# EXPERIMENTS ON NONISOTHERMAL MOISTURE MOVEMENT IN WOOD

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## ABSTRACT

Four experiments were conducted to measure the flux of water vapor through white pine wood transverse to the grain with an applied thermal gradient of 7 C/cm. The results were compared with a theoretical equation based on activation theory, in which both moisture-content and thermal gradients are taken into account. A reasonable agreement was found between the experimental and theoretical fluxes. The results could not be explained either on the basis of a moisture-content or partial-pressure gradient taken separately.

*Keywords:* Moisture movement, diffusion, activation energy.

## INTRODUCTION

Skaar and Siau (1981) have derived an equation to describe steady-state bound-water diffusion in wood in the transverse direction in response to two gradients: that due to moisture-content difference or water potential and that due to temperature difference. The derivation is based upon activation theory because Stamm (1964) and Choong (1963) have found an inverse linear relationship between the transverse bound-water diffusion coefficient of wood and the reciprocal of the Kelvin temperature in agreement with the Arrhenius equation. Choong (1962) has also found that the activation energy for transverse bound-water diffusion decreases as wood moisture content increases. The equation derived by Skaar and Siau may be expressed in the form of Fick's first law with an added term for thermal diffusion.

$$J = -\frac{K_M M}{(RT - M\,\partial E_b/\partial M)}\left[\frac{E_b}{T}\frac{dT}{dX} + \left(\frac{RT - M\,\partial E_b/\partial M}{M}\right)\frac{dM}{dX}\right] \qquad (1)$$

where $J$ = flux, $K_M$ = bound-water conductivity coefficient based upon a moisture-content gradient, $M$ = moisture content, $R$ = universal gas constant, $E_b$ = activation energy for transverse bound-water diffusion, $T$ = Kelvin temperature, $X$ = distance in the direction of flux movement. The value of $E_b$ has been measured by Stamm (1964) and Choong (1963) as 8,500 cal/mol at $M = 10\%$. Stamm (1959) measured the bound-water diffusion coefficient of cell-wall substance at 300 K at various moisture contents up to 28%. When his results were fitted to the Arrhenius equation, assuming $E_b = 8{,}500$ cal/mol at $M = 10\%$, to determine the relationship between $E_b$ and $M$, it was found that $E_b$ decreases approximately linearly with $M$ between values of 5% and 25%.

$$E_b = 9{,}200 - 70M \qquad (2)$$

with $E_b$ expressed in cal/mol and $M$ in %. Then by substitution,

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$$J = -\frac{K_MM}{RT + 70M}\left[\left(\frac{9{,}200 - 70M}{T}\right)\frac{dT}{dX} + \left(\frac{RT + 70M}{M}\right)\frac{dM}{dX}\right]. \tag{3}$$

Equation (3) reduces to Fick's first law when the temperature gradient is zero. It is also clear that the thermal term is significant even with relatively low temperature gradients.

The coefficient, $K_M$, may be expressed in terms of the transverse bound-water diffusion coefficient, $D_T$, by conversion of the moisture-content gradient to a basis of moisture concentration in grams of moisture per cubic centimeter of wood.

$$K_M = \frac{D_TG}{100\rho_\omega} \tag{4}$$

where G = specific gravity of wood, $\rho_\omega$ = normal density of water = 1 g/cm$^3$.

Siau (1971) has derived a model to calculate the transverse bound-water diffusion coefficient of wood from Stamm's value for cell-wall substance in which all of the resistance is assumed to be in the cross walls of the cells.

$$D_T = \frac{D_{BT}}{(1 - V_a)(1 - \sqrt{V_a})} \tag{5}$$

where $D_{BT}$ = transverse bound-water diffusion coefficient of cell-wall substance, $V_a$ = porosity of wood.

Stamm's (1959, 1960) values for the cell wall may be fitted to an Arrhenius-type equation that may be written as:

$$D_{BT} = 0.07\ \exp\left[\frac{70M - 9{,}200}{RT}\right]. \tag{6}$$

The decrease in activation energy with increase in moisture content indicated in Eqs. (2), (3), and (6) may be attributed to a decreased bonding energy of water molecules to sorption sites. At or above the fiber saturation point, its value should be essentially zero.

## EXPERIMENTAL PROCEDURE

The experimental set-up is illustrated in Fig. 1. An Aminco conditioning cabinet was fitted with a special wooden door with a thickness of 5 cm, equal to that of the circular test specimen. The specimen had a diameter of 14 cm and was made from eastern white pine (*Pinus strobus* L.). The specimen was machined to fit inside a rigid 6-inch OD plastic tubing which, in turn, was fitted inside a circular hole in the wooden door. Sealing between the specimen and the tubing and between the tubing and the door was accomplished with Sears Weatherstrip and Calking Cord. The edges of the specimen were sealed with epoxy cement to prevent moisture loss. The material from which the specimen was machined was flat-sawn, resulting in flux movement essentially in the radial direction. Furthermore, it was originally kiln-dried and was stored in an uncontrolled room at

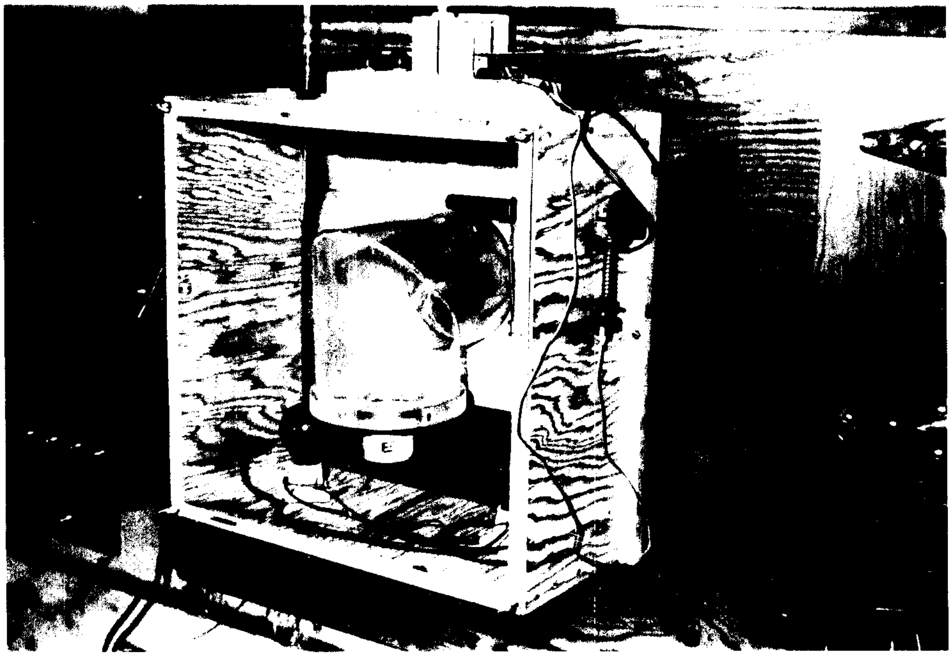

FIG. 1. Experimental set-up. The test specimen is indicated by A. The removable diffusion cup containing a reservoir of distilled water is indicated by E. The enclosure is covered in front by a polymethylmethacrylate sheet.

approximately 30% relative humidity, resulting in an equilibrium moisture content of 6 to 7%. A removable diffusion cup containing distilled water was mounted below the tubing and it was partially filled with distilled water to control the vapor pressure on the cool, outside surface of the wood specimen. The entire specimen-plastic-tube assembly was located inside an enclosure equipped with a heating element and temperature sensor to permit accurate temperature control.

Four experiments were conducted with varying conditions. The cool surface of the specimen was always maintained at 35 C with the diffusion cup at 28.5 C. This produced a relative humidity (RH) of 69% and an equilibrium moisture content (EMC) of 12%, based on the sorption isotherm data in the Wood Handbook (Anonymous 1955). The diffusion cup was assumed to be at the dew-point temperature. The warm side of the specimen inside the cabinet was maintained at 70 C for all tests (assumed to be the dry-bulb temperature) with wet-bulb temperatures of 60 C, 55 C, 50 C, and 30 C for the four experiments, corresponding to relative humidities of 61%, 47%, 35%, and 8%, and EMC's of 8.5%, 6.4%, 4.9%, and 1.5% respectively. Temperatures were measured with thermocouples. When conditions were changed, one or two weeks were required to achieve equilibrium to the new conditions in the specimen. The duration of each experiment was approximately two weeks after equilibrium was established. The diffusion cup was periodically removed, covered, and weighed to monitor the flux through the specimen. Special care was required to prevent condensation inside the plastic tube.

TABLE 1. *Summary of experimental and theoretical fluxes.**

| Equilibrium moisture contents | | Experimental flux g/cm² s × 10⁹ | Theoretical flux g/cm² s × 10⁹ |
|---|---|---|---|
| Cool side | Warm side | | |
| 35 C | 70 C | | |
| 12% | 8.5% | −4.1 | −5.7 |
| 12% | 6.4% | 0.0 | −1.4 |
| 12% | 4.9% | −3.4 | +1.5 |
| 12% | 1.5% | +19.0 | +6.4 |

* A positive flux indicates flow from the cool to the warm side of the specimen.

Equation (3) was adapted to the experimental conditions by the substitution of Eqs. (4), (5), and (6) and by solving the dM/dX. A value of 7 C/cm is used for dT/dX.

$$\frac{dM}{dX} = -\frac{J}{0.0039 \exp\left(\frac{70M - 9{,}200}{618 + 14X}\right)} - \frac{9{,}200M - 70M^2}{(44.1 + X)(618 + 14X + 70M)}. \qquad (7)$$

Successive solutions of Eq. (7) were obtained with a digital computer by the Euler method. The moisture-content profiles were determined for moisture contents of 8.5%, 6.4%, 4.9%, and 1.5%, which were the assumed EMC's for the warm surface of the wood. The theoretical fluxes corresponding to these moisture contents were then compared with the experimental values calculated from the diffusion cup weights. The effects of swelling due to changing moisture contents were ignored in the calculations since this effect is negligible.

## RESULTS

Figure 2 is a graphical presentation of the data. The experimental and theoretical fluxes (from Eq. 7) are revealed in Table 1. A good agreement between experimental and theoretical values is indicated for the first three experiments with EMC's of 8.5%, 6.4%, and 4.9% on the warm side. The experimental value at an EMC of 1.5% is approximately three times the theoretical value. When it is considered that the calculation of the theoretical values is based on several assumptions, the agreement may be considered to be reasonable. The most significant confirmation of the theory is the observed reversal of flux at an EMC of approximately 6% on the warm side of the specimen in close agreement with the theory.

It is clear from Table 1 that the moisture-content gradient alone cannot explain the observed results because the moisture content is always highest on the cool side which would result in positive fluxes in all four experiments.

Table 2 includes the partial vapor pressures existing on both sides of the specimen during the four experimental runs. If vapor pressure differential were the only driving force responsible for vapor movement, relatively high negative fluxes would result in the first three experiments with a small positive flux in the final run with an EMC of 1.5% on the warm side. Flux reversal would then occur at an EMC of approximately 2%, in disagreement with the experimental results where the reversal occurred at 6.4%. Therefore it can be concluded that observed

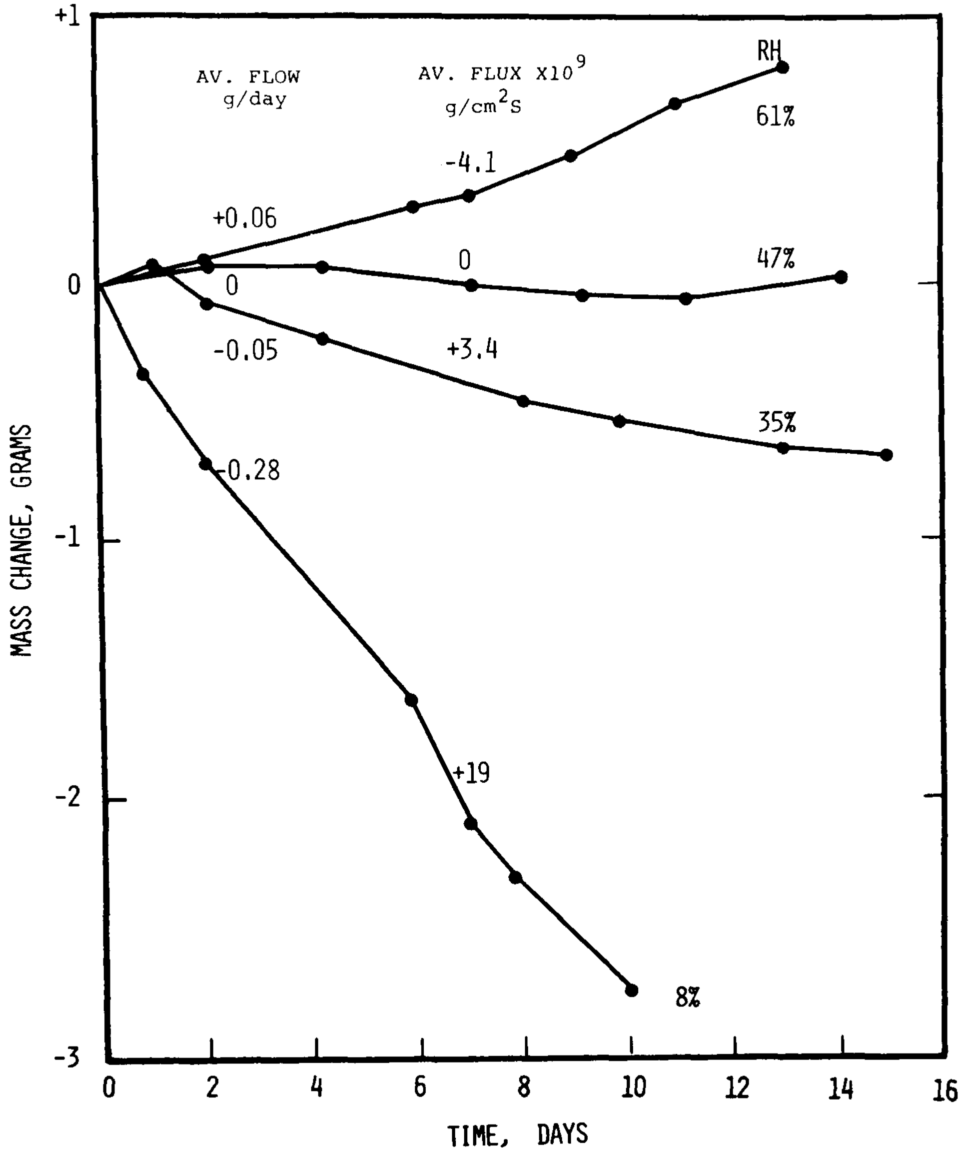

FIG. 2. Weight changes of diffusion cup vs. time for the four nonisothermal experiments. The cool side was maintained at 35 C, 69% RH. The warm side was at 70 C. Average fluxes are indicated for each of the experiments. A negative value represents transport from the cool to the warm side.

behavior cannot be explained by a moisture-content gradient alone, nor by a partial-pressure gradient alone. However if a combination of moisture-content and thermal gradient is considered in accordance with Eq. (3), a relatively good agreement is obtained between the experimental and theoretical fluxes as revealed in Table 1.

The moisture-content profiles calculated for the four experiments by the computer solution of Eq. (7) are illustrated in Fig. 3. The profiles are curvilinear in

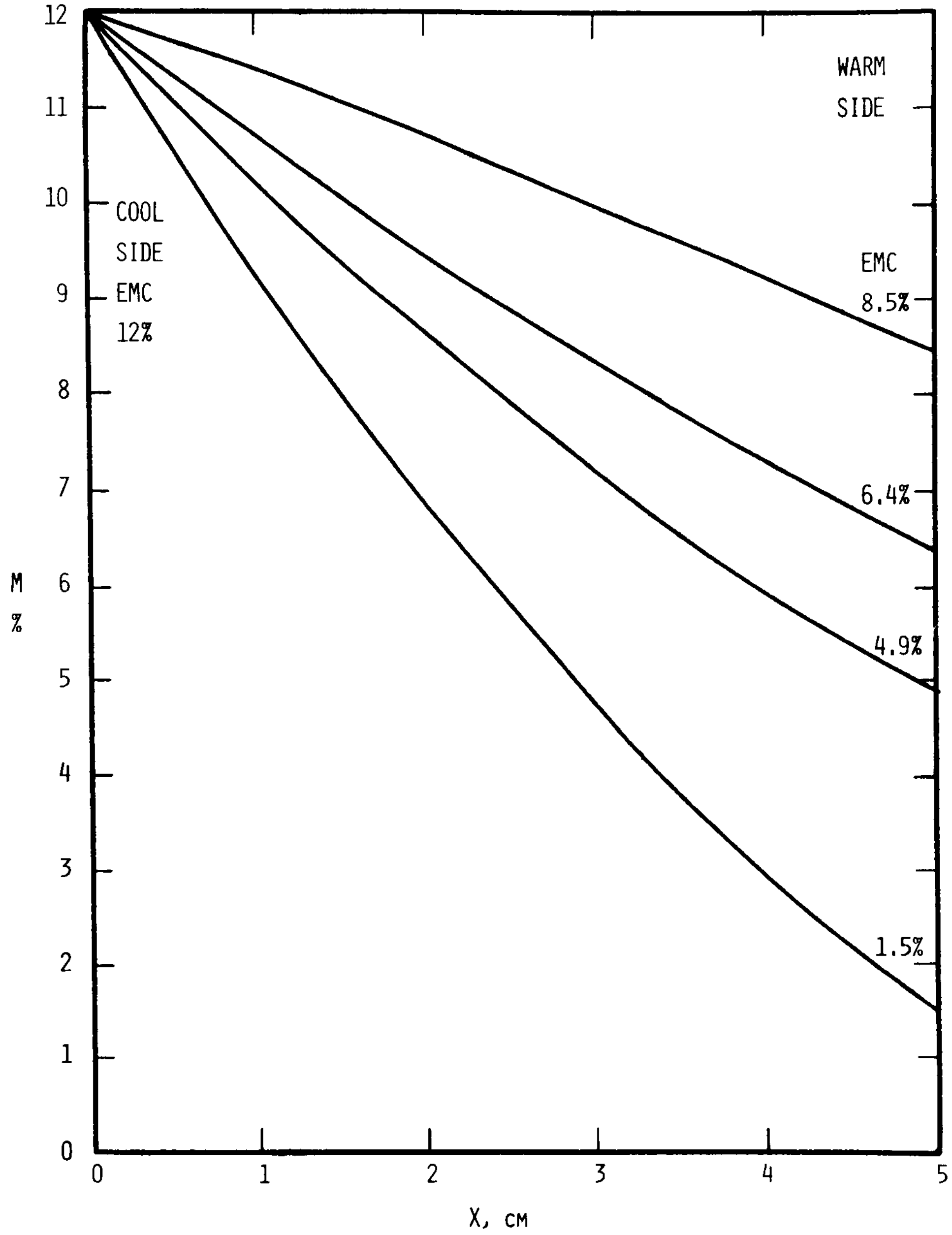

FIG. 3. Moisture-content profiles in specimen for four nonisothermal experiments calculated from Eq. (7).

all cases, being convex downward for the three experiments at low EMC on the warm side, but slightly convex upward for the experiment at an EMC of 8.5%. These calculated profiles were not confirmed experimentally.

It may be of interest to calculate the expected flux through solid wood walls of a heated building such as one constructed from logs approximately 20 cm in

TABLE 2. *Summary of partial vapor pressures on both sides of the test specimen.*

| Cool side | | Warm side | | | | |
|---|---|---|---|---|---|---|
| RH | P, cm Hg | RH | EMC | P, cm Hg | $\Delta P$ cm Hg | Experimental flux g/cm$^2$ s × $10^9$ |
| 69% | 2.9 | 61% | 8.5% | 14.3 | −11.4 | −4.1 |
| 69% | 2.9 | 47% | 6.4% | 11.0 | −8.1 | 0.0 |
| 69% | 2.9 | 35% | 4.9% | 8.2 | −5.3 | +3.4 |
| 69% | 2.9 | 8% | 1.5% | 1.9 | +1.0 | +19.0 |

thickness. If it is assumed that the inside is maintained at 20 C with an RH of 30%, while the outside is −10 C at 75% RH, the interior partial vapor pressure is 0.52 cm Hg, while that outside is 0.16 cm Hg. The vapor pressure gradient would indicate an expected flux from inside to outside. When this problem is solved by an equation similar to Eq. (7), a flux of $-7 \times 10^{-10}$ gm/cm$^2$ s is predicted from the outside to the inside. Therefore, moisture would be expected to enter the house from outside because the thermal gradient from inside out is overcome by the moisture-content gradient from the outside in.

## ACKNOWLEDGMENT

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