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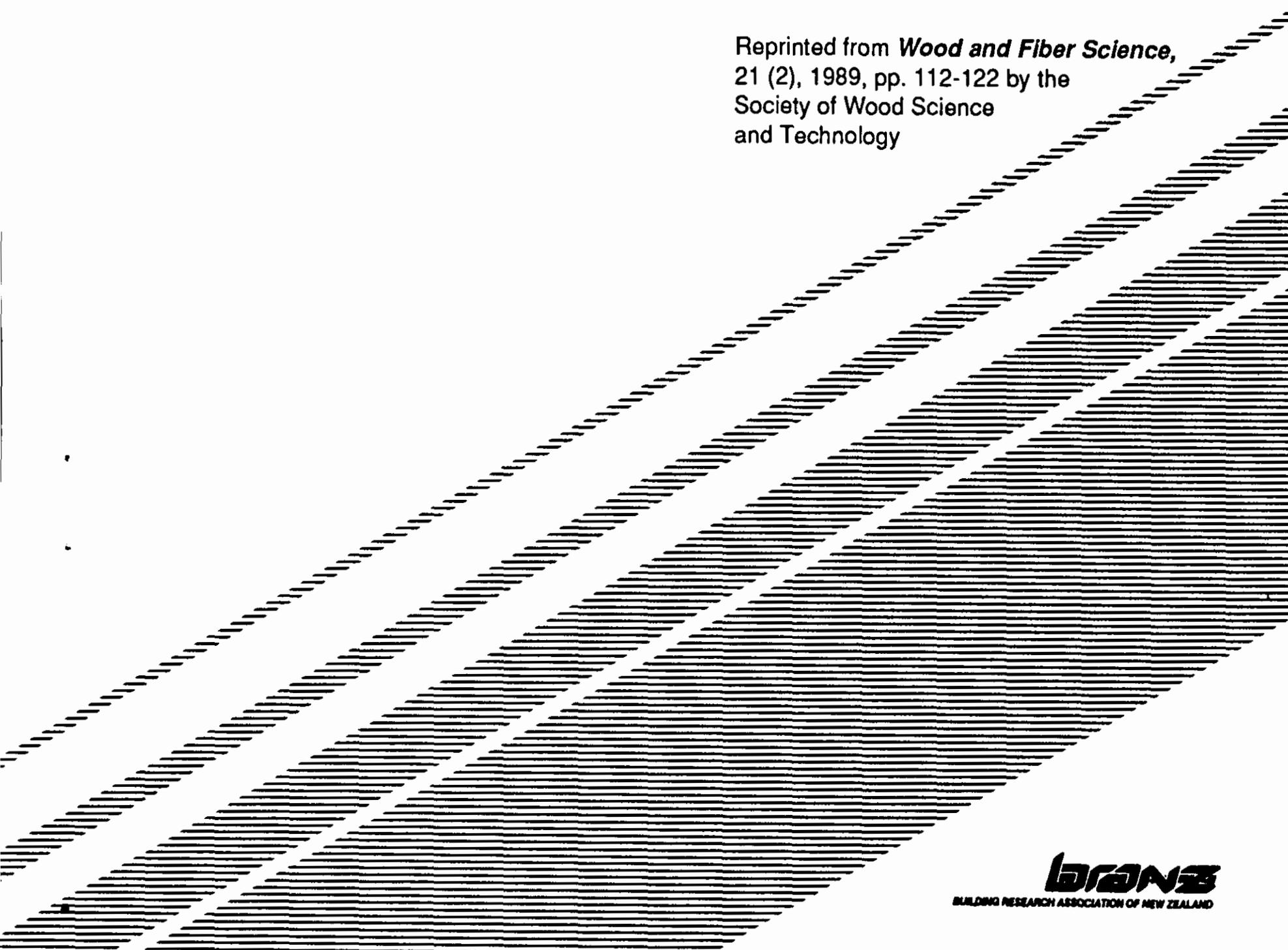
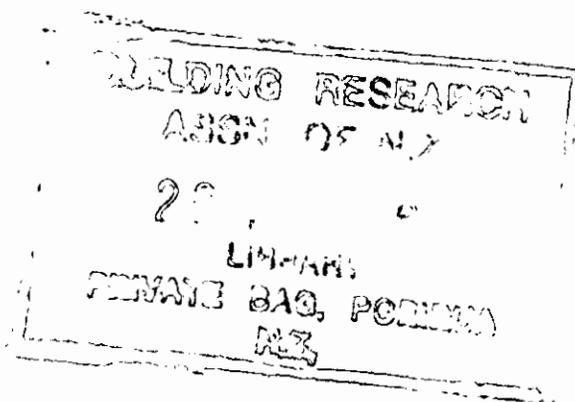
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**M. J. Cunningham,
R. B. Keey and
C. Kerdemelidis**

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ISOTHERMAL MOISTURE TRANSFER COEFFICIENTS IN *PINUS RADIATA* ABOVE THE FIBER-SATURATION POINT, USING THE MOMENT METHOD*

M. J. Cunningham

Building Research Association of New Zealand, Porirua, New Zealand

R. B. Keey and C. Kerdelidis

Department of Chemical and Process Engineering
University of Canterbury, Christchurch, New Zealand

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ABSTRACT

The "moment method" was used to measure the transfer coefficients for moisture movement above fiber-saturation in *Pinus radiata* under isothermal conditions using moisture concentration as the driving force. Measurements were made at 5 C, 17 C and 30 C, and in the longitudinal, radial and tangential directions. Results obtained lie between 1.6×10^{-10} m²/s and 1.24×10^{-7} m²/s. Despite scatter in the results, certain important trends are detectable, viz: (1) there is roughly an order of magnitude difference between the longitudinal results, and the results in the radial and tangential directions at 30 C; (2) there is an apparent increase in transfer rate as the temperature rises; (3) the transfer coefficient tends to increase with moisture content for most results.

Keywords: diffusion, *Pinus radiata*, moisture transport, water potential, transport coefficients, wood, construction moisture, fiber-saturation, capillarity, moment method.

INTRODUCTION

This work is motivated by the need to understand more deeply the moisture behavior of timber-framed structures, in particular the rate of drying of construction moisture in buildings. Construction moisture is defined as moisture present in the timber at the time that the structure has been enclosed, which is in excess of the final mean moisture content the timber achieves in situ once it has dried out. This excess moisture may be due to the timber being enclosed green, or may have been acquired from the environment (e.g. by rain) while the structure was being built. In New Zealand (and elsewhere) timber-framing is often enclosed wet, well above fiber-saturation, despite recommendations to the contrary (New Zealand Standards Association 1975). The drying of such moisture within a timber-framed structure is a complex problem involving the interaction of the timber's moisture with other properties of the structure such as its air and vapor tightness. To understand the true nature of this problem, and to understand more generally the overall moisture behavior of structures, it is necessary to explore theoretically and experimentally the moisture behavior of each part of the structure and the overall response of the system (see for example Cunningham 1987 and Cunningham 1988). This work addresses a key mechanism in this system viz, the rate of movement of moisture within timber above fiber-saturation.

There is an extensive literature on moisture movement in wood below fiber-

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saturation (see for example Siau 1984). Moisture-transfer coefficients, often taken as diffusion coefficients under vapor pressure driving forces, are widely reported, and well-defined techniques exist for their measurement. However, there is not yet a universal agreement on which physical parameters should be used to characterize the driving forces and the associated transfer coefficient for moisture movement above fiber-saturation in wood, even under isothermal conditions. Siau (1984) lists moisture content, partial water vapor pressure in equilibrium with the wood, relative humidity in equilibrium with the wood, chemical or water pressure, and spreading pressure. A transport equation can be written down for each driving force, and the resulting transfer coefficients can be connected together by use of partial differential calculus. For example, to relate the driving forces of moisture concentration c (kg m^{-3}) to water potential ψ (bar), we note that the flux F of moisture ($\text{kg m}^{-2} \text{s}^{-1}$) in each case is

$$F = -D \frac{dc}{dx}$$

$$F = -D_{\psi} \frac{d\psi}{dx}$$

where D is the transport coefficient under moisture concentration driving forces (m^2/s) and D_{ψ} is the transport coefficient under water potential driving forces ($\text{kg}/(\text{m bar s})$).

Thus

$$D_{\psi} = D \frac{\partial c}{\partial \psi}.$$

In this work, we have chosen to find the transfer coefficients for moisture movement above fiber-saturation under isothermal conditions using moisture concentration as the driving force. This choice has been made for three reasons:

(1) In modelling the transport of liquid in wood, it is moisture that is conserved. This implies that to use a driving force other than moisture concentration requires knowledge of how that driving force varies with moisture content in order to solve the transport equations. (Below fiber-saturation, for example, if one chooses to use vapor pressure as the driving force, then one must know the sorption curve of the material, connecting the moisture concentration and relative humidity and hence vapor pressure.) Although moisture concentration may not be the appropriate driving force on fundamental grounds, the use of moisture concentration as the driving force makes it unnecessary to make the additional difficult measurements to discover the relationship between the moisture concentration and the chosen driving force. (Indeed such relationships are very poorly known for wood above fiber-saturation.)

(2) Moisture concentration has an obvious physical meaning and is relatively easy to measure.

(3) Moisture concentration is the parameter of interest in the context of the problem we are addressing, namely the moisture behavior of building structures in general and the drying of construction moisture in particular.

The softwood species *Pinus radiata* was chosen since it is the most widely used framing timber in New Zealand.

THE MOMENT METHOD

Kiet reports (1973) a diffusion-cell method to measure transfer coefficients. This is a steady-state method in which one side of the wood is kept saturated while the other is exposed to a stream of drying air at constant conditions. The method does yield some preliminary data, but it provides little flexibility in choosing the moisture-content range to be investigated.

Extensive moisture-transfer coefficients are reported by Schauß (1940) for a European pine. The wood samples had been previously dried to below fiber-saturation and then rewetted under vacuum. In his tests, a substantial temperature drop (35 C) was impressed over a short (40-mm long) sample to introduce an uncertainty in the interpretation of the transport coefficient. Schauß's interpretation assumes that, at steady state, the liquid capillary motion in one direction is balanced entirely by vapor diffusion in the other; that is, the sample behaves like a heat pipe.

A number of methods were examined for finding the moisture-transfer coefficients involving the direct uptake of moisture into a partially dried sample above the fiber-saturation point, but apparently anomalous movements of moisture were observed, and these methods were discarded. More reliable data were obtained by measuring the moisture movement across the interface of joined samples at different mean moisture contents, a technique described by Gaffner and Wilhelmsen (1985) for determining moisture-transfer coefficients in porous materials. The double sample is supported at two fulcrum points, and the change in moment of the double sample is measured as the moisture redistributes itself.

In detail, a sealed sample is prepared with two uniform but different moisture contents in each half, and the initial rate of moisture transfer is observed by weighing the change in reaction at one of two fulcrum points as the moisture is transferred across the interface between the two halves. From the initial rate of moisture transfer, the transfer coefficient under mass concentration driving force can be inferred as follows:

Referring to Fig. 1 we have

$$W_1 + W_2 = W_T$$

where

W_1 , W_2 are reactions at each fulcrum (N)

W_T is the total specimen weight (N)

Therefore,

$$\frac{dW_1}{dt} = -\frac{dW_2}{dt}$$

since W_T is constant in a sealed specimen.

Taking moments about the fulcrum on the balance, we get

$$W_2 L_0 - W_T \gamma - A \int_{-\alpha}^{\beta} cx \, dx = 0$$

where

c is the moisture concentration (kg/m^3) at a distance x from the balance fulcrum.

A is the cross-sectional area of the sample (m^2).

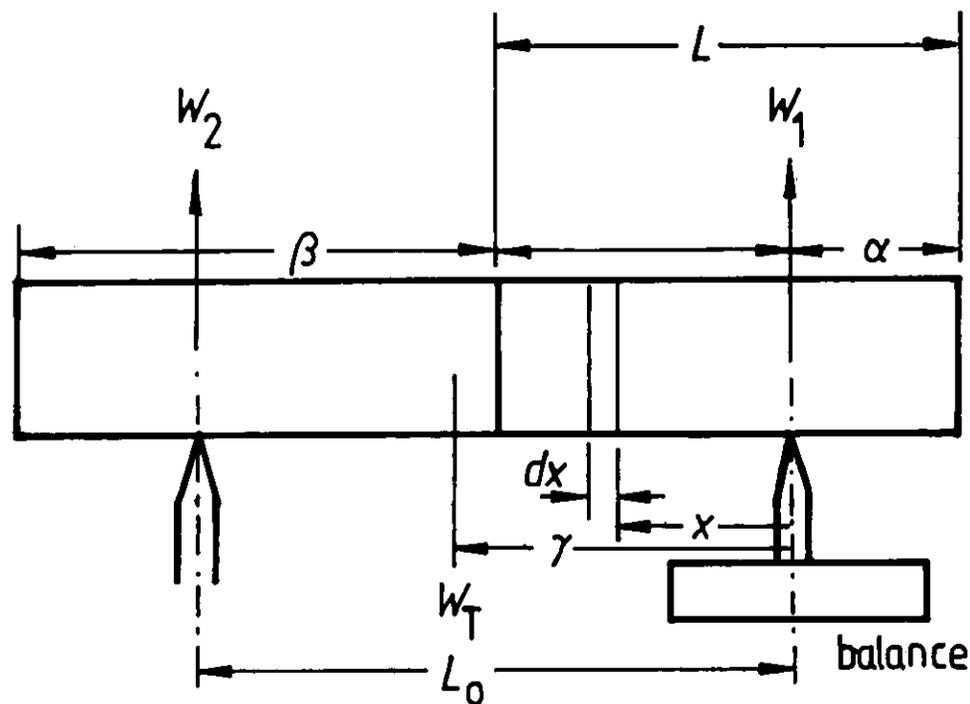


FIG. 1. Twin-supported sample (in two halves) for the moment method of determining moisture-transfer coefficients.

Differentiation with respect to t gives

$$L_0 \frac{dW_2}{dt} - A \int_{-\alpha}^{\beta} \frac{dc}{dt} x dx = 0$$

or

$$-L_0 \frac{dW_1}{dt} - A \int_{-\alpha}^{\beta} \frac{dc}{dt} x dx = 0.$$

From Fick's second law of diffusion,

$$\frac{dc}{dt} = \frac{\partial}{\partial x} \left(D \left(\frac{\partial c}{\partial x} \right) \right)$$

which yields

$$-L_0 \frac{dW_1}{dt} - A \int_{-\alpha}^{\beta} x \frac{\partial}{\partial x} \left(D \left(\frac{\partial c}{\partial x} \right) \right) dx = 0.$$

Integrating by parts

$$-L_0 \frac{dW_1}{dt} - A \left(\beta D \frac{\partial c}{\partial x} \Big|_{\beta} + \alpha D \frac{\partial c}{\partial x} \Big|_{-\alpha} - D(c_{\beta} - c_{-\alpha}) \right) = 0.$$

Assuming D to be constant over the range of interest, then

$$D = \frac{L_0 \frac{dW_1}{dt}}{A \left(c_{\beta} - c_{-\alpha} - \beta \frac{\partial c}{\partial x} \Big|_{\beta} - \alpha \frac{\partial c}{\partial x} \Big|_{-\alpha} \right)}.$$

If it is assumed that a uniform moisture concentration of c_1 and c_2 exists in the right- and left-hand pieces of the material respectively, then

$$W_1 = c_1 LA = c_{-\alpha} LA$$

and

$$W_2 = c_2 LA = c_{\beta} LA.$$

Since the sample is sealed at each end, and the initial moisture content is assumed uniform in each piece, then

$$\left. \frac{\partial c}{\partial x} \right|_{-\alpha} = \left. \frac{\partial c}{\partial x} \right|_{\beta} = 0$$

Hence, we have

$$D = \frac{L_0 \frac{dW_1}{dt}}{A(W_2/LA - W_1/LA)}$$

$$= \frac{L_0 L \frac{dW_1}{dt}}{W_2 - W_1}.$$

EXPERIMENTAL DETAILS

Samples were prepared from green timber, which was slowly dried to the estimated condition for the required moisture content, then sealed and allowed to reach moisture uniformity. Since the moment method described above can also be used to observe moisture transfer within single specimens, extensive experimentation was undertaken to find the best method of preparing samples with uniform moisture content.

The preferred method of sample preparation was as follows. The sample was dried very slowly under humid conditions, sealed in both plastic film and metal foil and held in an oven for about 10 days at 50 C. The prepared samples were then placed in a temperature-controlled chamber at the required experimental temperature and stored until needed.

Each run involved the use of two specimens, one at nominally 20% moisture content and another at a much higher moisture content. As a sensitive test to determine if these two samples to be used for a run were internally at equilibrium, i.e., no further moisture distribution was taking place within each sample, the following procedure was followed. Prior to the run, the two samples, both remaining sealed, were placed in an enclosed metal tube with floating ends. The tube was then placed on the two fulcrums as illustrated in Fig. 1 and, if no movement of moisture was detected over a 2-hour period as indicated by a change in balance reading, it was assumed that the two samples were uniformly moist.

The two samples were quickly removed from the tube, the two ends opened and pressed together, resealed, and then placed back in the tube. The wing nuts on the tube were tightened to a torque of 0.04 Nm and the tube was positioned on the fulcrums. The apparatus itself was enclosed in a temperature-controlled insulated container with refrigeration and heating. After about 5 to 10 minutes, the balance was zeroed and the recording started of the moment increase with time as measured by the balance. This induction period was allowed as large

fluctuations in the balance readings would appear initially. It was suspected that one cause was the condensation of moisture that might have taken place until the sample reached temperature equilibrium again. This initial period, however, was very short compared with the duration of a run, which was 24 hours or more.

To obtain a sample close to a required moisture content, a piece was cut off each green sample and oven-dried to establish a mean dry-wood density from which we could compute the end weight of the remaining piece of wood to reach the required uniform moisture content. An overweight allowance was made to compensate for the subsequent moisture loss during sample handling. Since there was a significant variability in wood density within the sample, this forecast of the moisture content was only approximate, the true moisture content being only established by oven-drying at the end of each run.

About one run in five showed an increasingly negative reaction reading for up to 4 hours or more, as though moisture were moving from the drier to the wetter sample. However, there was always a weight loss in the wetter sample, a weight gain in the drier one, and a negligible overall weight loss. Thus, in these instances, the moment method appeared to reflect local moisture movements caused by initial temperature gradients, particularly when the samples were being held at temperatures below ambient. These moment runs were discarded, and are not reported by us here.

The sample size used with longitudinally cut specimens was 22 mm × 22 mm × 145 mm length. Radially and tangentially cut specimens had a fractionally larger cross-section (25 mm × 25 mm), but were of the same length (145 mm).

The change in reaction, being never more than 0.6 g wt and often much less, was sufficiently small to imply that there was little change in mean moisture content over the whole run.

RESULTS

The set of experiments outlined below was carried out to determine the magnitude of the moisture-transfer coefficient (D) in three directions and its variation with temperature over the normal range of temperatures to be found in building structures in a temperate climate. Experiments were undertaken at the following conditions:

Directions: longitudinal, radial, tangential. Temperatures: 5 C, 17 C, 30 C. Nominal concentrations (wetter sample): 35, 40, 60, 80, 100% moisture (dry basis).

Two series of runs were undertaken. In the first series, a balance of 0.01 g precision was used. Three runs were undertaken at each condition of temperature and nominal concentration, in the longitudinal and radial directions. Of 90 runs, 8 were abandoned. In the second series, a balance of 0.001 g precision was used. Three runs were undertaken at each condition of temperature and nominal concentration, in the tangential direction and a repeat of the radial direction. In this series of 90 runs, 16 were abandoned.

An example of the reaction-time curves from each of the sets of experiments is shown in Fig. 2. A straight line was fitted by eye on each curve over the initial linear portion to obtain the gradient that is directly proportional to the coefficient D . There is considerable error in drawing these curves in the slower runs in the first set, owing to the relative insensitivity of the balance used. The enhanced sensitivity of the balance used in the second set was an attempt to reduce such

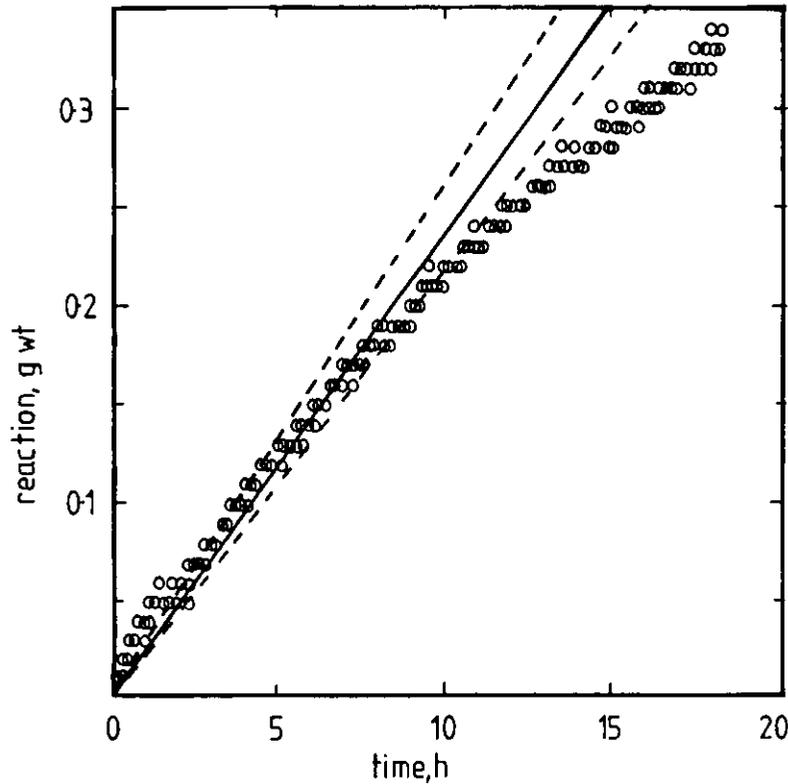


FIG. 2. Reaction-time graph for moisture movement with a nominal 60%–20% moisture-content (dry basis) driving force. Longitudinal direction (set 1).

errors. The possible errors are indicated by the extreme positions the lines may take. The variations in the estimated mean error limits are given in Table 1.

In the exceptional cases of very slow runs, when only two values of weight appear throughout the experiment, a time-weighted estimate was used to calculate the probable reaction at the end of the run. The error in these cases is not known.

The values of the moisture-transfer coefficient D were evaluated as

$$D = L_0LS/\Delta W$$

where S is the initial slope of the reaction-time graph and ΔW is the difference in weights of the two samples. In all runs, the dimensions L_0 and L were held

TABLE 1. Variation in the estimated errors for each run.

	Direction	Temperature	Estimated error range	Average estimated error
Set 1	longitudinal	30 C	7%–34%	18%
		17 C	6%–156%	33%
		5 C	3%–162%	35%
	radial	30 C	9%–52%	22%
		17 C	10%–73%	34%
		5 C	10%–233%*	49%*
Set 2	radial	30 C	28%–83%	57%
		17 C	6%–96%	48%
		5 C	21%–125%	76%
	tangential	30 C	8%–83%	40%
		17 C	13%–208%	66%
		5 C	28%–130%	54%

* One estimate with a 900% mean error omitted.

constant at 0.196 m and 0.145 m respectively. The true moisture contents, found from oven-drying tests, were used to correlate the data. The reported moisture content is the arithmetic mean value of the true moisture contents of the two samples joined in each run. Other means based on postulated relationships between the moisture-transfer coefficient and moisture content were tested without any improvement in the scatter of the data.

Graphs of the moisture-transfer coefficient for each of the transfer directions are shown in Fig. 3a–d as functions of the arithmetic mean moisture content (dry basis). Fig. 3a shows the results in the longitudinal direction, with temperature as a parameter, while Fig. 3b–d shows the results in all three directions at 30 C, 17 C and 5 C respectively.

DISCUSSION

Despite the scatter in the results, certain trends are discernible:

1. At 30 C, the longitudinal transfer coefficients are an order of magnitude greater than those in the radial and tangential directions (see Fig. 3b). Arguably, there is a tendency for the longitudinal results to be larger at 5 C (Fig. 3d); this tendency is confirmed if regression lines are fitted in each direction to these data. At 17 C (Fig. 3c) no such trend is discernible in the data.

2. Figure 3a shows a clear trend for the transfer coefficients to increase with temperature in the longitudinal direction. Similar, less pronounced trends can be found in all the rest of the data, except for one set of results, that for tangential movement at 5 C.

3. Most of the data for a particular direction at a given temperature could be regressed with a line of small positive slope as a function of moisture content, i.e. the transfer coefficients tend to increase with moisture content.

The variation of reaction W_1 is approximately exponential with time, reflecting the redistribution of moisture in the joined sample, but the initial variation is well represented by a straight line. The transfer coefficients estimated from the slope of this line have significant scatter, with averaged mean errors in the moisture-transfer coefficient or apparent moisture-diffusion coefficient ranging between 18% and 67% over the data sets. On comparing the data with those of Gaffner and Wilhelmsson (1985), it was noted that they had a similar scatter in their own results with porous lightweight concrete samples. It would be expected that timber samples would give an even greater scatter due to physiological variations of the wood.

Two observations suggest that the scatter of the results may indeed be chiefly biological in origin: first the use of a more sensitive balance did not lead to any diminution of this scatter; and second the driving force for the moisture transport is presented here as a function of the arithmetic mean of the moisture contents of the two pieces of wood making up the sample; attempts to use the logarithmic and exponential mean instead of the arithmetic mean to describe the “mean” moisture content gave no noticeable reduction in data scatter.

While it was possible to cut the longitudinal samples accurately, it was not possible to excise purely radial and tangential sections from the available log. In particular, there was always a small but significant radial component in the tangential cut. On the other hand, the data show no significant difference in behavior between radially and tangentially cut samples, which suggests the sectioning bias

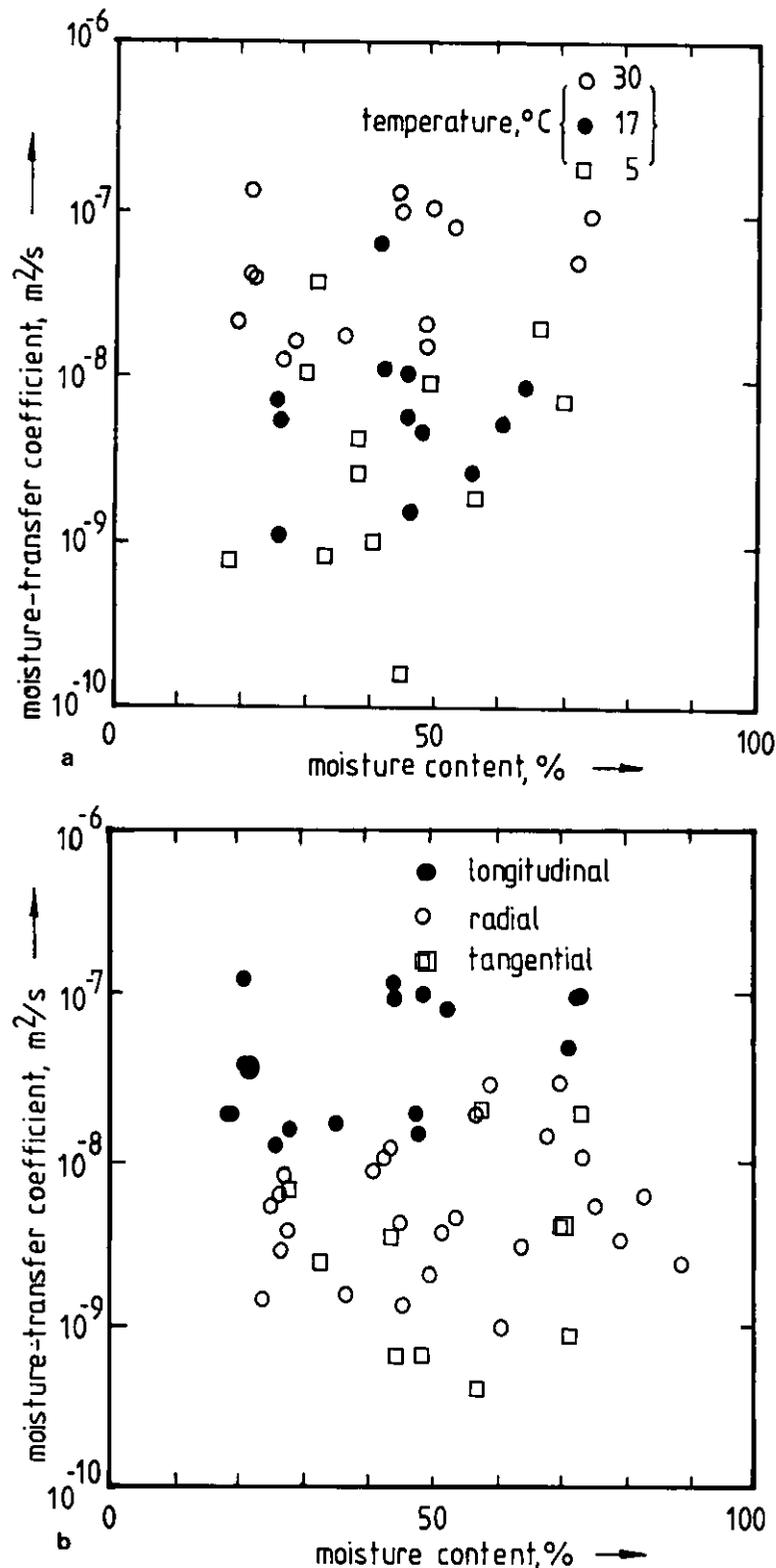
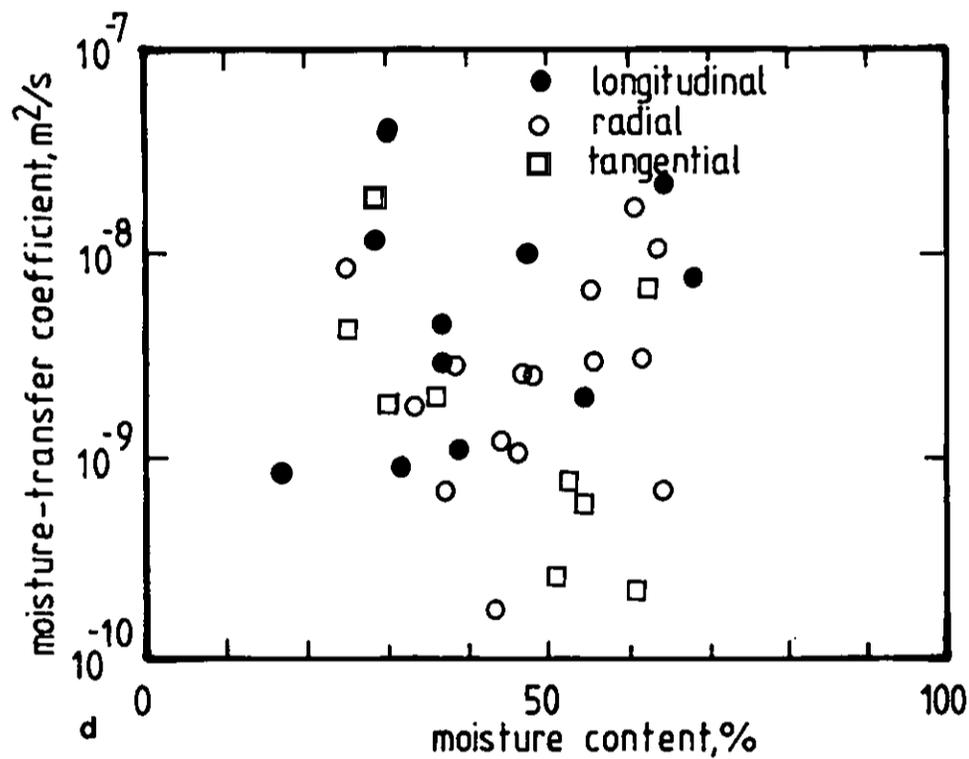
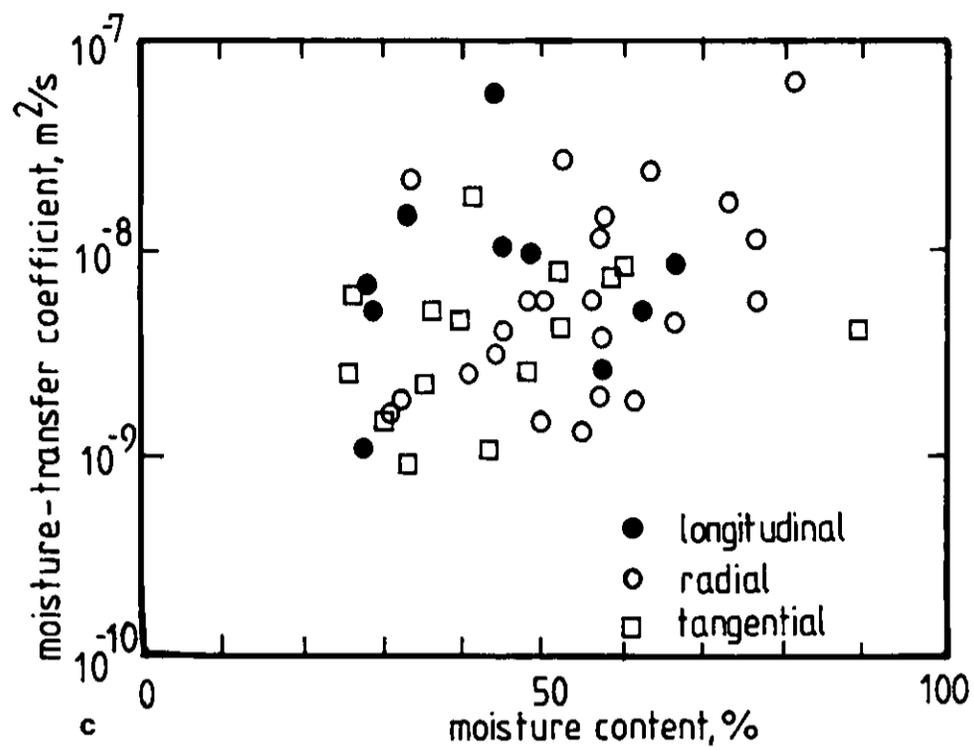


FIG. 3. Moisture-transfer coefficients as a function of direction, moisture content and temperature. (a) Longitudinal transfer coefficients at 30 C, 17 C, and 5 C; (b) Transfer coefficients at 30 C; (c) Transfer coefficients at 17 C; (d) Transfer coefficients at 5 C.

is of no consequence within the accuracy of our experiments, whereas the movement in the longitudinal direction is an order of magnitude greater than that in the radial and tangential directions in the runs undertaken at 30 C.

The results taken at temperatures substantially below the ambient temperature



in the laboratory (that is, the runs undertaken at 5 C) are believed to be less reliable than the others due to greater initial disturbances. In all data sets, the runs at 5 C exhibited more scatter than those at 30 C. In the lower-temperature experiments, some dew condensed on the metal of the sample container as the apparatus was being set up for a run, and there was a concomitant temperature disturbance. The excess moisture was removed during this start-up period. After about 10 minutes, these disturbances were no longer observed.

Kiet (1973) obtained a value of the moisture-diffusion coefficient of 1.8×10^{-9} m²/s at a temperature of 30 C with a moisture content (dry basis) of 120% with *Pinus radiata* at a dry density of 525 kg/m³. This value is close to one estimated from a regressed line for transport in the radial direction at 30 C. The coefficients estimated by Ashworth (1977), based on Stamm's model (1946) of softwood timber, are of similar order to those reported here. Our data, however, are too scattered to corroborate the appearance of a minimum in the moisture-transfer coefficient above the fiber-saturation point, which was predicted by Ashworth.

CONCLUSIONS

The use of the moment method to find the transfer coefficients for moisture movement under moisture concentration driving forces above fiber-saturation under isothermal conditions in *Pinus radiata* has been described. Although the results show considerable scatter, certain trends do show up in the data. They are:

1. There is roughly an order of magnitude difference between the longitudinal results, and the results in the radial and tangential directions at 30 C.
2. There is an apparent increase in transfer rate as the temperature rises.
3. The transfer coefficient tends to increase with moisture content.

Although it is not the intention of this work to explore the moisture transport properties of timber in the ranges of temperature of interest for kiln drying, nevertheless the moment method technique used here will be of interest in that field and should be usable to extend the results to the much higher temperatures of current commercial interest.

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