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RÉSUMÉ

L'auteur fait état des résultats expérimentaux d'une étude portant sur le transport et l'accumulation d'humidité dans un isolant de cellulose, en présence d'un gradient thermique. Il compare ces résultats, du point de vue qualitatif, avec ceux obtenus lors d'études précédentes avec un isolant en fibre de verre. La comparaison révèle qu'une quantité appréciable d'humidité est transportée à travers la cellulose par flux en phases condensées, en présence de gradients thermiques.

Comparison of Simultaneous Heat and Moisture Transport through Glass-Fibre and Spray-Cellulose Insulations

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ABSTRACT

Experimental results from an investigation of moisture transport and accumulation in cellulose insulation, in the presence of a thermal gradient, are reported. These results are compared, qualitatively, with the results obtained on glass-fibre insulation from earlier investigations. The comparison reveals that an appreciable quantity of moisture is transported through cellulose via condensed phase flow, in the presence of thermal gradients.

KEY WORDS

Thermal insulation, glass-fibre, spray-cellulose, heat transport, moisture transport, moisture distribution.

INTRODUCTION

TRANSPORT OF MOISTURE through glass-fibre insulation in the presence of thermal gradients has been investigated extensively at the Institute for Research in Construction [1–6]. The transport process represented by Figure 1 was chosen for the investigations. The process is similar to that investigated by Langlais et al. [7,8]. In this process a layer of liquid water (approximately 0.25 mm thick), originally present at the hot surface of a test specimen, was transported to the cold surface. The transport process was

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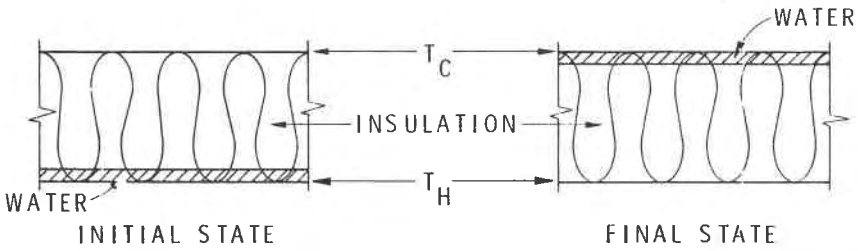

FIGURE 1. Simultaneous heat and moisture transport through insulation. T_H and T_C are the hot and cold surface temperatures of the insulation.

carried out in a heat flow meter (HFM) apparatus using the experimental method previously reported [1]. The test specimens chosen for the investigations included a wide range of commercially available glass-fibre insulation; the bulk densities of the specimens ranged from 17 to 120 kg m^{-3} and thicknesses from 2.5 to 15 cm. In spite of these wide differences in density and thickness, for all pairs of hot and cold surface temperatures, the heat flux across the specimens followed the general behaviour shown in Figure 2. This same behaviour was reported by Langlais et al. [8].

The initial steady state (the range BC in Figure 2) corresponded to a

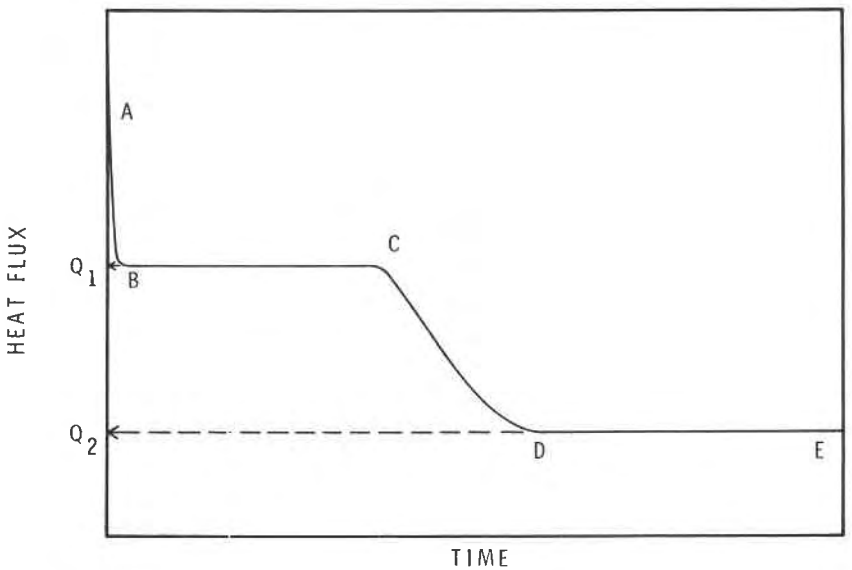

FIGURE 2. Mean heat flux through glass-fibre insulation, during the transport process represented by Figure 1.

steady and simultaneous heat and water vapour flux, the range CD to drying out of successive layers of the specimen from the hot to the cold surfaces and the range DE to only heat transfer across the specimen. For the amount of water used in these investigations, the heat flux at the final steady state was identical to the heat flux through the dry specimen.

A thermodynamic model was introduced [1] to represent the transport process; the model allowed calculation of water vapor flux (J_m) at the initial steady state from the equation

$$J_m = (Q_1 - Q_2)/\{\Delta H + (H_H - H_C)\} \tag{1}$$

where Q_1 and Q_2 are the heat fluxes at the initial and final steady states, ΔH is an average enthalpy of vapourisation between the hot and cold surface temperatures and H_H and H_C are the enthalpy of water at the hot and cold surface temperatures, respectively. Further, for each test specimen, it was shown conclusively [1–3] that the vapour flux can be accurately represented by the equation

$$J_m = K_1 \Delta p + K_2 \Delta T \tag{2}$$

where K_1 and K_2 are transport coefficients, characteristic of the specimen for a wide range of vapour pressure difference Δp, and temperature difference ΔT across the specimen.

The use of the coefficients K_1 and K_2 in the mathematical analyses of simultaneous heat and moisture transport through glass-fibre insulation was subsequently demonstrated [3] and it was shown [4] that the low hygroscopicity of commercial glass-fibre insulation plays only a negligible role in the details of simultaneous heat and moisture transport through these materials.

The present investigation was undertaken to gather information on simultaneous heat and moisture transport through cellulose insulation for subsequent use in the mathematical analysis of the transport processes. This material is known to be more hygroscopic than glass-fibre insulation. Earlier investigations by Tye and Spinney [9] and Benner et al. [10] have resulted in valuable information on absorption of moisture and the effect of absorbed moisture on the thermal performance of cellulose insulation. The work reported in this paper provides further information on transient distribution of moisture in a specimen of cellulose insulation during the simultaneous heat and moisture transport shown in Figure 1.

MATERIALS AND METHOD

A commercially available cellulose-spray insulation was chosen for the investigation. The average density of three dry slabs (60 × 60 × 10 cm) pre-

pared from the material was 50 kg m^{-3}. From these slabs the following two test specimens were prepared.

Specimen I: 60 × 60 × 6 cm slab
Specimen II: 19.5 × 19.5 × 5 cm slab in a plexiglas frame to fit all the four edges

Both specimens were used to set up the test system shown in Figure 1. For Specimen I the moisture was introduced initially by spraying 100 grams of water uniformly on one of the flat surfaces. For Specimen II, a 19.5 × 19.5 cm piece of blotting paper was wetted with 50.4 grams of water and placed against one of the flat surfaces and was encapsulated with an airtight polyethylene membrane.

Specimen I was placed in a horizontal, 60 × 60 cm HFM apparatus, with a metering area of 30 × 30 cm. The wet surface was in contact with the bottom hot plate maintained at 35.3°C. The upper cold plate was maintained at 12.5°C. Then the heat flux across the specimen was monitored until the final

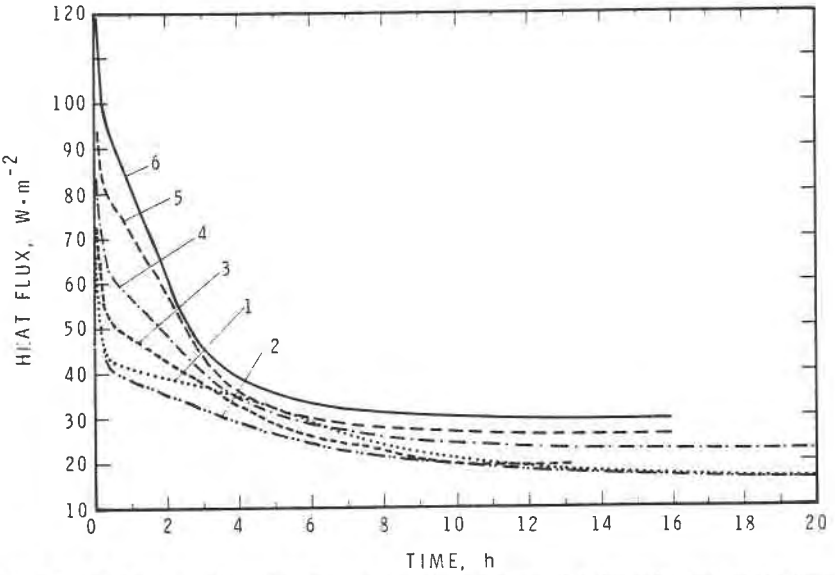

FIGURE 3. History of heat flux through Specimen I. Curve 1 is from the first set of measurements (T_H = 35.3°C and T_c = 12.5°C), just after spraying of water. (Curve 1 differs from the others in the figure; an explanation for this is given in the text.) In curve 2 the direction of the transport process was reversed by turning over the specimen in the HFM apparatus, without changing the plate temperatures. In subsequent tests (curves 3, 4, 5 and 6) the temperature difference ($T_H - T_c$) was successively increased as (39.9 − 12.8), (44.7 − 12.9), (49.0 − 13.1) and (54.1 − 13.4)°C.

steady state shown by curve 1 in Figure 3 was established. At this stage the hot plate temperature was increased to 39.9°C and the specimen was turned over in the HFM apparatus. The heat flux was again monitored until the final steady state was established. This procedure was repeated at three other hot plate temperatures, viz. 44.7, 49.0 and 54.1°C. The results from all these measurements are plotted in Figure 3.

Specimen II was placed in a 20 × 20 cm HFM apparatus, with a metering area of 15 × 15 cm, that formed a part of a gamma-spectrometer. In addition to monitoring of the heat fluxes, the test specimen was scanned periodically with the gamma-spectrometer, to determine moisture distribution in the specimen during the transport process. The details of this experimental technique are given elsewhere [5,6]. Once the changes in heat flux became negligible, the specimen was turned over in the HFM apparatus and the monitoring of heat fluxes continued. The results from the heat flux measurements are given in Figure 4 and the moisture distribution during the transport process is shown in Figure 5.

For a comparison, the experiments done on Specimen II were repeated on

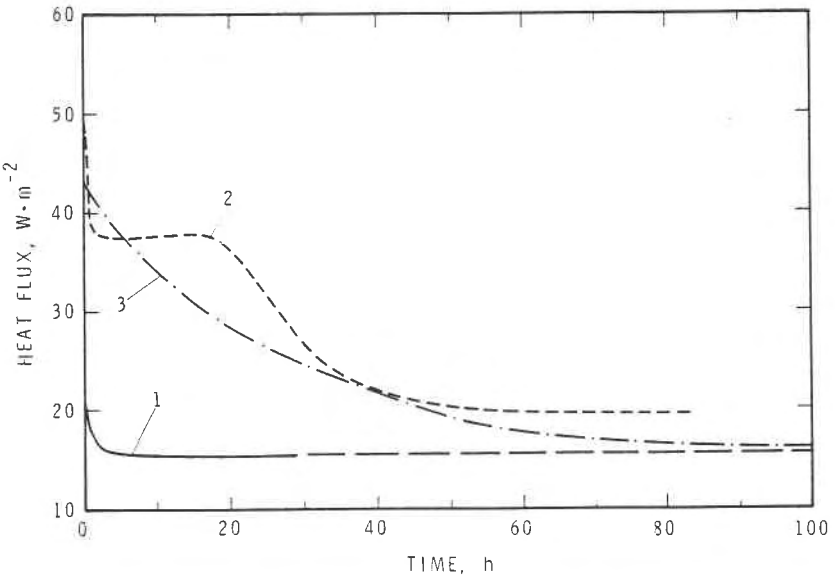

FIGURE 4. History of heat flux through Specimen II. The hot and cold surface temperatures were 33.2 and 14.3°C, throughout. Curve 1 shows the steady state heat flux through the dry specimen and curve 2, the history of heat flux when all the moisture was initially present in the blotting paper. Curve 3 begins when the specimen was turned over in the HFM apparatus 85 hours after the starting point of curve 2.

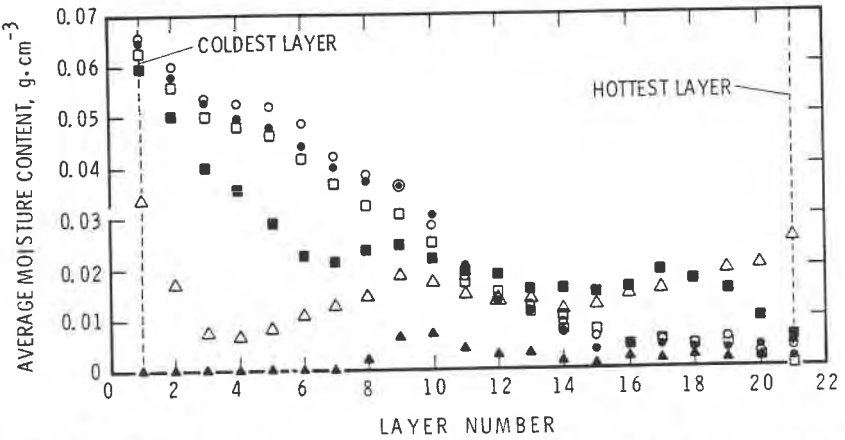

FIGURE 5. Changes in moisture distribution in Specimen II during the process represented by curve 2 in Figure 4. For each set of gamma-spectroscopic measurements, the specimen was scanned at 21 layers and each layer at 5 blocks. The duration of one set of measurements was 1 hour (see Reference 6 for details). Each symbol represents moisture content at the respective layer, calculated as the average of five blocks in the layer. The experimental points ▲ correspond to the first hour, △ between 14 and 15 h, ■ between 28.5 and 29.5 h, □ between 50 and 51 h, ● between 57 and 58 h and ○ between 64 and 65 h of the transport process.

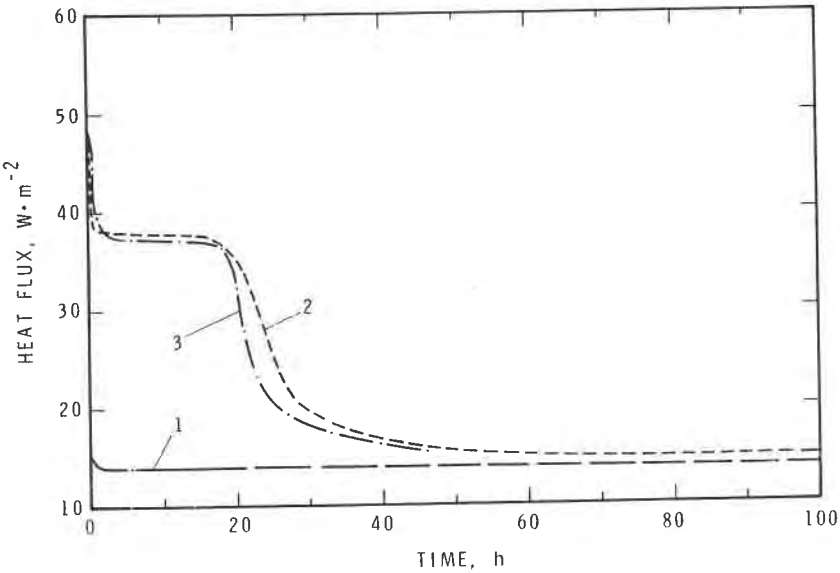

FIGURE 6. History of heat flux through a specimen of glass-fibre insulation, identical in dimensions to Specimen II. Curves 1, 2 and 3 represent processes comparable to that represented by curves 1, 2 and 3 in Figure 4.

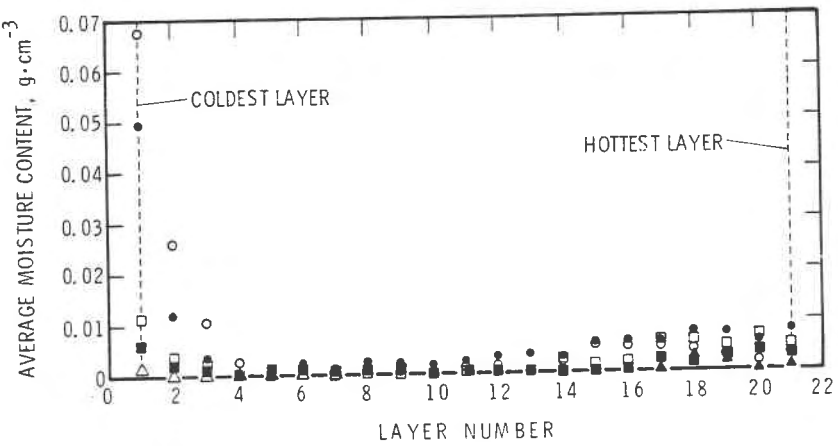

FIGURE 7. Changes in moisture distribution in glass-fibre insulation, during the transport process represented by curve 2 in Figure 6. The gamma-spectroscopic measurements were identical to those described for Figure 5. The experimental points ▲ correspond to the first hour, △ between 2 and 3 h, ■ between 12 and 13 h, □ between 17 and 18 h, ● between 21 and 22 h and ○ between 24 and 25 h.

a glass-fibre insulation specimen (density = 20 kg m^{-3}) of similar dimensions. The results from these measurements are shown in Figures 6 and 7.

DISCUSSION

As shown in Figure 3, Specimen I did not exhibit an initial steady state, as did the glass fibre specimens, represented schematically in Figure 2. In the first test the transport process was continuous throughout, until the final steady state was attained. At this final steady state the heat flux was substantially higher than that through the dry material, unlike the results for glass-fibre specimens in earlier investigations. For example, it was about 30% higher when the hot and cold surface temperatures were respectively 35.3°C and 12.5°C. This indicates that the moisture establishes a steady state distribution within the test specimen, probably characteristic of the thermal gradient for the given amount of moisture, and participates in the heat transport. This is contrary to the behaviour exhibited by glass-fibre insulation, where under all temperature gradients the moisture deposits at the coldest part of the test system, not contributing towards the heat transport. Thus, every time Specimen I (the cellulose insulation) was turned over in the HFM apparatus, the moisture was present not only on the cold surface, but distributed in the specimen. That means that, in the present set of experiments, the transport process represented by Figure 1 never occurred and an initial steady state (such as BC in Figure 2) was never established.

Even in the first experiment, when water was sprayed on the surface, the cellulose fibre absorbed the moisture and the initial requirement of all moisture on the surface layer was not met. However, the moisture was not distributed to any steady state values and hence in the first experiment some discontinuity in the transport process was seen, though no initial steady state was observed. It was then anticipated that if the moisture is admitted from a source outside the test system, an initial steady state as shown in Figure 2 is possible. This anticipation was also supported by an approximate mathematical analysis of the process by the method described in Reference 4. This was the reason for using the blotting paper as a source for moisture for Specimen II.

In fact, as seen in Figure 4, an initial steady state was observed with Specimen II when moisture was allowed to enter gradually, in the presence of the thermal gradient. This initial steady state was not as well defined as that which was seen with the various specimens of glass-fibre insulation, because the heat flux was slowly increasing throughout the simultaneous transport of heat and water vapour. Probably, this was due to a slow and steady buildup of moisture within the specimen. But after the supply from outside died out, the heat flux started to fall until the final steady state was attained.

The concurrent gamma-spectroscopic measurements plotted in Figure 5 show the changes in the moisture distribution during the above transport process. Moisture migrated gradually towards the cold surface until the final steady state distribution was attained. The last two measurements, done 57 and 64 hours after the start, gave the same moisture distribution within the specimen. Further, an integration of the moisture contents over the 21 layers of the specimen scanned at the final steady state gave a total moisture content of 48.4 grams. Within the limits of the precision of the experimental method, this 48.4 grams accounted for all the water that was initially present in the blotting paper. This confirms that at the final steady state, all the moisture involved in the transport process was retained by the specimen in achieving a steady state distribution.

After 85 hours the specimen was turned over in the HFM apparatus without changing the plate temperatures. As anticipated, no initial steady state was observed when the moisture was driven back to the surface covered with the blotting paper. As shown in Figure 4, the specimen went through a continuous process. After approximately 100 hours the specimen was scanned with the gamma-spectrometer. These measurements showed that the specimen was virtually dry, even though another steady state moisture distribution was anticipated. Probably the hygroscopicity of the blotting paper, now present at the cold surface, overshadowed that of the cellulose and allowed the moisture to migrate totally out of the insulation.

The difference between cellulose and glass-fibre insulation becomes ap-

parent from a comparison of Figures 4 and 6, with Figures 5 and 7. Apart from a small hysteresis effect, the present glass-fibre insulation behaved identically during the transport process in either direction. No such hysteresis was observed in any of the earlier investigations on glass-fibre specimens. It is probable that the blotting paper interfered with the overall transport process in this study.

The gamma-spectroscopic measurements on the glass-fibre specimen confirmed that there was no significant moisture retention by the layers in between the hot and cold surfaces. Moisture was continuously transported to the colder layers, as shown in Figure 7. At the final steady state an integration of the moisture contents in all the layers accounted for only 13 grams of water, most of it on the coldest slice, with the rest probably outside the specimen on the polyethylene film, as observed in earlier investigations.

Comparison of the family of curves (2 to 6) in Figure 3 with those obtained in earlier investigations on glass-fibre insulation [1] reveals another noticeable difference between the two types of insulation. The excess area enclosed by each curve over the steady state heat flux level, up to the establishment of the final steady state, is a measure of the energy involved in the transport of the moisture. For glass-fibre insulation there is no significant difference in this quantity for different pairs of hot and cold surface temperatures, for a given amount of moisture. However, for cellulose the additional energy expended in the transport of moisture increases with the difference in the hot and cold surface temperatures. This behaviour once again demonstrates the strong interaction between the two parallel transport processes in cellulose.

CONCLUSION

While the present experimental data do not allow for direct calculation of transport coefficients such as K_1 and K_2 in Equation (2) the following qualitative conclusions can be drawn.

The steady state distribution of moisture within the cellulose suggests that moisture transport in condensed phases cannot be neglected in comparison with water vapour transport. At no stage the vapour transport can be completely stopped. Hence the final steady state distribution as shown in Figure 5 means that the transport processes in the vapour phase and in the condensed phases operate in opposite directions, resulting in no net moisture flow.

The above phenomenon makes mathematical analysis of simultaneous heat and moisture transport through materials such as cellulose more tedious than similar analysis in the case of glass-fibre insulation. The moisture absorption-desorption isotherms and both vapour and condensed phase

transport processes are to be correctly modelled. At IRC, the absorption-desorption isotherms of the material used in this investigation and the transport coefficient K_1 in Equation (2) are already experimentally determined. It is hoped that the experimental data presented in this paper can be used to optimize the value of the constant K_2 in Equation (2) and that of the condensed phase transport coefficients through modelling and computer simulations.

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BIOGRAPHY

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