

## **Dependence of the water vapor diffusion coefficient of aspen (*Populus spec.*) on moisture content \***

**W. T. Simpson and J. Y. Liu, Madison WI, USA**

**Summary.** The dependence of the diffusion coefficient of water in aspen (*Populus sp.*) on moisture content over the range of 0 to 18 percent moisture content at 43°C was determined. The method requires a series of adsorption experiments and application of a numerical method for solving the diffusion equation with a moisture-content-dependent diffusion coefficient. The diffusion coefficient was found to increase exponentially with moisture content. The numerical method includes variable boundary conditions, as defined by the surface emission coefficient, so that the effect of surface equilibrium moisture content can be examined. The experimental moisture content-time curves can be predicted by the numerical method and showed an average deviation of 0.2 percent moisture content with the largest deviation being 0.7 percent moisture content. Practical implications and uses of the information derived from the numerical method are also discussed.

### **Introduction**

The ability to predict the time required for moisture content changes to occur in lumber would be useful in both drying and end use. If drying time and the effect of process and material variables on drying time could be estimated, then drying technology could be improved. Estimates of some performance characteristics of end products could be made if the time required for moisture content changes to occur in response to environmental changes can be estimated. The mathematics of diffusion offers a generalized system for predicting moisture content changes below the fiber saturation point. To use the mathematics of diffusion, it is necessary to know the diffusion coefficient and the factors that cause it to vary.

Simpson (1974) described a method for determining the moisture content dependence of the diffusion coefficient and applied it to aspen (*Populus sp.*) at 43°C over the moisture content range of 0 to 18 percent. The method consisted of a series of adsorption experiments and mathematical techniques based on procedures described by Crank and Park (1949) and Crank (1975). Unfortunately, an error was made in Simpson's application of the mathematical technique, so the relationship between the diffusion coefficient and moisture content should be disregarded.

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In this paper, we present a correct and improved application of Crank and Park's (1949) mathematical technique and reanalyze Simpson's (1974) experimental data to determine the relationship between diffusion coefficient and moisture content of aspen at 43°C. In addition, we introduce into the analysis the ability to deal with variable boundary conditions. We compare experimental moisture content-time curves and those calculated using the numerical method with the relationship found between the diffusion coefficient and moisture content. We then present illustrations of practical uses of the results.

### **Previous research**

#### *Diffusion*

Research on the dependence of the diffusion coefficient on moisture content was reviewed by Simpson (1974). In general, past research has established that the transverse diffusion coefficient of wood increases with increasing moisture content. Avramidis and Siau (1987) found an exponential increase in the radial diffusion coefficient with moisture content for western white pine. Droin-Josserand and others (1988) also found an exponential increase in the transverse diffusion coefficient with moisture content for Scots pine sapwood. Bui and others (1980) found that the radial diffusion coefficient of cottonwood increased with increasing moisture content up to about 12 percent but then decreased from 12 to 18 percent moisture content.

#### *Boundary conditions*

Diffusion is only one factor that determines how fast water moves through wood. Diffusion describes the movement of water between the interior and the surface of the wood. Internal resistance to moisture movement is characterized by the diffusion coefficient  $D$ , which depends on several factors including wood moisture content and temperature. Movement of water across the surface of the wood is also a factor in determining the rate of water adsorption or desorption. This external or surface resistance to moisture movement is characterized by the surface emission coefficient  $S$ , which depends on temperature, air velocity, and relative humidity (Rosen 1978; Avramidis, Siau 1987). Many studies that measure the diffusion coefficient did not consider surface resistance. The usual boundary condition assumption is that the surface comes to immediate moisture content equilibrium with the surrounding atmosphere. However, Choong and Skaar (1969, 1972) and Rosen (1978) showed that if surface resistance is ignored, the apparent diffusion coefficient is less than the true diffusion coefficient determined by methods that account for surface resistance.

Choong and Skaar (1969, 1972) developed a method to separate the internal and external resistances to moisture movement. The analysis they developed results in values for both  $D$  and  $S$ . Their method requires sorption rate data on specimens of two different thicknesses. Liu (1989) developed an alternative method that requires sorption rate data for only one thickness.

### Numerical method of successive approximations

#### First approximation

The method for determining the dependence of the diffusion coefficient on moisture content was developed by Crank and Park (1949) (also Crank 1975) and is based on a series of approximations. Fick's second law for a system where the diffusion coefficient is independent of moisture content can be written as

$$\partial m / \partial t = D (\partial^2 m / \partial x^2) \quad (1)$$

where  $m$  is fractional moisture content,  $t$  is time (s),  $D$  is diffusion coefficient ( $\text{cm}^2/\text{s}$ ), and  $x$  is distance in the direction of diffusion (cm).

A mathematical solution to Eq. (1) is used to make approximations to the moisture-content-dependent system. When half the total sorption has occurred, Crank and Park's method applies the solution approximated by

$$D = (0.049 a^2) / t_{0.5} \quad (2)$$

where  $a$  is thickness (cm) and  $t_{0.5}$  is time required for half the total sorption to occur (s). This solution is based on the boundary condition that the surface comes to immediate moisture content equilibrium with the surrounding atmosphere. Liu (1989) has developed an alternative equation that separates  $D$  from the surface emission coefficient  $S$ . Use of both  $D$  and  $S$  can provide numerical methods that deal with cases where the surface does not come to immediate equilibrium.

$$D = \frac{-0.165 (a/2)^2}{0.701 dt_{0.5}/dE + 2.05 t_{0.5}} \quad (3)$$

where  $E = (m - m_r)/(m_i - m_r)$  and  $m_i$  and  $m_r$  are initial and final moisture contents. The surface emission coefficient is

$$S = \frac{0.701 D}{(a/2) \{Dt/(a/2)^2 - 0.196\}} \quad (4)$$

Application of Eq. (3) to some sorption interval in a system where the diffusion coefficient depends on moisture content yields some average value of the diffusion coefficient over that moisture content range.

The integral diffusion coefficient in a moisture-content-dependent system is defined as

$$D_a = \{1/(m_r - m_i)\} \int_{m_i}^{m_r} D dm \quad (5)$$

for the moisture content range  $m_i$  to  $m_r$ . The approximation involved is that the  $D$  determined by Eqs. (2) or (3) is a reasonable approximation to  $D_a$  and thus to

$$\{1/(m_r - m_i)\} \int_{m_i}^{m_r} D dm$$

By calculating a value for  $D_a$  from Eqs. (2) or (3) for each of a series of sorption experiments where  $m_i$  is at the same fixed initial moisture content in all experiments

and  $m_f$  is the final moisture content that varies with each individual experiment with the series, we can establish a relationship between  $D_a(m_f - m_i)$  and tiating this relationship gives a first approximation to the relationship between  $D$  and moisture content, i.e.,

$$D(m) = d[D_a(m_f - m_i)]/d(m_f - m_i)$$

or, since  $m_i$  is constant in the experiment,

$$D(m) = d(D_a m_f)/dm_f . \quad (6)$$

Therefore, if the half-times of sorption from initial moisture content  $m_i$  to a number of different final moisture contents  $m_f$  are known, the approximation to  $D_a$  can be calculated from Eqs. (2) or (3). These values are then multiplied by the corresponding values of  $m_f$ , and differentiated as in Eq. (6) to give the first approximation to the value of  $D$  at the corresponding value of  $m_f$ . Differentiation can be done numerically or by choosing a mathematical function to relate  $D_a m_f$  to  $m_f$  and differentiating the function.

#### *Successive approximations*

The first approximation to  $D$  as a function of moisture content may or may not be sufficient. If it is not sufficient, the approximations can be repeated any number of times. The first approximation to  $D$  is used in a numerical solution to calculate a new series of sorption-time curves. From the half-times or these calculated curves, a new set of  $D_a$  values are determined using Eqs. (2) or (3), and further approximations are calculated in the same way as the first. The approximations continue until the calculated values of  $D_a$  approach agreement with the original experimental values of  $D_a$  tis determined by Eqs. (2) or (3). A reasonable criterion for ending the series of approximations is when the difference between the calculated values of  $D_a$  and the original experimental values is less than a specified number.

To continue the series of approximations to relate  $D$  to moisture content, the diffusion equation must be solved numerically so that the moisture content dependence of the diffusion coefficient can be incorporated. Fick's second law for a system where  $D$  depends on moisture content can be written as

$$\partial m / \partial t = \partial (D \partial m / \partial x) / \partial x . \quad (7)$$

In addition to solving Eq. (7) with a moisture-content-dependent diffusion coefficient, the solution includes resistance to surface transfer. The boundary condition involving the rate of transfer across the surface can be stated as

$$-\partial m / \partial x = (S/D) (m_e - m_s) \quad (8)$$

where  $m_s$  is the surface moisture content at time  $t$ , and  $m_e$  is the equilibrium moisture content (EMC) the surface will eventually attain.

When the ratio  $S/D$  approaches infinity, the boundary condition reverts to the common one of the surface coming to immediate equilibrium. The finite difference formulas for solving Eqs. (7) and (8) are given in the Appendix.

*Experimental procedure*

The rate of moisture adsorption was measured from an initial 0 percent moisture content to eight different final moisture contents  $m_f$ ; that is, eight separate sets of specimens. The specimens were 76 by 146 by 12.7 mm thick. The edges of the specimens were coated with three coats of heavily pigmented aluminum paint, so adsorption occurred into the 12.7-mm-thick plane (radial direction). Three replicates were included in each of the eight adsorption experiments. Each specimen was oven-dried at 104°C for 24 h before adsorption was started. The specimens were then wrapped in aluminum foil and cooled to 43°C in a desiccator over phosphorous pentoxide.

The adsorption experiments were conducted in small cabinets in which the relative humidity was controlled by saturated salt solutions; temperature was 43 °C; air velocity was 1 m/s. The average EMC of the three specimens in each set is shown in the first column of Table 1.

**Results and discussion**

The eight adsorption-time curves are shown in Fig. 1, and the time for half the adsorption to occur is marked on each curve. Table 1 lists the time for half the sorption to occur (linear interpolation on log time scale), the integral diffusion coefficient  $D_a$  as calculated from Eq. (3), and the product  $D_a m_f$ . Data in Table 1 and Fig. 1 are the average values of the three replicates, and subsequent numerical analysis is based on these values.

As previously outlined, the first approximation to  $D$  as a function of moisture content is obtained by differentiating  $D_a m_f$  with respect to  $m_f$ .  $D_a m_f$  is plotted against  $m_f$  in Fig. 2 and fitted with a function of the form

$$D_a m_f = A [\exp(B m_f) - 1] \quad (9)$$

**Table 1.** Values necessary to determine the moisture content dependence of the diffusion coefficient

Upper adsorption $m_f$ (fractional)	Adsorption half-time $t_{0.5} \times 10^{-5}$ S	Diffusion coefficient $D_a \times 10^6$ cm <sup>2</sup> s <sup>-1</sup>	Product $D_a m_f \times 10^6$ cm <sup>2</sup> s <sup>-1</sup>
0.0269	1.55	0.377	0.0101
0.0506	1.22	0.505	0.0256
0.0750	0.955	0.685	0.0513
0.0995	0.45	0.918	0.0914
0.1216	0.06	1.21	0.147
0.1365	0.13	1.47	0.201
0.1622	0.396	2.01	0.326
0.1791	0.34	2.48	0.445

<sup>a</sup> Average EMC of three specimens in each of specimens

<sup>b</sup> calculated from Eq. (3)

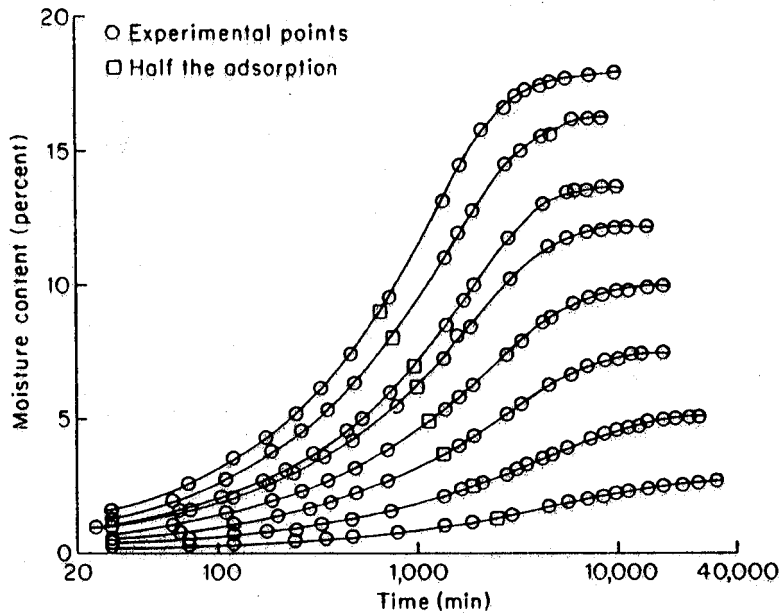


Fig. 1. Adsorption-time curves for aspen at 43°C between 0 percent moisture content and eight different final moisture contents

$$D_a m_f = 0.0142 \times 10^{-6} (\exp(20.4 m_f) - 1)$$

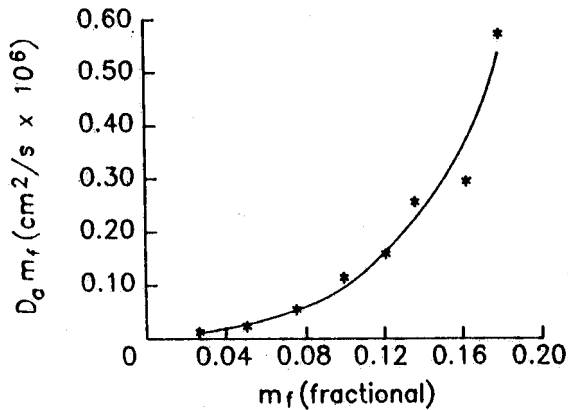


Fig. 2. Relationship between product  $D_a m_f$  and  $m_f$  of the form  $D_a m_f = A[\exp(Bm_f) - 1]$

where A and B are coefficients determined by nonlinear regression (Scarborough 1962).

From Eq. (6), the diffusion coefficient is therefore related to moisture content as follows:

$$D = A B \exp(B m) \tag{10}$$

**Table 2.** Successive approximations for determining the moisture content dependence of the diffusion coefficient and the surface emission coefficient<sup>a</sup>

Upper adsorption (fractional)	$D_a \times 10^6$ , experimental $\text{cm}^2 \text{ s}^{-1}$	$(1/m_t)$ $D \text{ dm} \times 10^6$ $\text{cm}^2 \text{ s}^{-1}$	$D \times 10^6$ $\text{cm}^2 \text{ s}^{-1}$	$D_a \times 10^6$ , calculated $\text{cm}^2 \text{ s}^{-1}$	$S \times 10^5$ $\text{cm s}^{-1}$
First approximation					
0.0269	0.371	0.377	0.544	0.513	—
0.0506	0.505	0.505	0.834	0.696	—
0.0750	0.685	0.685	1.29	0.930	—
0.0995	0.918	0.918	2.00	1.27	—
0.1216	1.21	1.21	2.97	1.73	—
0.1365	1.47	1.47	3.88	2.11	—
0.1622	2.01	2.01	6.16	3.05	—
0.1791	2.48	2.48	8.34	3.91	—
Second approximation					
0.0269	0.377	0.278	0.415	0.386	1.88
0.0506	0.505	0.373	0.620	0.517	2.01
0.0750	0.685	0.504	0.934	0.689	2.57
0.0995	0.918	0.670	1.41	0.924	3.39
0.1216	1.21	0.873	2.05	1.25	3.65
0.1365	1.41	1.05	2.63	1.52	4.12
0.1622	2.01	1.39	4.06	2.13	5.35
0.1791	2.48	1.69	5.39	2.63	6.61

<sup>a</sup> Of aspen at 43°C when  $D = AB \exp(Bm)$   
 $D = 0.264 \times 10^{-6} \exp(16.8 m)$

Equations (9) and (10) were used throughout the series of approximations because the general shape of the curves remained the same. The values of the coefficients A and B change with each approximation.

Results of two approximations are shown in Table 2. The approximations were taken through four cycles, but only two were necessary. Values of S calculated by Eq. (4) are also listed. The minimum deviation between the calculated values of  $D_a$  and the original experimental values occurred after the second approximation. For example, in the second approximation of Table 2 compare  $D_a$  calculated with  $D_a$  experimental; that is, 0.386 to 0.377, 0.517 to 0.505, etc. The final equation for the dependence of the diffusion coefficient on moisture content is

$$D = (0.264 \times 10^{-6}) \exp(16.8 m) \text{ cm}^2/\text{s}. \quad (11)$$

The test of the method is how well the experimental moisture content-time curves can be reproduced by the results of the numerical analysis. The average deviation between experimental and calculated moisture contents (fractional basis) at any experimental time is 0.003 and the largest deviation is 0.008. Examples of the comparisons are shown in Fig. 3 for the experimental conditions of  $m_t = 0.0506, 0.0995, 0.1365,$  and  $0.1791$ .

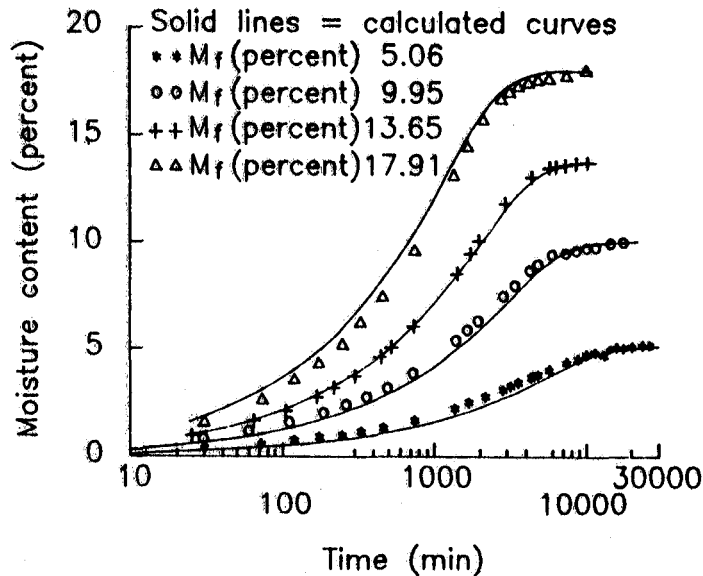


Fig. 3. Comparison of experimental and calculated moisture content-time curves

#### *Practical uses of the numerical analysis method*

Knowledge of the dependence of the diffusion coefficient on moisture content and the numerical method we developed offer a way to examine some of the practical issues involved when wood changes moisture content. Not all of the experimental background has been developed to make authoritative predictions in the examples that follow. However, they do illustrate what can be estimated when experimental data are fully developed.

#### *Moisture content gradient*

The numerical method can calculate moisture content gradients at any time during moisture content change, although experimental gradients were not measured for verification of accuracy. A series of moisture content gradients is shown in Fig. 4 when drying from a uniform initial moisture content of 18 percent to a final moisture content of 9 percent at EMC conditions of 6 percent. Specimen thickness is 29.4 mm. This type of gradient information gives insight into stress development and is a necessity for modeling of drying stresses.

The numerical method works from either a uniform or nonuniform initial moisture content. Figure 5 shows what information the model provides relative to conditioning for stress relief at the end of drying. In the example, a 29.4-mm-thick specimen is first dried from a uniform initial moisture content of 18 percent to an average of 6 percent at EMC conditions of 3 percent. These are typical conditions for the last step in hardwood drying schedules. Figure 5 shows the final moisture gradient after reaching the average moisture content of 6 percent—3.0 percent at the surface and 7.4

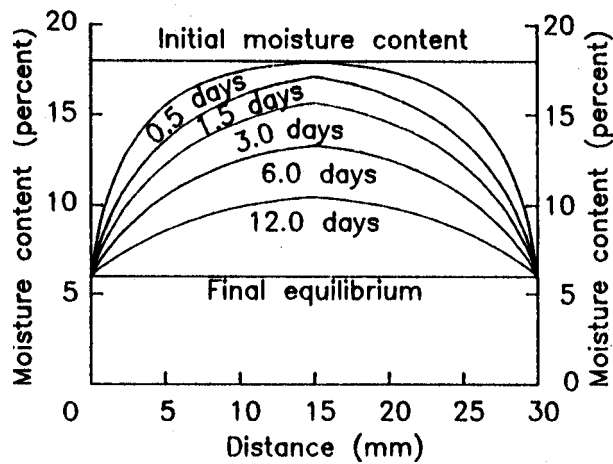


Fig. 4. Calculated moisture content gradients when drying aspen from 18 to 8 percent moisture content at EMC conditions or 6 percent at 43°C

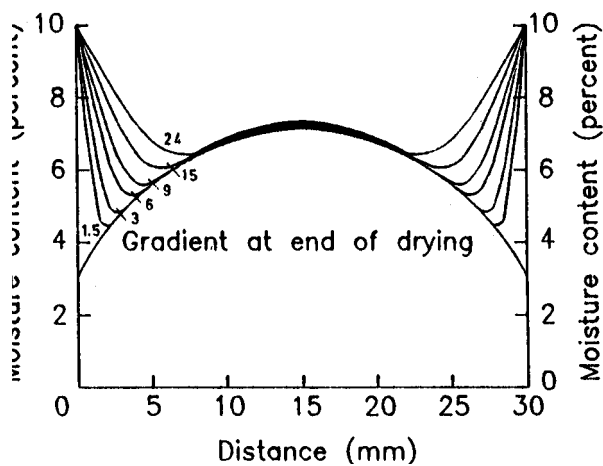


Fig. 5. Calculated moisture content gradients at 1.5, 3, 6, 9, 15, and 24 h during conditioning of aspen at EMC conditions of 10 percent at 42°C

percent at the center. Figure 5 also shows the gradients after certain times of conditioning at 10 percent EMC, illustrating the wetting of surface fibers that is necessary in stress relief. The times shown are not realistic because conditioning is usually done at about 80°C – not the 43°C used in this experiment. However, Fig. 5 does illustrate how the model can be used to gain insight into stress relief when the dependence of the diffusion coefficient on temperature is known.

*Surface resistance*

Rosen (1978) showed that the surface emission coefficient  $S$  increases with increasing air velocity. This is the common observation that drying rate increases with increasing

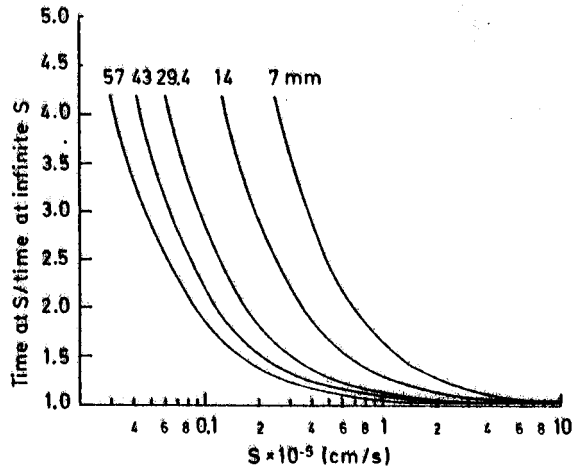


Fig. 6. The effect of the surface emission coefficient  $S$  (cm/s) on the ratio of drying time (18 to 8 percent moisture content at EMC conditions of 6 percent) at  $S$  to the drying time when  $S$  is infinite. Specimen thickness is marked on each curve

air velocity. Thus, drying time should decrease as  $S$  increases, which is shown in Fig. 6. Knowing the relationship between  $S$  and air velocity, we can make calculations that will guide us when making decisions on the amount of air velocity to use in drying. We can also estimate the importance of stagnant or slow-moving air on changes of moisture content of wood in use.

Figure 6 also shows the effect of specimen thickness on the effect of  $S$  on drying time; that is, high air velocity becomes less important as thickness increases. Figure 6 shows that drying of thin boards is slowed more by slow airflow (low  $S$ ) than thick boards. For example, at  $S = 0.1 \times 10^{-5}$  cm/s, the drying time of a 29.4-mm-thick specimen is about 2.8 times that when  $S = 10 \times 10^{-5}$  cm/s, but this ratio is only about 1.9 for a 57-mm-thick specimen.

The value of  $S$  also affects the surface moisture content and the moisture content gradient that develop during drying. Figure 7 illustrates the effect of  $S$  on the surface moisture content as a function of time. Drying conditions are from 18 percent initial moisture content at EMC conditions of 6 percent, with a 29.4-mm-thick specimen. When  $S$  is low, the surface attains its EMC at a slower rate than when  $S$  is high (that is, high air velocity). Figure 7 shows the importance of air velocity in controlling surface moisture content as a means of controlling surface checking. When surface moisture content decreases rapidly to EMC conditions, the danger of surface checking increases. Because  $S$  affects surface moisture content, it also affects the moisture content gradient during drying. This is illustrated in Fig. 8, where after 8 h of drying the moisture content gradients are compared to several different  $S$  values. The higher the value of  $S$ , the more severe the gradient.

#### *Comparison of adsorption and desorption*

One consequence of a diffusion coefficient that increases with concentration of a diffusing substance is that desorption is always lower than adsorption (Crank 1875).

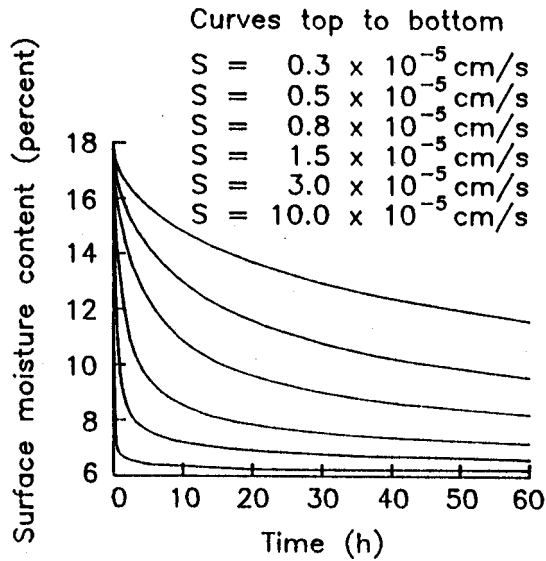


Fig. 7. The effect of the surface emission coefficient  $S$ (cm/s) on the rate that the surface approaches EMC in drying from an initial 18 percent moisture content at EMC conditions of 6 percent

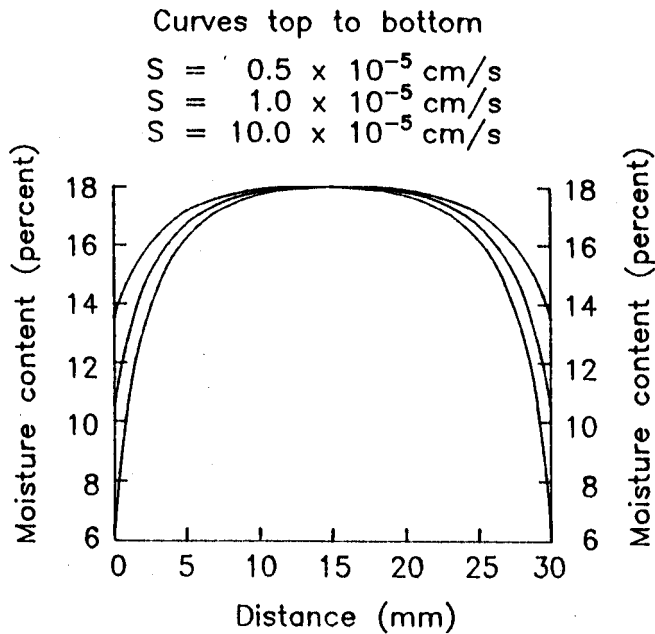
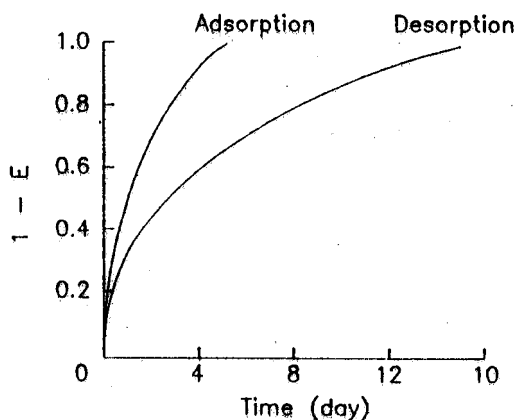


Fig. 8. The effect of the surface emission coefficient  $S$ (cm/s) on the moisture content gradients that develop during the first 8 h of drying from 18 percent moisture content at EMC conditions of 6 percent



**Fig. 9.** Comparison of adsorption or desorption rate between 8 and 16 percent moisture content at EMC conditions of 18 percent to the desorption rate between 16 and 8 percent moisture content at EMC conditions of 6 percent.  $1 - E$  is the fraction of total sorption that has occurred at any time

The final stages of desorption are especially slow because the diffusion coefficient is at its lowest level. A comparison of adsorption and desorption, as predicted by the results of the analysis, is shown in Fig. 9, where  $1 - E$  (the fraction of total sorption that has occurred at any time) is plotted as a function of time. The comparison is between adsorption from 8 to 16 percent moisture content at EMC conditions of 18 percent and desorption from 16 to 8 percent at EMC conditions of 6 percent. These conditions are comparable because both sorption intervals are the same and both EMC conditions are 2 percent more than the final moisture content. This observation has practical significance in moisture content changes of wood products in use during cyclic changes in EMC conditions. The products should have moisture contents greater than the midpoint moisture contents of the extremes of the EMCs.

### Conclusions

The diffusion coefficient  $D$  of water in aspen at  $43^{\circ}\text{C}$  was found to increase with moisture content  $m$  over the range of 0 and 18 percent in a way that can be described by an exponential function of the form  $D = A \exp(Bm)$ . A numerical method described by Crank (1975) for determining the moisture content dependence of the diffusion coefficient works well with wood below the fiber saturation point, and the results of adsorption-time experiments can be reproduced within less than 1 percent moisture content.

Additional research is needed to (1) increase our understanding of how the diffusion coefficient depends on temperature and species; (2) determine the dependence of the surface emission coefficient on relative humidity, air velocity, and temperature; and (3) extend our knowledge of the dependence of  $D$  on moisture content to higher levels of moisture content so that we can use the numerical method to estimate events in kiln drying lumber that is first air dried or predried to below the fiber saturation point.

**Appendix: Finite difference solutions**

The finite difference solutions to Eqs. (5) and (6) consist of three parts. The indexing system is  $m_{i,j}$ , where  $i$  is  $x$  (thickness) increment, and  $j$  is  $t$  (time) increment.

1. Surface moisture content  $m_0$  (Crank 1975)

$$m_{0,j+1} = m_{0,j} + 2R D_{0,j} [m_{1,j} - m_{0,j} - (S/D) \Delta x (m_{0,j} - m_e)]$$

where  $R = \Delta t / (\Delta x)^2$ .

2. Interior moisture content  $m_i$

$$m_{i,j+1} = m_{i,j} + R [D_{i+0.5,j} (m_{i+1,j} - m_{i,j}) - D_{i-0.5,j} (m_{i,j} - m_{i-1,j})]$$

3. Center moisture content  $m_n$

$$m_{n,j+1} = m_{n,j} + 2R D_{n-0.5,j} (m_{n-1,j} - m_{n,j}).$$

The criterion for accurate and stable results is based on the Euler method of solution (Myers 1971), which requires that

$$D \Delta t / (\Delta x)^2 \leq 0.5.$$

In this solution, the half-thickness was divided into 21 increments, so  $\Delta x = 0.29\text{mm}$  and  $\Delta t = 30\text{ s}$ . Thus,  $D \Delta t / (\Delta x)^2 < 0.5$ , assuming a maximum value for  $D$  of  $4 \times 10^{-6}\text{ cm}^2/\text{s}$ .

**References**

- Avramidis, S. T.; Siau, J. F. 1987: Investigation of the external and internal resistance to moisture diffusion in wood. *Wood Sci. Technol.* 21: 249–256
- Bui, X.; Choong, E. T.; Rudd, W. G. 1980: Numerical methods for solving the equation for diffusion through wood during drying. *Wood Sci.* 13: 117–121
- Choong, E. T.; Skaar, C. 1969: Separating internal and external resistance to moisture removal in wood drying. *Wood Sci.* 1: 200–202
- Choong, E. T.; Skaar, C. 1972: Diffusivity and surface emissivity in wood drying. *Wood Fiber* 4(2): 80–86
- Crank, J. 1975: *The Mathematics of Diffusion*. 2d Ed. Oxford University Press. 414 pp
- Crank, J.; Park, G. S. 1949: An evaluation of the diffusion coefficient for chloroform in polystyrene from simple absorption experiments. *Transactions Faraday Society* 45: 240–249
- Droin-Josserand, S. T.; Taverdet, J. L.; Vergnaud, J. M. 1988: Modeling the absorption and desorption of moisture by wood in an atmosphere of constant and programmed relative humidity. *Wood Sci. Technol.* 22: 299–310
- Liu, J. Y. 1989: A new method for separating diffusion coefficient and surface emission coefficient. *Wood Fiber Sci.* 21: 133–141
- Myers, G. E. 1971: *Analytical methods in conduction heat transfer*. McGraw-Hill Book Co. 508 pp
- Rosen, H. N. 1978: The influence of external resistance on moisture adsorption rates in wood. *Wood Fiber* 10: 218–228
- Scarborough, J. B. 1962: *Numerical Mathematical Analysis*. 5th Ed. The Johns Hopkins Press. 394 pp
- Simpson, W. T. 1974: Measuring dependence of diffusion coefficient of wood on moisture concentration by adsorption experiments. *Wood Fiber* 5: 299–307

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W. T. Simpson, Research Forest Products Technologist  
 J. Y. Liu, Research General Engineer  
 USDA Forest Service, Forest Products Laboratory  
 Otic Gifford Pinchot Drive  
 Madison, WI 53705-2398  
 USA