flux, transfer coefficients.

Reprinted from *JOURNAL OF* **THERMAL INSULATION** *Volume 11—January 1988*

INTRODUCTION

MOISTURE IS PERVASIVE. In most instances it has a harmful effect on buildings. In the case of thermal insulation, addition of moisture will reduce its effectiveness by an amount that varies with the quantity of moisture, the nature of the insulation and the temperature conditions [1–7].

Studies on the roof of the Outdoor Test Building of the Institute for Research in Construction/National Research Council in Saskatoon produced results of thermal performance for glass fiber insulation in which the moisture contents ranged from dry to 15% by volume. Heat flow rates were measured with heat flux transducers (HFTs) and temperatures were measured with thermocouples. The glass fiber specimens were 60 mm thick. The experimental arrangement is shown in Figure 1. Measurements were made throughout the year thus providing data for all seasons.

The results of earlier analyses [1,5] showed that moisture may be almost immobilized as frost during cold weather but in warmer weather the evaporation-condensation cycle causes a marked increase in the heat transfer rate. Evidence leading to this conclusion is given by the fact that a sudden increase in thermal conductance coincides with the onset of reversals in temperature difference across the insulation. This is illustrated in Figure 2, reproduced from an earlier publication [5]. It shows that conductance (C_{TF}) increased when the mean temperature of the insulation exceeded 15°C. Inspection showed that this occurred when weather conditions were warm enough so that the temperatures at the top surface of the insulation exceeded those at the bottom surface for part of the day.

In the course of a year three different heat transfer phases were identified:

1. Type A prevailed during warm weather when reversals of temperature difference across the insulation occurred on a daily basis. This produced latent heat flow due to vapor movement.
2. Type C heat flow occurred in a transition period in autumn after reversals in temperature difference had ceased to occur. On some occasions it continued for about a month and may have been sustained by liquid flowing from the cold to the warm surface to offset the counter movement of moisture by vapor transfer. Occurrence of type C heat flux depended on moisture content and was not always evident in the present data.
3. Type B heat flux occurred in cold weather. The onset of type B heat flow occurred when the temperature in the upper region of the insulation failed to exceed the freezing point. The initial part of type B heat flow as marked by a reduction in thermal conductance, over a period of several days, as moisture migrated toward the cold surface to be deposited as frost in the upper part of the insulation.

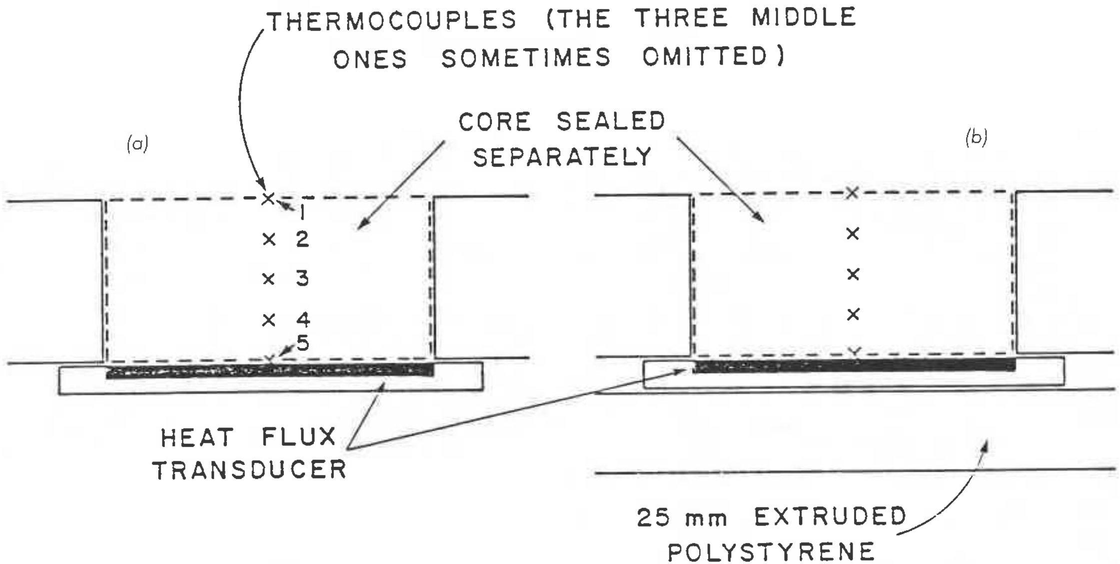
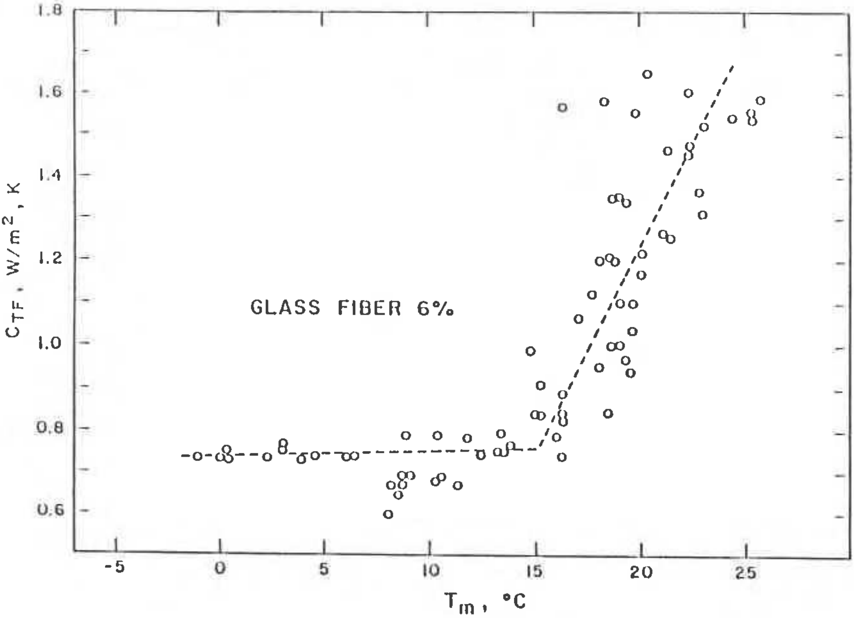
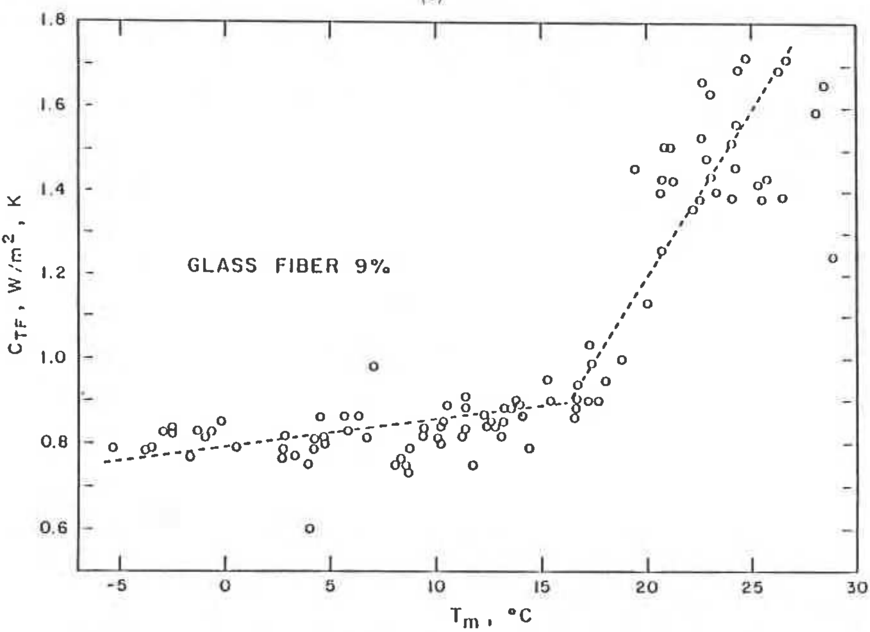


FIGURE 1. (a) Shows mounting of heat flux transducer, thermocouple locations and the core of the specimen. (b) Identical except for 25 mm thick extruded polystyrene beneath the HFT.



(a)



(b)

FIGURE 2. Thermal conductance (C_{TF}) versus mean insulation temperature, T_m. (a) Glass fiber with 6% moisture content; (b) glass fiber with 9% moisture content. Roughly speaking, Type B heat flux occurs for T_m less than 15°C and Type A for T_m greater than 15°C.

The following report comprises three main parts:

1. Representations of heat flow data in terms of sensible and latent components using transfer functions to represent each mode separately.
2. Calculation of sensible and latent heat conductances—the latter is analogous to sensible conductance but uses vapor pressure differences in place of temperature differences to represent latent heat transfer.
3. Calculation of heat flux:
   a) Instantaneous flux calculated with transfer functions
   b) Daily average inward and outward heat flows calculated using data in the period between spring and autumn, to show the effect of moisture on heat gains and losses in warm weather
   c) Daily average heat flux for insulations ranging in moisture from dry to 9% mc, in cold weather data when the moisture is probably present as frost

The analyses are empirical in nature. A simple model for latent heat transfer is used and best-fit relationships based on it are used with it to describe the results.

SENSIBLE AND LATENT HEAT TRANSFER

General Description of the Two Components of Heat Flux

SENSIBLE HEAT FLUX

Steady state conduction of sensible heat can be expressed approximately as

$$Q_s = A\Delta T + B\Delta T T_m \qquad (1)$$

where

ΔT = temperature difference = $TB - TT$
T_m = mean temperature = $(TB + TT)/2$

TB and TT are the temperatures at the bottom and top locations in the insulation (usually the upper and lower surfaces but not always).

LATENT HEAT FLUX

From this a proportionality constant

$$K_v = D\Delta h \frac{\text{kJ}}{\text{s,m,Pa}} \qquad (2)$$

where

D = vapor diffusion constant kg/s, m, Pa
Δh = difference in enthalpy between vapor at temperature $T1$ and liquid at temperature $T2$, kJ/kg
kJ, kg, Pa, s are respectively kilojoule, kilogram, pascal (vapor pressure) and second (time).

The vapor permeability for still air is given as:

$$175 \times 10^{-12} \frac{\text{kg}}{\text{s,m,Pa}} \text{ (i.e., 120 perm-in)}$$

or

$$175 \times 10^{-9} \frac{\text{kg}}{\text{s,m,kPa}}$$

The enthalpy change (Δh) from the vapor state at T_w to the liquid state at T_c varies with the temperatures. In these measurements the enthalpy change ranges from about 2400 to 2500 kJ/kg. Taking an average of these extremes, i.e., 2450 kJ/kg the rate of heat transfer due to moisture diffusion would be:

$$K_v = 175 \times 10^{-9} \times 2.450 \times 10^{6} = 0.43 \frac{\text{J}}{\text{s,m,kPa}} = 0.43 \frac{\text{W}}{\text{m,kPa}}$$

For a gap 60 mm wide (the thickness of the glass fiber insulation used here), the vapor or latent heat conductance would be:

$$C_v = .43/.060 = 7.1 \text{ W/m}^2\text{, kPa}$$

Steady state latent heat transfer might be expressed as

$$Q_v = C_v \Delta P \tag{3}$$

where ΔP = vapor pressure difference across the specimen kPa. A simple model which assumes evaporation at the warmer surface and condensation at the colder one is used in the following analysis. However, it only approximates the situation since condensation at intermediate locations between the surfaces will occur due to the non-linearity in the temperature–vapor pressure relationship and due to temperature fluctuations that occur in the practical case. Further, one investigator [7] concludes that the rate of moisture movement n is dependent also on ΔT, i.e., $n = K_1\Delta T + K_2\Delta P$. Hence the assumption that Q_v depends solely on ΔP is only an approximation.

Approximately [Reference 8, Equations (3),(4)], the saturation vapor pressure at absolute temperature, $T^\star = T + 273.15°K$, over liquid water is:

$$P = e^A \tag{4}$$

where

$$A = -5800/T^\star + 1.39 - .0486T^\star + .0004176T^{\star 2} - 1.445 \times 10^{-8}T^{\star 3} + 6.546 \ln T^\star \tag{5}$$

and over ice:

$$P = e^B \tag{6}$$

where

$$B = 5674/T^\star + 6.393 - .00968T^\star + .622 \times 10^{-6}T^{\star 2} + .2075 \times 10^{-8}T^{\star 3} - .948 \times 10^{-12}T^{\star 4} + 4.163 \ln T^\star \tag{7}$$

Distinction Between Latent and Sensible Heat Flux Components

The distinction between the two modes will be blurred. For example, sensible heat transfer may include a convective component which would directly influence the movement of vapor. Efforts to estimate the contribution of moisture to heat transfer are further complicated by the fact that the reservoir of moisture is limited. The lower regions dry out in winter; in summer, the upper part may become dry after a period of hot sunshine falling on the roof. Nevertheless, it is likely that conditions approximating that of the model do prevail, if only temporarily.

The following analyses are carried out assuming that the total heat flux (Q) is the sum of sensible and latent heat components

$$Q = Q_s + Q_v \text{ W/m}^2$$

hence that

$$Q_v = Q - Q_s \text{ W/m}^2 \tag{8}$$

Using transfer functions (9) the rate of sensible ($Q_s = Q_0$) heat flow can be expressed:

$$K_0Q_0 = I_0TT_0 + I_1TT_1 + \text{---}I_nTT_nJ_0TB_0 + J_1TB_1 + \text{---} + J_nTB_n + K_1Q_1 + \text{--}K_nQ_n \tag{9}$$

The subscripts 0,1--*n*, refer to values at the time 0 and values 1,2--*n* time steps earlier, e.g., 1 and 2 hours earlier.

Q, TT and TB represent heat flow rate (W/m²) and top and bottom surface temperatures (°C) respectively.

The subscripted values of I, J and K are the transfer coefficients. K_0 is taken to equal unity.

CALCULATON OF CONDUCTANCES—SENSIBLE AND LATENT

Sensible Heat Conductances

Transfer coefficients can be used to estimate the thermal conductances. For sensible heat transfer:

$$C_s = \frac{\sum_0^n (-I_i) + \sum_0^n J_i}{2\left(1 - \sum_1^n K_i\right)} \tag{10}$$

Latent Heat Conductances

Equation (9) was modified to express latent heat flux ($Q_v = Q_0$):

$$N_0Q_0 = L_0PT_0 + L_1PT_1 + \text{--}L_{n-1}PT_{n-1} + M_0PB_0 + M_1PB_1 + \text{--} + M_{n-1}PB_{n-1} \text{--} + N_1Q_1 + N_2Q_2 + \text{--} + N_{n-1}Q_{n-1} \tag{11}$$

where $N_0 = 1$.

Equation (10) was changed to produce Equation (12). It was used to calculate latent heat conductance (C_v) using coefficients from Equation (11).

$$C_v = \frac{\sum_{0}^{n} (-L_i + M_i)}{2\left(1 - \sum_{1}^{n} N_i\right)} \text{ W/m}^2\text{,kPa} \tag{12}$$

Equation (8) requires that sensible heat flux (Q_s) be defined. Given the continual change in moisture distribution and periodic change of phase it is improbable that any simple single definition of Q_s will be correct in all situations. In cold weather the moisture was frozen and heat flow could, with reasonable accuracy, be assumed to take place as sensible heat. An expression for Q_s could be obtained under those conditions, however, it was not deemed to be valid in warm weather. Two approaches are considered here:

- In the first it is assumed that sensible heat flow does not vary with the moisture content of the insulation.
- In the second, it is assumed that sensible heat flow is affected by moisture content.

ASSUMPTION 1:
SENSIBLE HEAT FLOW IS UNCHANGED BY THE MOISTURE

One of many possible options for defining Q_s was applied to the analysis of the warm weather data; it was assumed that Q_s is equal to heat flux for dry insulation. This is obviously an approximation but appeared to work reasonably well in the empirical expressions that resulted.

If the heat flux for dry insulation is subtracted from total heat flux the result [Q_v in Equation (8)] should be approximately equal to the increase caused by moisture. The resulting comparison of performance for a wet and a dry roof is not exact, however, since temperature conditions at the surfaces of the insulation would be different even though the ambient conditions (apart from moisture content) were the same.

Using hourly data covering one or more days transfer coefficients for dry insulation were found. Three sets of coefficients are given in Table 1. The first is based on 96 1-hour datasets of TT, TB and Q and the second is based on 120 such datasets. The third was based on temperatures within the insulation, i.e., at points 2 and 4 in Figure 1(a). These were used in a subsequent analysis.

In calculations of coefficients in Table 1, i.e., involving sensible heat transfer [Equation (9)] the data were linearized using the relationship $T^\star = T + .0016T^2$. $T^\star$ was then used in the analyses. However, in calculations of coefficients in Table 2, i.e., involving latent heat transfer, lack of adequate information prevented linearization treatment for Equation (11), though varia-

Table 1. Sensible heat transfer coefficients for dry glass fiber specimens, calculated using 24 datasets/day from the days indicated in Col. 3. These transfer coefficients are used to calculate values of Q_s.

Specimen	Set #	From Days	10	11	12	K1	K2	J0	J1	J2
GF 60 mm	1	173–76/79	−.18952	−.20342	+.12617	+.49013	.04006	+.57626	+.14134	−.45087
GF 60 mm	2	203–07/82	−.09753	−.07165	+.12562	+1.2201	−.28791	+.16852	−.15986	+.03338
GF 30 mm	3	174–77/82	−.63588	−.01594	+.26966	+.78535	+.09851	+.84039	+.07173	−.53015

Table 2. Latent heat transfer coefficients for wet glass fiber specimens, calculated using 24 datasets/day from the days indicated in Col. 4. These coefficients are used to calculate Q_v. Set #1 Table 1 was used to calculate these coefficients.

Specimen	Set #	MC % Vol.	From Days	L0	L1	L2	N1	N2	M0	M1	M2
GF 60 mm	1	3	209/79	−1.2089	−2.4582	−.40079	+1.5311	−1.1874	+4.8190	+9.3081	−9.8809
GF 60 mm	2	1	176–77/82	−5.8630	+7.1765	−4.6245	+1.3614	−.81792	+5.4444	−3.4702	+1.4158
GF 60 mm	3	3	224–25/79	−.52921	−1.8284	+.34238	+.96587	−.33614	+1.3760	+.81811	−.21697
GF 60 mm	4	3	228–29/79	−1.4382	+.70297	−.90463	+1.5672	−.81684	−1.5248	+9.3280	−6.1059
GF 60 mm	5	6	224–25/79	−.79507	−4.8245	+1.5569	+.61430	−.08998	+6.1881	+.77132	−3.0049
GF 60 mm	6	6	228–29/79	−1.2718	−2.1370	+1.9658	+1.3702	−.52860	+2.8395	+3.0453	−4.4318
GF 60 mm	7	9	184–85/82	−.54096	−2.5413	+.76453	+1.0705	−.38352	+3.2261	+.88373	−1.7747
GF 60 mm	8	15	184–85/82	−.26923	−2.9261	−.30259	+.88173	−.26844	+5.4839	−.72000	−1.2932

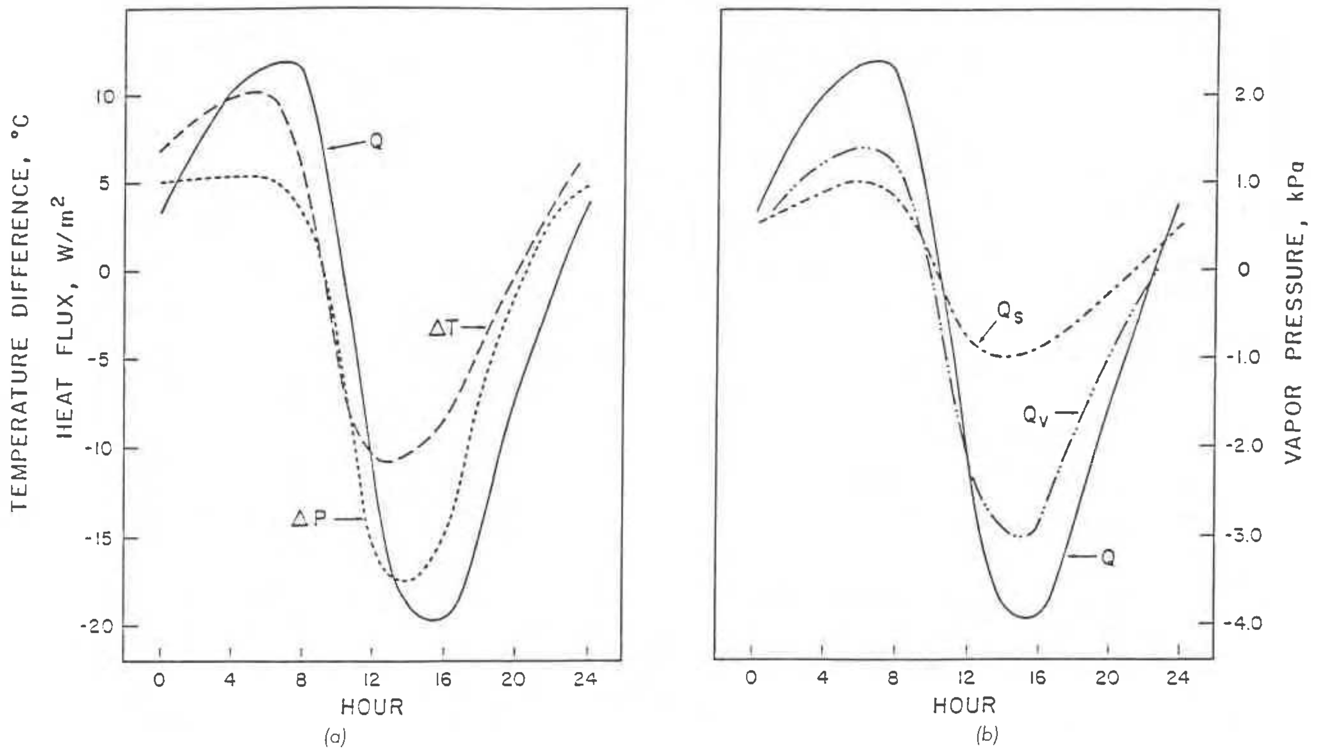


FIGURE 3. (a) Total heat flux (Q), temperature differences (ΔT) and vapor pressure differences (ΔP) for a summer day for 3% mc glass fiber 60 mm thick. (b) Calculated sensible (Q_s) and latent (Q_v), and total heat flux for the same data.

tions in latent and sensible heat contents and variations in vapor diffusion characteristics, with temperature, suggest the need for it.

Figure 3(a) shows the heat flux, temperature difference and vapor pressure difference for a day in summer. The vapor pressure was estimated using Equation (4) or (6). These temperature data were used with the first set of coefficients in Table 1 to estimate Q_s. Also, the difference

$$Q_v = Q - Q_s$$

was calculated. The three values Q, Q_s and Q_v are plotted in Figure 3(b).

This plot demonstrates the large effect of moisture on heat flow in this case. The maximum rate of negative sensible heat flux is estimated to be about 5 W/m² at 1400 hours. The maximum total heat flux is nearly 20 W/m². The difference, about 15 W/m², apparently occurs due to the effect of moisture.

Using Equation (11) with saturation vapor pressures for the above data, coefficients for Q_v in Figure 3(b) were found. They are given (set 1) in Table 2. Other sets of transfer coefficients were found using temperature and heat

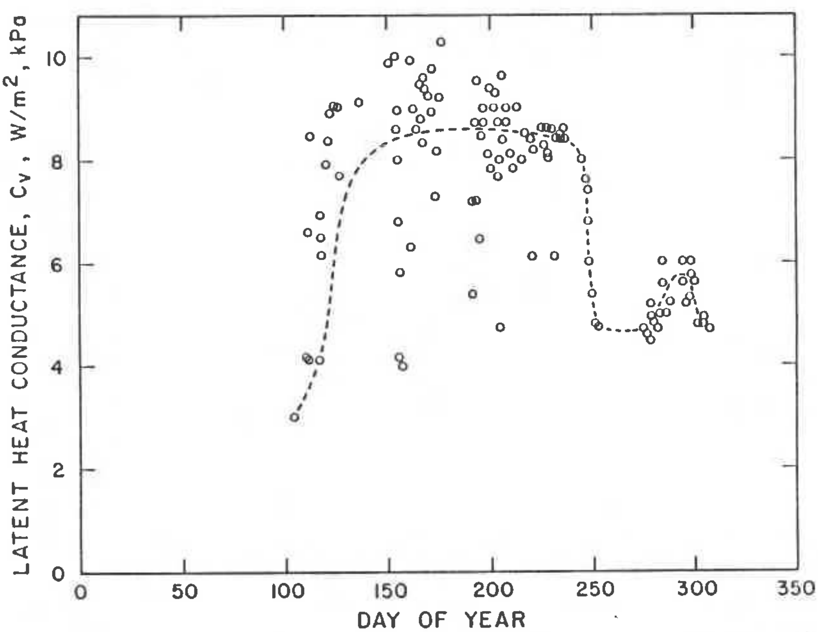


FIGURE 4a. Plots of vapor conductance (C_v) for a specimen of glass fiber with 6% moisture content and 60 mm thick through a summer period. The dotted line follows through the bulk of the data points, as suggested by visual inspections.

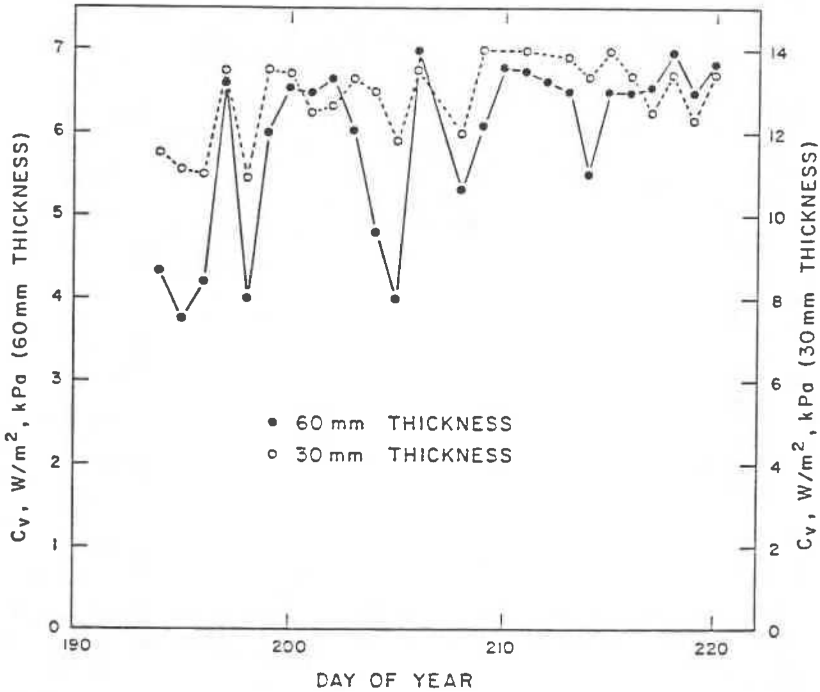


FIGURE 4b. Plots of C_v for glass fiber containing 3% moisture content by volume based on the full 60 mm thickness (left ordinate) and on the middle 30 mm (right ordinate).

flux data for glass fiber specimens having 1%, 3%, 6%, 9% and 15% moisture content (vol.). All were 60 mm thick. In each of the last 5 cases, 48 1-hour datasets were used.

Using the first set of data in Table 2 in Equation (12)

$$C_v = \frac{-(-1.2089 - 2.4582 - .40079) + [4.8910 + 9.3081 - 9.8809]}{2[1 - (1.5311 - 1.1874)]}$$

$$C_v = 6.4 \text{ W/m}^2\text{,kPA}$$

This should be regarded as an apparent rather than a real value.

This was repeated using data obtained throughout the spring, summer and into the fall for the 6% mc specimen. The resulting vapor conductances are plotted against the time of year [Figure 4(a)]. The value of C_v rose to about 9 W/m²,kPa in the summer; as the weather cooled in the fall it fell sharply to about 5 W/m²,kPa, then rose briefly before falling again. The plot terminates at day 310. At about that time the moisture was apparently deposited as frost. At the low temperatures the driving vapor pressure difference is small and the transfer of heat in the latent form almost ceases, though sublimation and condensation probably continue.

The data show a large amount of scatter. Even in the summer when reversals of temperature difference occur C_v varies from about 4 to 10 W/m²,kPa reflecting changes in the vapor flux characteristics.

In some of the insulation specimens thermocouples were located at the quarter points [Figure 1(a)]. Using temperature data for points 2 and 4, and set 3 of the coefficients in Table 1, C_v values for the middle 30 mm of the insulation were calculated for the 3% mc specimen for a 30 day period in summer. These values are shown in Figure 4(b) along with C_v values for the full (60 mm) thickness. As expected, C_v for the center section is about twice as large as C_v for the full thickness. Two ordinate scales are used in Figure 4(b) to allow comparison of the two sets of data. The scatter for the center section is relatively small; C_v for it ranges from about 11 to 14 W/m²,kPa for a ratio of 1:1.27. For the full thickness, C_v ranges from about 3.7 to 7.0 W/m²,kPa

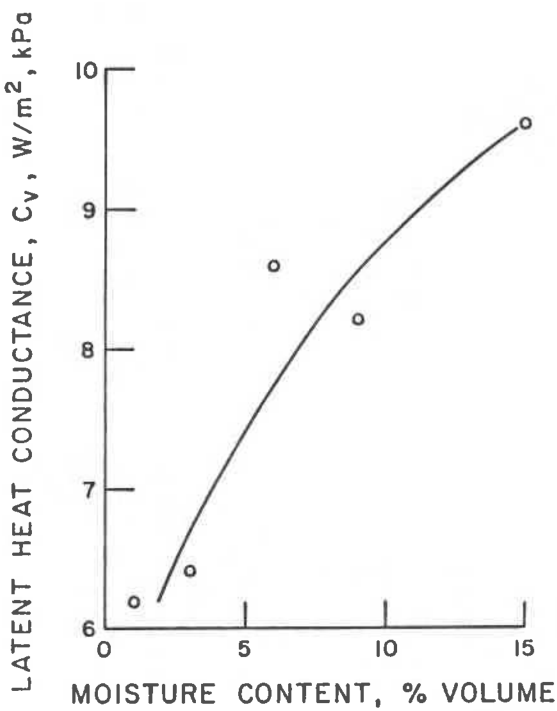


FIGURE 5. Latent heat conductance, calculated using Equation (12) for glass fiber specimens 60 mm thick, with moisture content varying up to 15% by volume.

for a ratio of 1:1.9. This may suggest that the moisture supply was usually adequate in the middle section. Apart from the low values experienced by the full thickness, the C_v values, when converted to a common thickness base, agreed within about 5%. This corresponded to about 6.7 and 13.5 W/m²,kPA for the 60 and 30 mm thicknesses, respectively.

Average values of C_v were calculated for specimens having different moisture contents. Each average covered about 30 days. The results are plotted against moisture content in Figure 5. It shows an increase in C_v of about 50% as the moisture content changed from 1 to 15%.

ASSUMPTION 2: SENSIBLE HEAT FLOW VARIES WITH MOISTURE CONTENT

If it is assumed that the vapor flux cannot exceed 7.1 W/m²,kPa (the value for an air space 60 mm wide) then the fact that values here exceed it would be attributed to the inadequacy of the model. For one thing it assumes that the sensible heat transfer is the same as for dry insulation; in fact, it should be higher than that. Thus part of the heat flux attributed to latent heat transfer is really due to sensible heat transfer. This leads to a second approach for the estimation of sensible and latent heat components.

One would expect that the presence of moisture would increase the sensible heat flux by reducing the thermal resistance of the insulation. At the very least, if it was deposited as a layer of liquid at one of the surfaces, it would effectively nullify the thermal resistance of the insulation there: e.g., 1% of moisture would cause a loss of about 1% of the thermal resistance. At the other extreme, if one supposes that the moisture formed a bridge from one surface of the insulation to the other, the effect would be much greater. Since water has a thermal conductivity about 16 times as great as that of the insulation, the thermal conductance would be increased by about 15% for a 1% increase in moisture content. Probably the effect on sensible heat flow lies somewhere between these two extremes.

Actual contributions of sensible and latent heat flows were estimated using two assumptions:

a) Sensible heat flux increases in proportion to the moisture content.
b) Latent heat flux is independent of the moisture content.

The sensible heat component (Q_s) used in the equation

$$Q_v = Q - Q_s$$

was increased, thus reducing the latent heat flux and the resulting value of C_v. This was done for specimens having 1, 3, 6 and 9% mc. The data were selected to include days on which the values of C_v were near to the top for

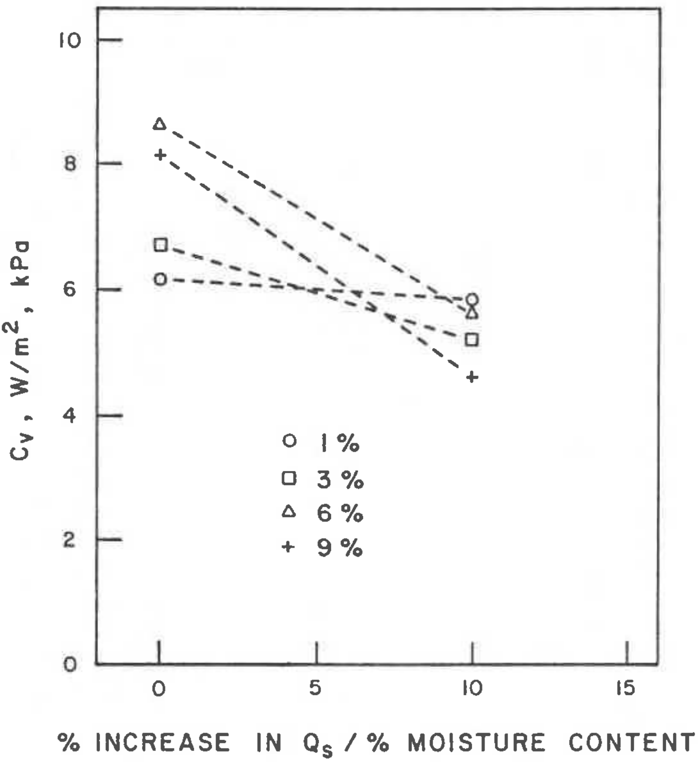


FIGURE 6. Plots of latent heat conductance C_v for no increase in the estimated sensible heat component Q_s and for an increase of 10%/% mc in Q_s. The dotted lines represent interpolations between these extremes.

each specimen. It was assumed that these would correspond to a relatively small moisture depletion effect.

C_v values were calculated using a sensible heat increase of 10%/% mc, i.e., sensible heat flux calculated using Equation (9) was multiplied by 1.1, 1.3, 1.6 and 1.9 for the 1, 3, 6 and 9% mc specimens, respectively, before subtracting it from the total flux, when calculating latent heat flux. In Figure 6 the two sets of C_v are plotted. Interpolation suggested the resulting lines are most closely grouped for a sensible heat flow increase of about 7–9%/% mc. Based on this analysis an effective value C_v of about 6 W/m²,kPa would appear to come closest to satisfying all of the data. Using this result, a vapor flux could be calculated. It would be about 150×10^{-12} kg/Pa,m,s (compared to 175×10^{-12} kg/Pa,m,s for still air).

Techniques for measurement of permeance of materials to water vapor are well established. They are regularly employed to find measures of their probable performance where resistance to vapor movement is important. Standard techniques often employ wet- or dry-cup methods where condensation does not occur. In moist insulations, liquid water is present and the process of moisture movement is somewhat different.

PREDICTION OF HEAT FLUX

Instantaneous

The transfer coefficients can be used to predict heat flux. The predictions are based on the assumption that the sensible heat flow is simply that which would occur if the insulation was dry.

Figure 7(a) and (b) shows calculated and measured heat fluxes for the specimens with 3 and 6% moisture contents respectively. Both graphs are for the same 6-day period (days 165–70/1980).

A computer program was used with coefficients (set 1) in Table 1 to estimate sensible heat flux. Latent heat flux was determined by calculating vapor pressure differences using the same temperature data with coefficient sets 3 and 6 from Table 2. The sensible and latent heat fluxes are combined to give total heat flux.

In Figure 7 the maxima and minima measured and predicted values agree within about 20% except for day 168 when the relationship overpredicted the negative flux by about 80% for the 3% mc specimen and 30% for the 6% specimen. It was a hot day and the drying effect may have caused moisture depletion at the upper surfaces, as previously discussed. The difference is greater for the 3 than the 6% specimen, perhaps because of the larger reservoir of moisture in the latter. Alternatively, the prediction method may be in error, perhaps because the temperature conditions on which the coefficients were based were less extreme than those for which the estimates were made. The arithmetic and absolute heat flux differences between measured and predicted values were 1.0 and 1.8 W/m² for the 3% and 0.1 and 1.2 W/m² for the 6% specimen respectively.

Daily Average Heat Fluxes—Warm Weather

Daily average latent and sensible heat fluxes for 1, 9 and 15% moisture content specimens were calculated using data for different times of the year. Also, measurements were made on dry specimens. The heat fluxes were divided into positive (outflow) and negative (inflow) components. Average values were found for periods ranging from about 5 days to 2 weeks. Values for the dry insulation are plotted in Figure 8(a) and for the 1, 9 and 15% specimens in Figure 8(b), (c), and (d). These plots cover the period between later April and the end of September for the dry and 1% specimens, while these for the 9 and 15% specimens do not start until June.

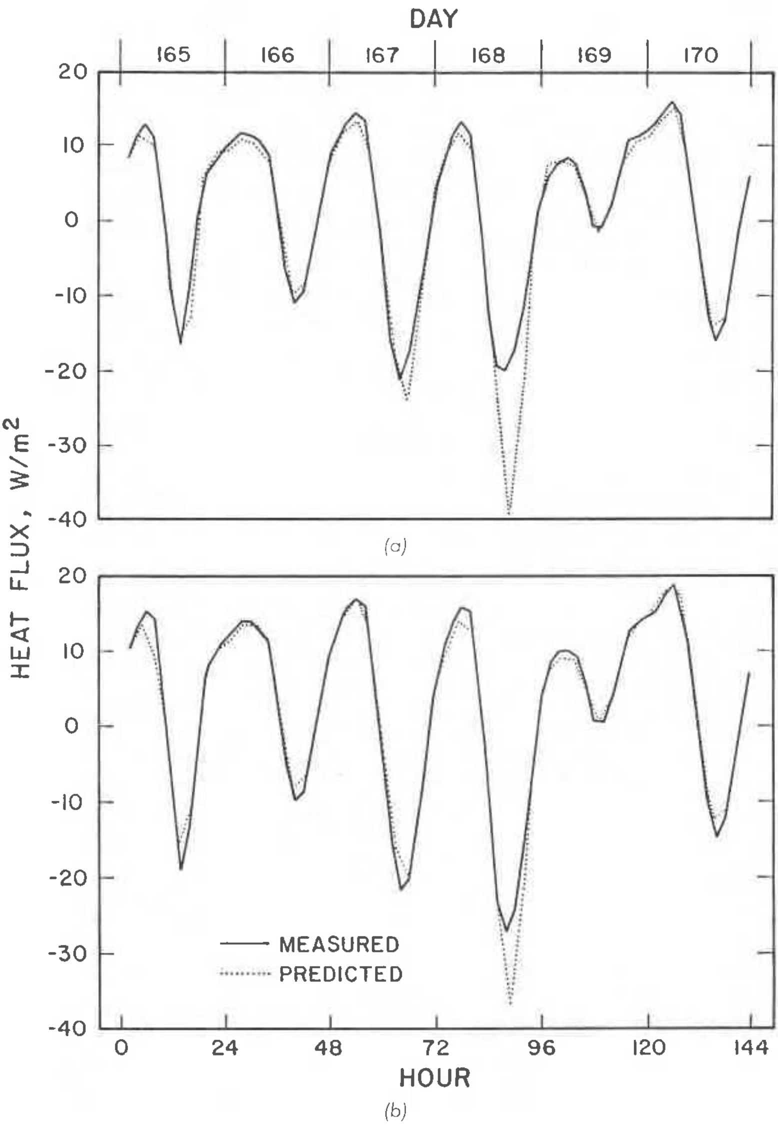


FIGURE 7. Measured heat flux (solid line) and predicted heat flux (dotted line). (a) Data from 165–70/80 for the 3% mc glass fiber specimen 60 mm thick. Prediction based on transfer coefficients calculated from data for days 224–25/79 for the same specimen. (b) Measured heat flux (solid line) and predicted heat flux (dotted line). Data from 165–70/80 for the 6% mc glass fiber specimen 60 mm thick. Transfer coefficients were calculated using data for days 228–29/79 for the same specimen.

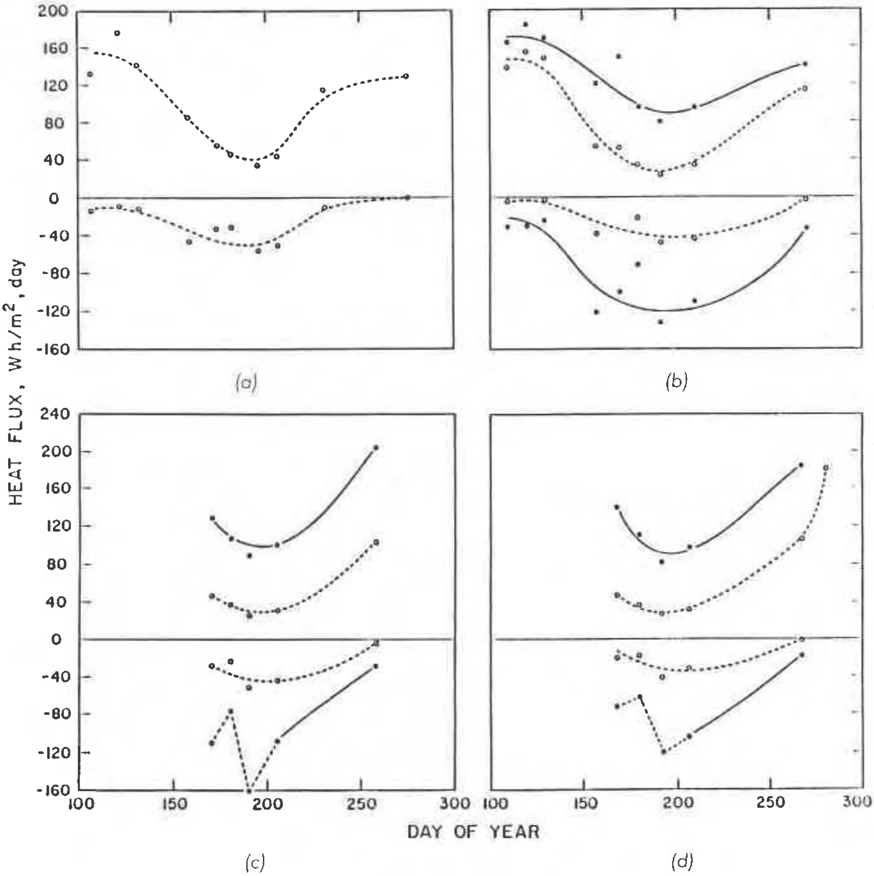


FIGURE 8. Daily average positive (outward) and negative (inward) heat fluxes for dry, 1%, 9% and 15% mc specimens. Each dot represents an average for a period ranging from 5 days to about 2 weeks. Dashed lines represent sensible heat flow. Solid lines represent total heat flow though a dashed line joins total heat flow points where the scatter is large.

The data show large increases in negative flux in the summer season. The smooth curve indicates that the estimated sensible heat component for the wet specimens reached about 40 Wh/m², day. The value for the dry specimen, measured at the same time, was a little larger—about 50 Wh/m², day.

In one hot 5-day period, i.e., days 190–94 (early August) the rate of heat inflow reached 160 Wh/m², day (see the individual point) for the 9% specimen. The maximum 1-day value for that specimen (day 191—not shown) was 190 Wh/m². In the same 5-day period the maximum negative fluxes for the dry, 1 and 15% specimens were 70, 160 and 165 Wh/m², day respectively.

The heat fluxes did not change significantly with increased moisture content. This is not necessarily inconsistent with the increase in apparent latent heat conductance that accompanies increased moisture content (Figure 5) since the temperature differences decrease somewhat with increased moisture content.

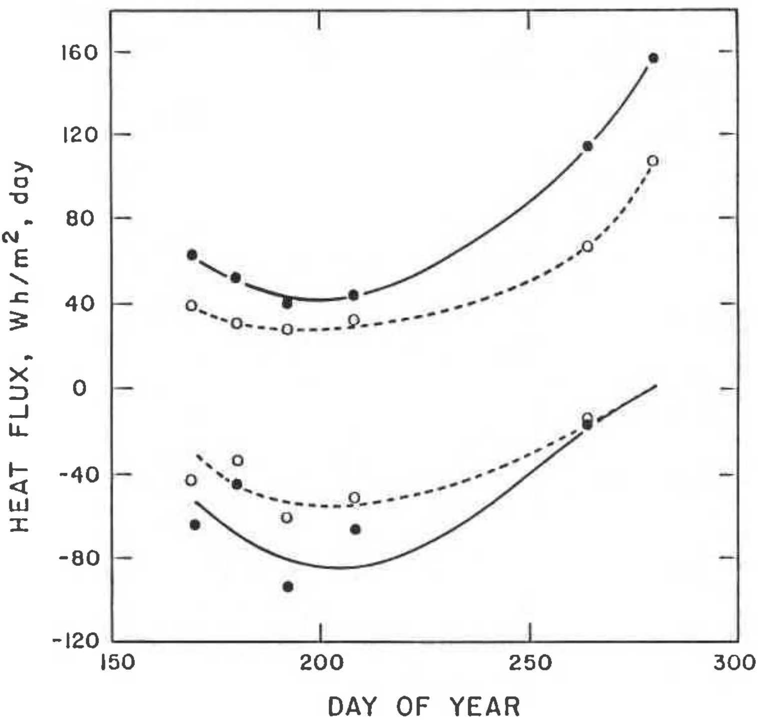


FIGURE 9. Daily average positive and negative heat fluxes for 9% mc glass fiber located over 25 mm thick extruded polystyrene. Solid lines represent total heat flow; dashed lines represent sensible heat flow.

The total negative fluxes for wet insulation are about 2–3 times as large as the sensible heat flux components estimated for the wet specimens and the measured heat fluxes for the dry specimen. Positive heat fluxes exceeded estimated or measured sensible heat fluxes by about 3 times in summer. A laboratory study [3] found a ratio between the vapor and sensible heat components to be about 1:2.5. In that case the ratio of the total sensible heat flux would be about 1:3.5. A field study [6] on wet roofs showed a ratio of about 3.

In addition to the above measurements, a 9% specimen was located over dry extruded polystyrene insulation 25 mm thick. The heat fluxes are shown in Figure 9. The total negative heat flux reached about 90 Wh/m², day. The presence of the dry insulation along the path of heat flow reduced the heat flow and the overall effect of moisture on the thermal performance of the roof panel.

Daily Average Heat Fluxes—Cold Weather

The preceding discussion has been devoted principally to heat flow in summertime. In cold weather the moisture may accumulate as frost in the upper region of the insulation [5]. Movement of heat due to vapor flux is very much reduced; however, the frost provides highly conductive paths and the thermal conductance is substantially higher than for dry insulation. Heat flux can be expressed:

$$Q_s = A\Delta T + B\Delta T T_m$$

ΔT, T_m are temperature difference and mean insulation temperature, respectively. A and B can be found using least squares analysis, with data for which $T_m < 15°C$.

The thermal conductance can be expressed:

$$C = \frac{dQ_s}{d\Delta T} = A + BT_m$$

Table 3 contains these values for 60 mm thick insulation having 0, 1, 3, 6, and 9% moisture contents.

SUMMARY AND CONCLUSIONS

1. Moisture in thermal insulation has an important effect on heat flow. In summer the transport of heat includes an evaporation–condensation process which transfers latent heat from warm to colder regions of the insulation along with the tranfer of sensible heat.

Table 3. Constants for $C_s = A + BT_m$ for 60 mm thick glass fiber with 0 to 9% mc for T_m 15°C. A and B have units W/m², K and W/m² respectively.

mc%, Vol.	A Units	B Units
0	.55	.00175
1	.57	.002
3	.63	.009
6	.78	.0056
9	.79	.0069

2. Heat flux measurements were made on glass fiber insulations 60 mm thick having moisture contents ranging from dry to 15% by volume. The specimens were encapsulated in polyethylene and mounted on the roof of an outdoor test facility. Measurements were made at all seasons of the year.

3. The rate of heat transfer was represented as the sum of sensible and latent components.

4. Each of these components can be expressed in terms of transfer functions. In the present case sensible heat fluxes (Q_s) were assumed to be the same as for dry insulation. Q_s was subtracted from the total flux Q to find the latent flux (Q_v). Using Q_v and saturation vapor pressures corresponding to the temperatures at the upper and lower surfaces of the insulation "vapor transfer coefficients" were found. Using these coefficients "apparent vapor conductances" having the units W/m²,kPa were calculated.

5. Latent heat conductances calculated in this way varied somewhat with moisture content of the specimen. Values for 1% moisture content specimens reached about 6.5 W/m²,kPa while those for a 9% moisture content specimen reached about 9.5 W/m²,kPa, for glass fiber 60 mm thick. The latter exceeds the value of 7.1 W/m²,kPa estimated for still air. It seems improbable that the rate of vapor movement in the glass fiber, which produces this heat flow, would exceed that in still air. Presumably the sensible heat component exceeds that for dry insulation, hence part of the heat flow attributed to vapor movement in this model is, in fact, due to sensible heat flow.

6. By assuming that the sensible heat flux increased in proportion to the moisture content and that latent heat flux was independent of it, an estimate of the actual contributions of sensible and latent heat flux was made. Based on these assumptions, it appeared that sensible heat flux increased by about 7–9%/% mc. and that the latent heat flux was about 6 W/m²,kPa for the 60 mm thick glass fiber. The latter translates to a vapor flux of 150×10^{-12} kg/s,m,kPa.

7. Net movement of moisture in one direction due to prolonged or large temperature differences appears to cause local depletion of moisture and a reduction of the rate of heat transfer. This occurs in early winter when mois-

ture accumulates as frost in the upper part of the insulation and can occur in summer when hot upper surface temperatures drive moisture downward in the insulation.

8. The results showed that glass fiber specimens containing 1, 9 and 15% moisture by volume produce daily average heat gains and losses about three times as great as dry insulation. The ratio did not appear to vary significantly with increased moisture content.

REFERENCES

1. Hedlin, C. P. "Effect of Moisture on Thermal Resistances of Some Insulations in a Flat Roof System Under Field-Type Conditions," ASTM STP 789, Thermal Insulation Materials and Systems for Energy Conservation in the 80's, pp. 602–25 (Jan., 1983).
2. Bomberg, M. and C. Shirtliffe. "Influence of Moisture and Moisture Gradients on Heat Transfer Through Porous Building Materials," ASTM STP 660, Thermal Transmission Measurements of Insulation, pp. 211–233 (NRCC 17138) (1978).
3. Langlais, C. et al. "Influence of Moisture on Heat Transfer Through Fibrous Insulating Materials," ASTM STP 789, Thermal Insulation Materials and Systems for Energy Conservation in the 80's, pp. 563–81 (1983).
4. Thomas, W. C. et al. "Heat and Moisture Transfer in Glass Fiber Roof-Insulating Material," *ibid.*, pp. 582–601.
5. Hedlin, C. P. "Seasonal Variations in Modes of Heat Transfer in a Moist Porous Thermal Insulation in a Flat Roof," *Journal of Thermal Insulation*, 11(1):54–66 (1987).
6. Shuman, E. C. "Field Measurement of Heat Flux Through A Roof with Saturated Thermal Insulation and Covered with Black and White Granules," ASTM STP 718, pp. 519–39 (Dec., 1980).
7. Kumaran, M. K. "Moisture Transport Through Glass-Fibre Insulation in the Presence of a Thermal Gradient," *Journal of Thermal Insulation*, 10:243–255 (April, 1987).
8. *ASHRAE Handbook of Fundamentals*. Chap. 6 (1985).
9. Hedlin, C. P. "Calculation of Thermal Conductance Based on Measurements of Heat Flow Rates in Flat Roofing Using Heat Flux Transducers," ASTM STP 885, Building Applications of Heat Flux Transducers, pp. 184–201 (Dec., 1985).