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Estimations of Moisture Profiles During Wood Drying Using an Unsteady-State Diffusion Model(Ⅱ)[*1]
- Experimental Verification for Red Oak -

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非正常 狀態의 擴散모델을 이용한 水分 傾斜의 豫測(Ⅱ)[*1]
- 實驗的 檢證 -

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요 약

包水狀態의 루부라참나무(*Quercus rubra*)시험편을 3가지 等溫條件에서 건조한 결과를 非正常狀態의 擴散모델로 추정한 결과와 비교하였다. 표면이 충분히 젖은 상태인 건조초기에는 不安定한 擴散現象이 관찰되었으나, 含水率별 건조속도의 변이를 Fick's의 확산법칙과 비교할 때 유사한 형태를 보였다. 실험에서 얻은 건조조건별 건조곡선은 확산모델의 數値解析 결과와 거의 일치하였으며, 같은 平衡含水率 조건에서 건조온도의 증가는 목재표면 보다 내부의 함수율 변화에 더 크게 영향하여 결과적으로 낮은 온도에서의 건조조건이 목재 내의 水分傾斜를 급하게 하는 것으로 밝혀졌다. 본 연구를 통해 목재 건조 중의 내부에 발생하는 수분경사를 추정하는데 비정상상태의 확산모델이 모든 함수율 범위에 걸쳐 유용하게 사용될 수 있음이 밝혀졌다.

Keywords : Unsteady state diffusion, red oak, unstable state of diffusion, moisture gradient, moisture profile

1. INTRODUCTION

During earlier research(Park & Smith, 1996), drying behavior of wood was analytically manipulated using numerical solution of the unsteady state diffusion equation. Computation of this solution, however, needs moisture transfer parameters such as surface transfer coefficient and diffusion coefficient, and practical applications of this solution also need experimental verification. In this study, red oak specimens which were fully saturated with distilled water were subjected to three different isothermal drying conditions. Moisture transfer was

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confined to one dimension in the radial direction on the tangential surface, and drying characteristics were examined. Moisture transfer parameters were also derived. By comparing experimental results with numerical solution of the diffusion equation, it is intended to justify the validity of the diffusion model for the entire moisture content range.

2. MATERIALS & METHODS

2.1 Material preparation

Northern red oak (***Quercus rubra***) was selected for this study. The specimens were reduced from 2-inch dimension squares to 1.90cm (3/4-inch) thicknesses flat sawn boards of 5cm in width and 12cm in length.

The average initial Moisture Content (MC) of the prepared specimens was about 9%. The specimens were fully saturated with distilled water under one hour's vacuum (29 in Hg) and 2 hour's pressure (100psi) treatment. The water saturated specimens were kept in plastic bags in a cold room (5℃) until use to minimize any moisture gradients. Before the drying experiments, the specimens were coated with silicon sealer on the cross ends and two edges or sides to provide one dimensional moisture flow in the radial direction on the tangential surface. The weights of silicon sealer were determined by measuring the sample weight before and after coating.

2.2 Experimental procedures

Three different drying conditions, namely 35℃, 45℃, and 55℃, and corresponding Relative Humidity(RH) conditions 46%, 49%, and 54%, respectively, were used with Aminco-temperature/humidity-controlled conditioning chambers. Each of these drying conditions essentially resulted in the same Equilibrium Moisture Content(EMC) of about 8.2%. The water saturated specimens, five for each drying condition, were then subjected under unsteady states of diffusion into one dimension of the radial direction on the tangential surface. The specimen weights were measured at convenient time intervals during drying until the weight change decreased to less than 0.05g/day. The specimens were then dried at 105℃ to determine the oven-dry weight.

2.3 Estimation of moisture transfer parameters

The surface transfer coefficients were empirically estimated from the maximum sustained drying rate on the sufficiently wet surface of specimens during the early stages of drying. As a result, three different surface transfer coefficients were obtained from 10 specimens for each drying temperature condition. The weight changes of specimens were measured at 20 minute intervals until the drying rate showed no significant decrease. By plotting the drying rate with MC, average surface transfer coefficients were determined for each drying condition.

Since the solution of unsteady state diffusion equation by Boltzmann's transformation is valid for a constant diffusion coefficient case (Crank, 1975), and represents an average value of diffusion coefficients over the whole sorption period, a differential form of the solution was employed to examine the moisture dependent diffusion

$$D = \frac{-\pi a^2 (M_i - M)}{2(M_i - M_e)^2} \frac{dM}{dt} \quad \cdots\cdots (1)$$

coefficients as follows:

Diffusion coefficients were functionally related with MC as polynomial forms by the least square method for each drying condition. The coefficient of multiple correlation squared, R^2, were employed to examine the goodness of fit of drying curves between the computational results of numerical solution of diffusion equation and the experimental results.

3. RESULTS & DISCUSSION

3.1 Drying behavior under isothermal conditions

Under isothermal drying conditions, the typical drying rate curve can be characterized for the case of permeable species by a constant drying rate period (stage I), a falling rate transition period (stage II), and a final Fickian falling rate (stage III) (Hart & Darwin, 1971). With the red oak in this research, the plots of drying rate under each drying condition showed a little different decrease pattern when compared to Hart's model. At the beginning of drying within the high MC range, namely stage I, drying rates were fluctuating near their maximum, followed by a steep decrease. The constant drying rate period was not clearly observed. The period of constant drying rate might be instantaneous or sometimes might not be exhibited for impermeable species such as red oak. Therefore the stage I of constant drying rate in the plot would be the implication of maximum possible drying rate of red oak at given environmental conditions.

The stage II period was characterized by a transition of a steep concave downward decrease from the fluctuating period of stage I. A linear decrease in hygroscopic MC range was followed in the stage III, as referred to Hart's model.

Typical Fickian diffusion exhibits a continuous concave downward shape drying rate curve with a linear decrease from FSP to EMC condition. A break in the vicinity at fiber saturation can be found in the actual drying rate curve depending on the permeability of wood. Since the drying below FSP is regarded as a true Fickian diffusion process, the deviation of actual drying rate curves from Fickian diffusion above the FSP is the result of free water movement. The stage II drying period is therefore quite useful to describe the drying behavior of wood by comparing it with Fickian diffusion as a reference level. Even though the diffusion types showed slightly different patterns, with true Fickian diffusion depending on the drying conditions, the shape of the drying rate curves in Figure 1,2 and 3 indicate that the drying behavior of red oak can be confirmed as a true diffusion process.

3.2 Fractional MC Changes

The fractional MC change, which is the amount of water remaining to be evaporated from wood, is plotted with the square root of time in Figure 4. From the solution of the diffusion equation by Boltzmann's transformation (Crank, 1975), one can predict a linear relationship, especially during the first half sorption period, between fractional MC and square root of sorption time. As long as the sorption curve is linear during the first half of sorption, the moisture dependent diffusion coefficient can be obtained from the solution of the diffusion equation (Crank, 1975). However, the curves in Figure 4 did not show linear relations, but rather a non-linear behavior during first half sorption. This phenomenon can be termed as ***unstable state diffusion***, particularly occurring during the early stage of drying. This might be related to the MC distribution at the early stage of drying such that the surface of the wood specimen is totally wet, and a constant rate of evaporation from the surface is sustained during only the short period of time until the MC of the surface decreases to FSP. However, the center of the wood specimen is still wet, and moisture gradients would not be well established continuously through the thickness of a board. According to Stamm(1964), the diffusion processes for green wood that contain an appreciable amount of free water are assumed to arise under a well developed, continuous moisture profile from the surface to center of a board without a break. Thus a true diffusion process might not occur in such an unstable state period.

As discussed earlier, stage II and stage III can be considered a true diffusion process, regardless of drying conditions, while stage I can not. This fact could be a particular phenomenon observed during the drying of water saturated red oak. Two distinct drying behaviors therefore can be depicted such as the unstable state of diffusion during the first half sorption period and a true diffusion process for the last half sorption.

3.3 Moisture Transfer Parameters

From the maximum possible drying rates displayed in Figure 1, 2 and 3, surface transfer coefficients are obtained as shown Table 1. Since the maximum drying rates are obtained during the period of free water evaporation from the wet surface of wood, the period to sustain the maximum drying rate is confined while the surface is wet. Even though constant drying rates were not clearly observed in red oak drying in this research, the plots of drying rate with MC in Figure 1, 2, and 3 showed some consistencies in the fluctuations of the stage I drying period. The fluctuation might likely be caused by the variations in initial moisture content of the specimens. Thus the values of maximum drying rate in Table 1 would represent the maximum possible drying rate of red oak under each drying condition. Since the drying rate is directly related to the surface transfer coefficient, it can be confirmed that the surface transfer coefficient is a property of the drying condition or air stream, and is independent of wood properties.

The surface transfer coefficient, derived from

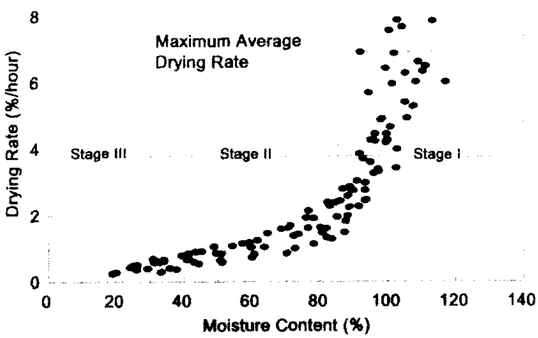

Fig. 1. Drying rates and moisture content under 35℃ drying condition.

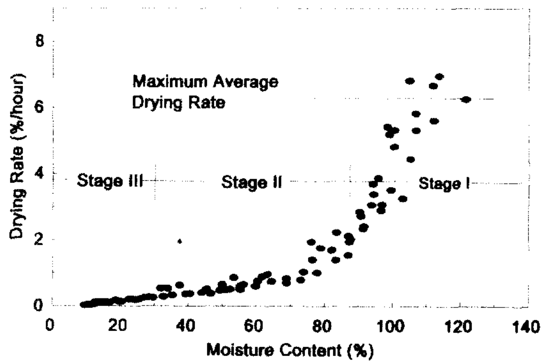

Fig. 2. Drying rates and moisture content under 45℃ drying condition.

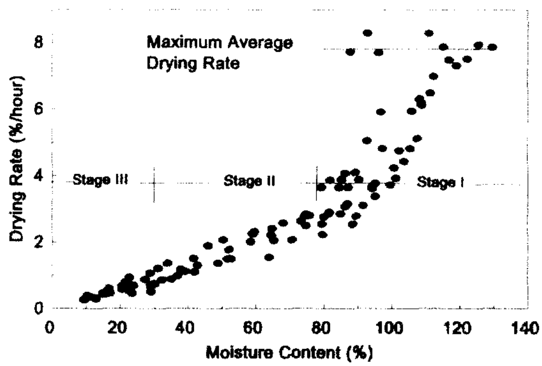

Fig. 3 Drying rates and moisture content under 55℃ drying condition.

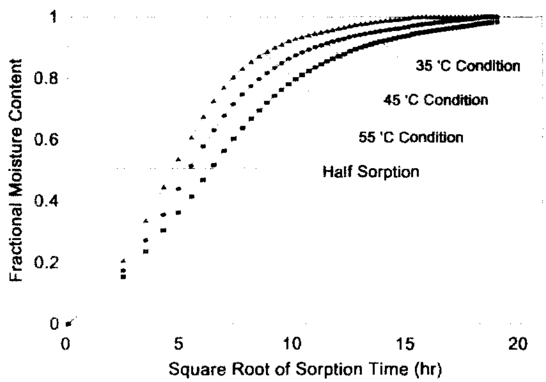

Fig. 4. Fractional moisture changes and sorption time for each drying condition.

Table 1. Maximum drying rates and surface transfer coefficients.

Drying Temperature (℃)	Initial MC (%)	Max. Drying Rate (%/hr)	Surface Transfer Coefficient (cm/hr)
35	115 ± 7.0*	6.3 ± 1.1*	0.037
45	106 ± 7.9	6.9 ± 1.1	0.044
55	111 ± 5.0	7.8 ± 1.2	0.050

* Average and standard deviation values, five specimen replicates per group.

the maximum drying rate, is also associated with the Wet Bulb Depression (WBD) of drying conditions. The WBDs were 10.5℃ for 45℃ and 55℃ drying conditions, and 9.5℃ for the 35℃ drying condition. These two values of WBD are not great in difference. As discussed by Stevens *et al.* (1956) and Rosen(1978), the surface transfer coefficient or surface resistance is strongly dependent on the air velocity. That is, as air velocity increases, there is a decrease in the surface resistance, or increase in the surface transfer coefficient. Since the conditioning chambers employed in this experiment had the same air velocity, the variations of surface transfer coefficient with drying conditions (Table 1) are exclusively the effect of dry bulb temperature. This positive effect of temperature on the surface transfer coefficient was also found by Avradmis and Siau(1987). One reason for elevation of surface transfer coefficients with temperature increase could be the increase of the saturated vapor pressure in the air of the drying chamber, resulting in a potential increase of air capability to hold water vapor evaporated from the wood surface.

During the unstable state diffusion in stage I, diffusion coefficients also fluctuated, but kept some consistency. As the diffusion process becomes more stable in stage II and stage III, the diffusion coefficients tend to decrease in concave downward shapes. Therefore a moisture dependent diffusion coefficient could be depicted with a constant and functional region. Transitional points from a constant diffusion coefficient to functional form were determined by finding a zero slope for each function. Table 2 summarizes these.

Table 2. Diffusion Coefficients for Each Drying Condition as Functions of MC.

Temperature (℃)	Diffusion Coefficient ($\times 10^3$ cm²/hr)		
	Max.	Function	Trsn.*
35	5.44	$-1.1+0.15\times-0.00096x^2$	76.0
45	7.85	$-2.1+0.25\times-0.0016x^2$	78.0
55	10.62	$-3.9+0.51\times-0.0046x^2$	56.4

* Transitional point of MC from maximum diffusion coefficient to functional relationship.

Bramhall(1979) formulated the dependence of the diffusion coefficient on moisture content as an exponential function below and above the bound water range. The trend in value for the diffusion coefficient found in this study showed a similar pattern to that predicted by his function. General trends of diffusion coefficients in the hygroscopic range have been found to be either exponential or polynomial functions with a concave downward shape. The polynomial function in this study, however, would become zero at low MCs if no inflection point exists. Bramhall(1979) applied a parabola at 7~8 percent MC for convenience. In this study, diffusion coefficients were assumed to remain at a constant value below 15 percent MC, since the change of diffusion coefficients at low MC is relatively small compared to the steep increase above 15 percent.

3.4 Correlations between Numerical Solutions and Experiments

The computational results of numerical solution for each of the drying conditions provided the average moisture content changes and the

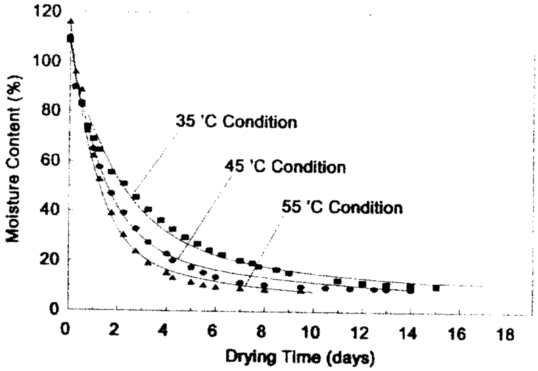

Fig. 5. Correlations of drying curves between the experimental and computational results of red oak drying. The solid lines are from the computational results and the marks are from the experimental results.

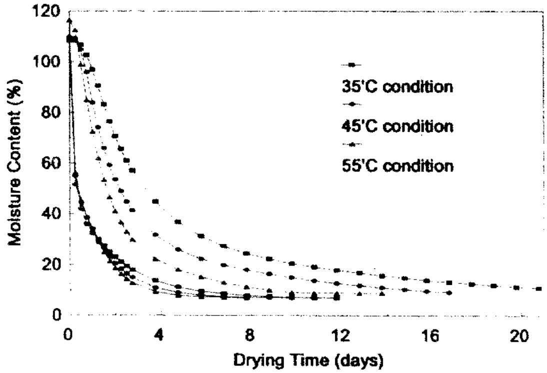

Fig. 6. Local MC characteristics from the computational results. The solid lines are for the surface and the broken lines are for the center of a board.

detail of moisture profiles developed during the moisture transfer process. The validity of computational results using the diffusion model could be evaluated by comparing them with experimental results. As shown in Figure 4, good agreement was obtained between the experimental and computational results for each drying condition. The coefficients of multiple correlation squared, R^2, were 0.967, 0.992, and 0.995 for 35℃, 45℃ and 55℃ drying conditions, respectively.

3.5. Characteristics of local MC changes

From the computational results, the MC changes at the surface and the center of boards are provided in Figure 5. The surface boundary condition of the diffusion model assumed that equilibrium for each drying condition was attained instantly at the surface of the specimen. That condition was not strictly met as shown in Figure 5. This discrepancy between the assumption and computational results can be attributed to a compromise in the computational method of the mathematical model. The surface MCs are average values of outer-most finite meshes. However, the surface boundary condition would only be adequate for an infinitely thin layer at the surface. Moreover, while the boundary conditions are held constant across the profile through the thickness of a specimen, the flux rate between adjacent meshes are calculated repeatedly by updating their new values from their adjacent meshes. Therefore, higher concentrations of inner meshes are continuously transferred to outer meshes, but outer-most finite meshes are not infinitely thin enough to meet the surface boundary condition. Thus the values plotted in Figure 5 did not meet the true boundary condition but might represent an actual average MC occurring at the surface of wood during drying.

The effect of temperature was not pronounced on the surface MC although there was a positive effect of temperature on the surface transfer coefficients. Since the surface transfer coefficient represents the current environmental condition in the drying chamber, the temperature effect would be lumped into the effect of the increased RH condition. An increase of drying temperature also resulted in the increase of a RH condition to maintain the same EMC. Since the boundary condition at the surface was set up to the same EMC condition, the increase of temperature would be more effective in the total drying rate rather than in the surface MC.

However, the MC changes at the center of boards seemed to be more susceptible to the

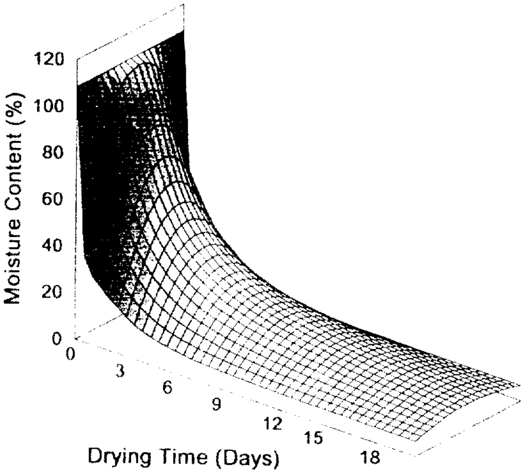

Fig. 7. Three dimensional moisture profiles computed for 35℃ drying condition of red oak.

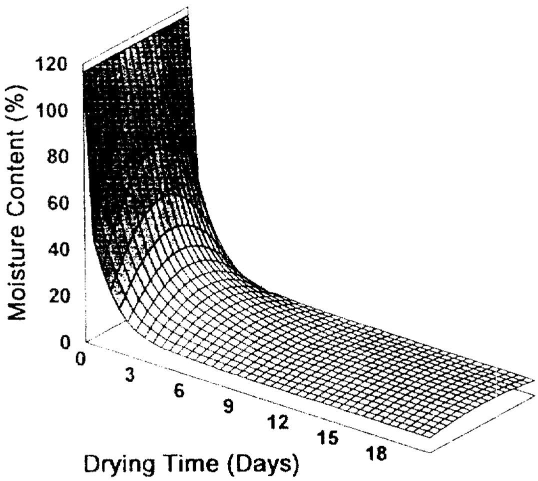

Fig. 8. Three dimensional moisture profiles computed for 55℃ drying condition of red oak.

temperature effect than that at the surface. This is reasonable because the internal diffusion coefficient strongly depends on temperature. There is more or less a linear relationship between the logarithm of the diffusion coefficient and the reciprocal of absolute temperature (Stamm, 1964; Choong, 1965). A greater fraction of water molecules can attain enough kinetic energy to overcome the potential barrier from their sorption sites with an increase in temperature, resulting in an increase in moisture movement.

3.6. Moisture Profiles

Typical three-dimensional moisture profiles are shown in Figure 7 and 8 for 35℃ and 55℃ drying conditions. The maximum observed moisture gradients between the first two out-most layer were 44.9%/cm, 40.6%/cm and 33.1%/cm for 35℃, 45℃ and 55℃ drying condition, respectively, and similarly 10.1%/cm, 9.6%/cm, and 7.7%/cm for the two center layers. The steep moisture gradients in 35℃ drying condition are the results of rapid evaporation at the surface and slow moisture diffusion processes from the center. Since there were no significant differences between the surface moisture changes with increased temperature, internal diffusion coefficients would be dominant factors in determining the moisture gradients. The magnitude of moisture gradient is reported to have a positive effect on drying stress development (Kawai *et al.*, 1979). It is therefore expected that steep moisture gradients in the 35℃ drying condition would develop higher drying stress criteria than the higher drying conditions employed in this research.

4. CONCLUSION

Water saturated red oak specimens were dried under three different isothermal drying conditions. The mathematical model of moisture transfer was numerically solved and the computational results were compared with experimental ones. This research leads to the following conclusions :

The unstable state of diffusion depicted the early stage of water saturated red oak drying. This behavior was believed to be caused by the excessively high drying rate from the wet surface, and the discontinuity of moisture profiles at the beginning of the drying period. The shape of drying rate curves verified application of the unsteady state diffusion model to red oak drying as Fickian diffusion despite the unstable state at the beginning of drying. The results of numerical approximations of the diffusion model showed good agreement with experimental results in drying curves of MC-time relations. Increase of temperature in drying was more effective on the internal MC change than on the surface. More steep moisture gradients therefore resulted under high than low temperature condition. As a result, mathematical modeling for drying of wood was confirmed to be useful tool to compute the moisture profiles for entire moisture range.

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