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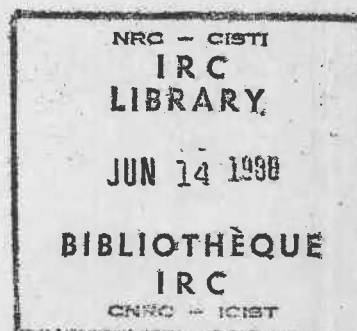
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## ***Simultaneous Heat and Moisture Transport Through Glass Fibre Insulation: An Investigation of the Effect of Hygroscopicity***

by G.P. Mitalas and M.K. Kumaran

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## RÉSUMÉ

On se sert d'une expression empirique qui représente le transport de vapeur d'eau à travers de l'isolant en fibre de verre non hygroscopique pour étudier l'influence de l'hygroscopicité sur le transport simultané de chaleur et d'humidité à travers les isolants fibreux. Les auteurs présentent un modèle mathématique servant à représenter l'hygroscopicité. Ils comparent les informations produites numériquement aux données expérimentales correspondantes.

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# SIMULTANEOUS HEAT AND MOISTURE TRANSPORT THROUGH GLASS FIBRE INSULATION: AN INVESTIGATION OF THE EFFECT OF HYGROSCOPICITY

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## ABSTRACT

An empirical expression that represents the water vapour transport through non-hygroscopic glass fibre insulation is used to investigate the influence of hygroscopicity on simultaneous heat and moisture transport through fibrous insulating materials. A mathematical model is introduced to represent the hygroscopicity. The numerically generated information is compared with corresponding experimental data.

## INTRODUCTION

A simple mathematical model that describes the simultaneous heat and moisture transport through glass fibre insulation was recently reported by the authors [1]. The model is based on empirical relations for heat and water vapour fluxes in terms of arbitrarily chosen driving potentials. The advantage of the approach is that the transport coefficients can be determined reliably for a range of boundary conditions that represent practical building situations. The empirical relations used are,

$$J_m = K_1 \frac{dp}{dx} + K_2 \frac{dT}{dx} \quad (1)$$

for the water vapour flux, and

$$J_q = (K_3 + K_4 T) \frac{dT}{dx} \quad (2)$$

for the heat flux. In the above equations  $dT/dx$  is the temperature gradient,  $dp/dx$  is the corresponding vapour pressure gradient and  $K_1$ ,  $K_2$ ,  $K_3$  and  $K_4$  are empirical constants that characterize the insulation;  $J_m$  and  $J_q$  are respectively water vapour and heat fluxes. The model considers only one-dimensional fluxes and uses the conservation equation

$$\frac{d\beta}{dt} = \frac{d}{dx} J_\beta + I_\beta \quad (3)$$

for each of the entities,  $\beta$ , transported. In Eqn. (3),  $t$  represents time and  $I_\beta$ , a source (or sink) term for  $\beta$ , accounts for any generation (or removal) of  $\beta$ . For the analysis reported earlier,  $I_\beta$  was neglected for

moisture by assuming that glass fibre insulation is non-hygroscopic. But laboratory studies show that commercial glass fibre insulations adsorb and desorb moisture when in contact with water vapour. The amount of moisture so adsorbed is a function of temperature and the equilibrium water vapour pressure. For example, a specimen of medium density glass fibre insulation ( $\approx 80 \text{ kg m}^{-3}$ ) at  $23^\circ\text{C}$  adsorbed moisture from air with varying relative humidities as shown in Figure 1. Conventionally the adsorption or

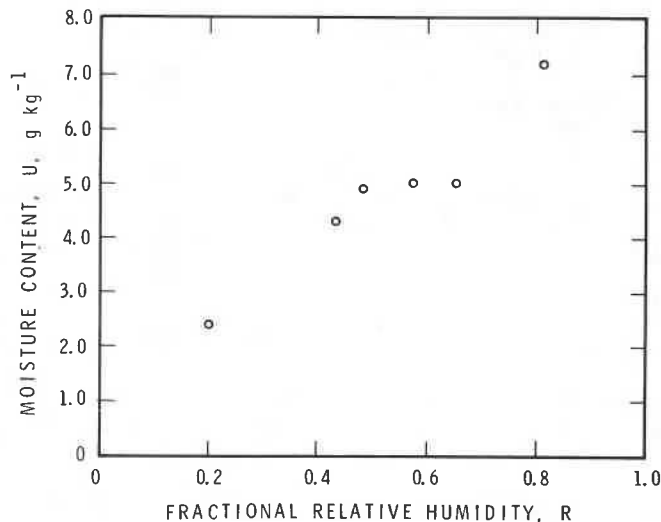


Fig 1 Moisture adsorbed by a specimen of glass fibre insulation at  $23^\circ\text{C}$  and various relative humidities; the density of the dry specimen  $\approx 80 \text{ kg m}^{-3}$ .

desorption characteristics of any material are represented by a family of adsorption (or desorption) isotherms. Thus Pierce and Benner have recently reported [2] desorption isotherms for a glass fibre board with a density of  $101 \text{ kg m}^{-3}$  and the general

characteristics of such a family of isotherms are shown in Figure 2. The objective of the work reported in this paper was to determine the sensitivity of the heat and moisture fluxes to the way the isotherms are represented.

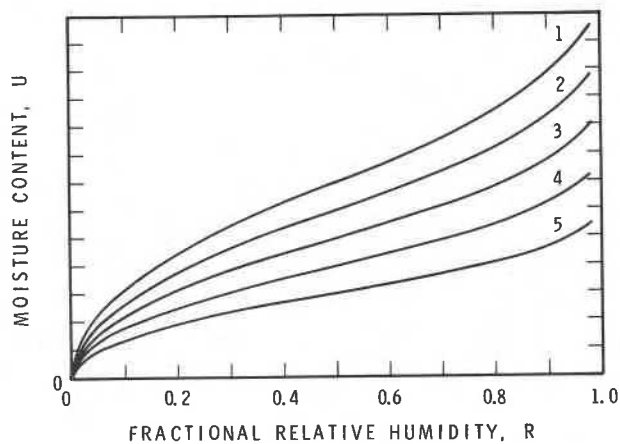


Fig 2 General characteristics of a family of adsorption isotherms for a hygroscopic material; the isotherms 1 to 5 are at temperatures  $T_1$ ,  $T_2$ ,  $T_3$ ,  $T_4$  and  $T_5$  respectively and  $T_5 > T_4 > T_3 > T_2 > T_1$ .

The present paper introduces a mathematical model that approximates the family of adsorption (or desorption) isotherms of glass fibre insulations when the moisture content is in the hygroscopic range. Subsequently, the above model is coupled with the model reported earlier [1] and the effect of hygroscopicity of the insulation on simultaneous heat and moisture transport is determined numerically.

#### THE MATHEMATICAL MODEL FOR ADSORPTION (OR DESORPTION) ISOTHERMS

The model approximates the relationship between the experimentally measured moisture content,  $U$ , adsorbed by the insulation, the vapour pressure,  $p$ , of the water vapour in equilibrium with the adsorbed moisture and temperature,  $T$ . This model can be used to calculate any one of the three quantities if the other two are known.

For generalization, the vapour pressure  $p(T)$  is expressed as a fractional relative humidity [2],  $R$  defined by

$$R = \frac{p(T)}{p_s(T)} \quad (4)$$

and the moisture content as a dimensionless quantity,  $U_N$ , defined by

$$U_N = U / (A \cdot U_r) \quad (5)$$

In Eqn. (4)  $p_s(T)$  is the saturation vapour pressure of free water at temperature  $T$ . In Eqn. (5)  $U_r$  is the moisture content at an arbitrarily chosen temperature  $T_r$  and at  $R = 0.5$ ;  $A$  at  $T_r$  is unity while at any other temperature  $T$  it is defined by

$$A = A_1 - A_2 T \quad (6)$$

where  $A_1$  and  $A_2$  are two adjustable parameters.

The model makes use of the quantities defined above and approximates  $R$  at a given temperature  $T$  as

$$R = 0.5 U_N^{1/\gamma} \quad ; \quad 0 < U_N < 1.0 \quad (7)$$

$$R = 1.0 - 0.5(2 - U_N)^{1/\gamma} \quad ; \quad 1.0 < U_N < 2.0 \quad (8)$$

$$R = 1.0 \quad ; \quad U_N > 2.0 \quad (9)$$

where  $\gamma$  is another adjustable parameter. Thus the family of desorption curves reported by Pierce and Benner can be approximately represented by

$$T_r = 20^\circ\text{C}$$

$$U_r = 10 \text{ g kg}^{-1}$$

$$A_1 = 1.4$$

$$A_2 = 0.02 \text{ } ^\circ\text{C}^{-1} \text{ and}$$

$$\gamma = 0.1$$

The desorption isotherms corresponding to these data at 10, 20, 30 and 40°C are shown in Figure 3 along with the experimental values reported by Pierce and Benner [2].

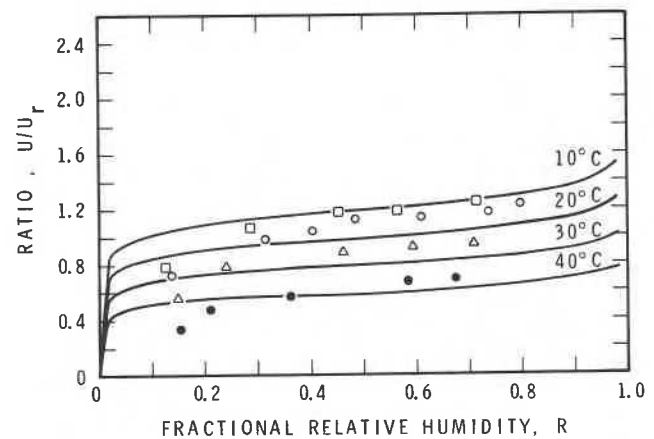


Fig 3 A family of desorption isotherms represented by the model (see text) with  $T_r = 20^\circ\text{C}$ ,  $U_r = 10 \text{ g kg}^{-1}$ ,  $\gamma = 0.1$  and  $10^\circ\text{C} > T > 40^\circ\text{C}$ ; the points on the figure represent experimental values reported by Pierce and Benner [2].

#### SOLUTION OF THE CONSERVATION EQUATIONS

For non-hygroscopic glass fibre insulation, the conservation equations were solved using the finite-difference method summarized in the Appendix of Ref. 1. The numerical procedure included two iterations; at the first stage the temperature and vapour pressure fields that correspond to each other were generated and at the second stage the thermal conductivity values were updated to match the temperature field. The temperature-vapour pressure correspondence was assumed to be completely defined by the temperature dependence of the saturation vapour pressure of free water. But in the case of an hygroscopic insulation the vapour pressure field

depends on the temperature field as well as on the moisture content field. Hence an additional iterative stage had to be introduced to generate the temperature, moisture content and vapour pressure fields simultaneously. This additional stage makes use of the model for adsorption isotherms presented in the previous section. Except for the above modification, the procedure for the numerical analysis in this paper is identical to that reported earlier [1]. The different steps of the calculation are summarized in Figure 4.

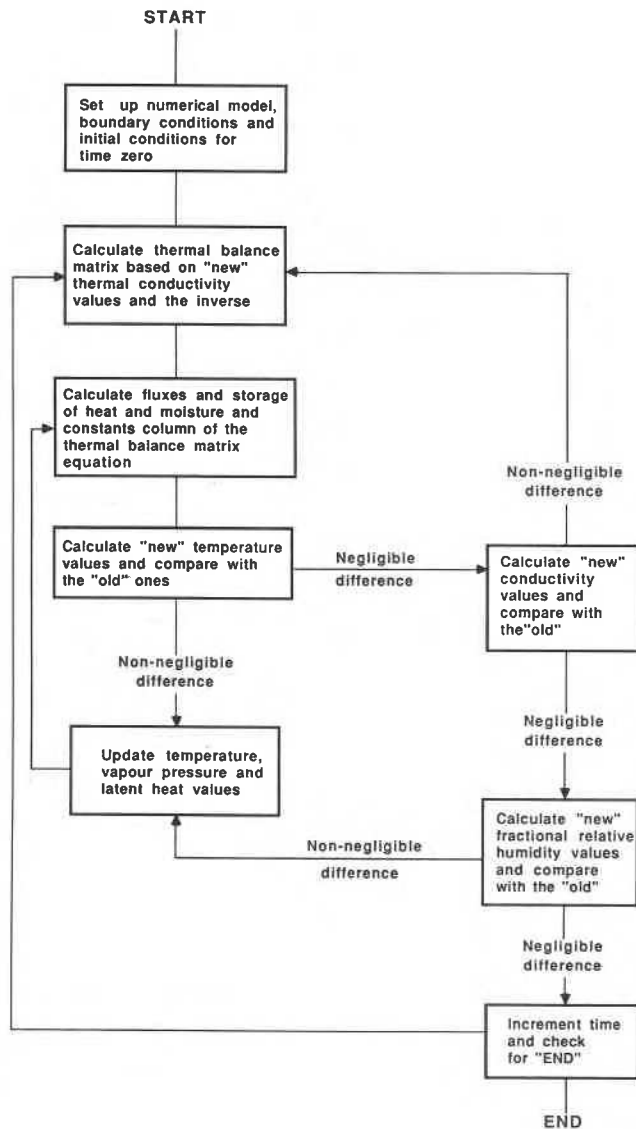


Fig 4: Calculation Flow Diagram

## THE TRANSPORT PROCESS AND THE SYSTEMS

The simultaneous heat and moisture transport process considered for the present analysis is shown schematically in Figure 5. In that process, a specified thermal gradient is established across a slab

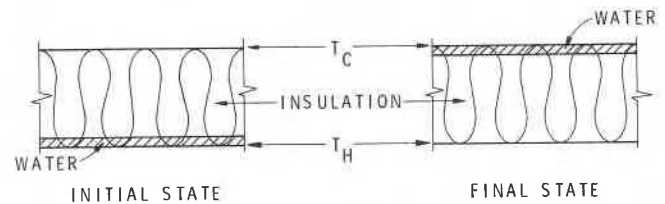


Fig. 5 Schematic representation of the transport process considered for the present analysis;  $T_H$  and  $T_C$  are respectively the hot and cold surface temperatures of the insulation.

of an insulation. Then a fixed amount of liquid water, initially present at the hot surface, is transported across the slab to the cold surface, in the presence of the thermal gradient. Four different sets of data that represent the hygroscopicity of glass fibre insulations are chosen to determine their effect on the transport process. These data sets are:

- I  $T_R = 20^\circ\text{C}$ ,  $U_R = 50 \text{ g kg}^{-1}$ ,  $A_1 = 1.4$ ,  
 $A_2 = 0.02^\circ\text{C}^{-1}$  and  $\gamma = 0.1$
- II  $T_R = 20^\circ\text{C}$ ,  $U_R = 50 \text{ g kg}^{-1}$ ,  $A_1 = 1.4$ ,  
 $A_2 = 0.02^\circ\text{C}^{-1}$  and  $\gamma = 0.5$
- III  $T_R = 20^\circ\text{C}$ ,  $U_R = 50 \text{ g kg}^{-1}$ ,  $A_1 = 1.4$ ,  
 $A_2 = 0.02^\circ\text{C}^{-1}$  and  $\gamma = 1.0$  and
- IV  $T_R = 20^\circ\text{C}$  and  $U_R = 0$

For all the four systems the empirical constants  $K_1$ ,  $K_2$ ,  $K_3$  and  $K_4$  are assumed to be the same. Thus

$$\begin{aligned}
 K_1 &= 1.16 \times 10^{-7} \text{ g m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}, \\
 K_2 &= 2.15 \times 10^{-6} \text{ g m}^{-1} \text{ s}^{-1} \text{ K}^{-1}, \\
 K_3 &= 1.004 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1} \text{ and} \\
 K_4 &= 8.6 \times 10^{-5} \text{ W m}^{-1} \text{ K}^{-2}.
 \end{aligned}$$

The heat capacity of all systems in the dry state was assumed to be  $795 \text{ J K}^{-1} \text{ kg}^{-1}$ , the thickness  $56 \text{ mm}$  and the density  $117.4 \text{ kg m}^{-3}$ . Initially the sample was assumed to be at a uniform temperature of  $12.58^\circ\text{C}$  and an adsorbed moisture content corresponding to  $100\% \text{ RH}$  at that temperature.  $200 \text{ g m}^{-2}$  of liquid water was assumed to be present at one surface. At time zero the temperature of this wet surface was raised to  $47.45^\circ\text{C}$  and kept at this temperature thereafter. These initial conditions were used so that the calculated values of temperature and surface heat flux could be compared with the corresponding quantities that had been determined experimentally.

The results from the numerical analysis on the four systems, relevant to the present discussion, are summarized in Figures 6 and 7. Figure 6 contains information on the variation of temperature with time, at 26 mm into each system from the hot surface and Figure 7 on the history of the average of the heat fluxes at the hot and cold surfaces of each system.

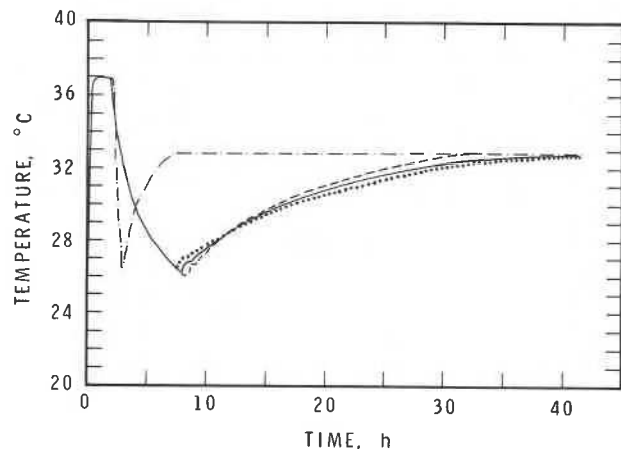


Fig. 6 Results of the mathematical analysis showing variation of temperature at 26 mm into the four systems from the hot surface, during the transport process; the systems are represented by the curves as follows:

— I  
 - - - II  
 ..... III  
 - . - IV

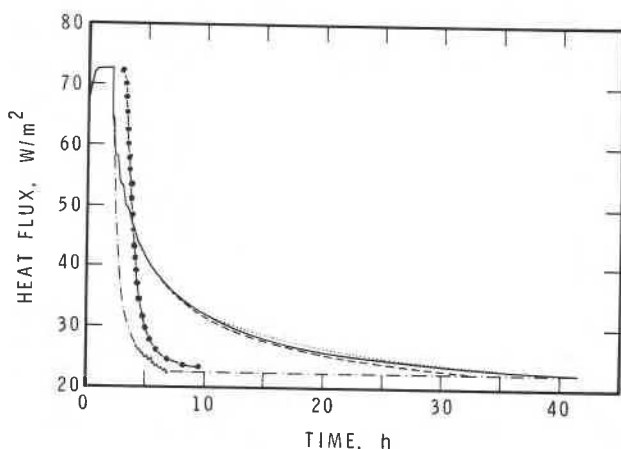


Fig. 7 Results of the mathematical analysis showing the history of heat flux during the transport process through the four systems; the systems are represented by the curves as follows:

— I  
 - - - II  
 ..... III  
 - . - IV

The part of a curve, ●—●, from an experimental measurement is also plotted for comparison (see text).

Both the Figures 6 and 7 clearly establish the difference between the non-hygroscopic (System IV) and the hygroscopic (Systems I, II and III) glass fibre insulations, with respect to the variation of the quantities namely temperature and heat flux. The above difference can be attributed entirely to a delay in the drying out of successive layers from the hot to cold surfaces, caused by the hygroscopicity.

Figure 7 also includes the results of an experimental investigation on a high density glass fibre board (density =  $117.4 \text{ kg m}^{-3}$ , thickness = 55.4 mm,  $T_H = 47.45^\circ\text{C}$  and  $T_C = 12.58^\circ\text{C}$ ) during the transient state between the initial and final steady states [1]. This experimental curve, though arbitrarily displaced on the time coordinate (the amount of moisture involved was  $\approx 300 \text{ g m}^{-2}$  in comparison with  $200 \text{ g m}^{-2}$  used for the numerical analysis) is very similar to the curve calculated for the non-hygroscopic system but quite different from those for the hygroscopic systems. The experimental results thus indicate that the hygroscopicity of this glass fibre board has little influence on the heat and moisture transport through it.

The above figures also show that there is hardly any difference between the three hygroscopic systems considered. This indicates that an accurate knowledge on the adsorption (or desorption) curve is not necessary for the mathematical analysis of the effect of hygroscopicity on the simultaneous heat and moisture transport through glass fibre insulation. An approximate linear relationship between  $U$  and  $p$ , as in the case of System III is adequate to bring out the effect of hygroscopicity on the transport process.

The value,  $50 \text{ g kg}^{-1}$  chosen for  $U_r$  in the present investigation is an upper limit that one may expect for currently available glass fibre insulation. For a few specimens it was found that  $U_r \approx 10 \text{ g kg}^{-1}$ . The area under each curve in Figure 7 is a measure of the total energy involved in the transport process. Though the present analysis shows clear difference between the area enclosed by the hygroscopic systems and non-hygroscopic systems, it is to be remembered that the initial moisture distribution in the hygroscopic systems is partially responsible for the higher energy transport. If this aspect is disregarded, from a practical point of view, the difference between the hygroscopic and non-hygroscopic systems is of little significance during the transport process considered here even for the extreme case of hygroscopicity. However, that need not be the case in real building situations, where there can be daily reversals of the heat and moisture fluxes. The method presented in this paper can be used to calculate the effect of daily temperature cycles on simultaneous heat and moisture transport through glass fibre insulation.

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2. Pierce, D.A. and Benner, S.M. "Thermally induced hygroscopic mass transfer in a fibrous medium". Int. J. Heat and Mass Transfer, Vol. 29, No. 11, pp 1683-1694, 1986.

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