MATHEMATICAL MODELING OF THE DIFFUSION OF WATER IN WOOD DURING DRYING

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ABSTRACT

The drying of lumber was modeled by the diffusion of water in wood, according to Fick's second law. In the model the following assumptions were made: (1) Moisture content is the driving force; (2) the diffusion coefficient is a constant value above the fiber saturation point and one-fourth that value below the fiber saturation point; (3) equilibrium exists between the moisture content at the wood surface and the film of air adjacent to the surface; (4) moisture movement from the film to the bulk air stream occurs by film mass transfer. Five independent variables—half thickness of the board, species factor (density-diffusivity), temperature, relative humidity, and air velocity—were found to influence the drying process. This study reveals that variable interactions are important considerations when one wishes to predict drying times.

Using red oak and constant values for lumber thickness and kiln air velocity, three cases were modeled to illustrate the potential for improved operation. The first case follows temperature and humidity schedules typical of current kiln operations, forming a basis for comparison. In the second case, a solar-powered kiln produces harmonic variations in temperature and relative humidity. The most favorable drying conditions occur in the late afternoon, the least favorable before dawn. Slower drying with nightly relaxation of the moisture profile may produce a board with few defects. In the final study, temperature and maximum permissible drying rate are specified, with relative humidity chosen according to the model. This case produced the most rapid drying, yet has milder moisture gradients than the base case. The results of these studies show the possibility of producing a high-quality product at low cost in a solar-powered dryer, or optimizing drying schedules to reduce drying time and increase product quality.

Keywords: Kiln drying, diffusion, air velocity, humidity, solar power.

INTRODUCTION

The drying technology of wood is largely an art rather than a science, because fundamental knowledge about the wood-drying process is still lacking. Most studies have dealt with either the external factors affecting the evaporation of moisture from the wood surface or with the internal factors causing the moisture to move from the wood interior to the surface. In moisture movement, most studies have centered on the hygroscopic moisture, which represents a small portion of the

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entire moisture range. Thus, moisture movement during drying has been largely expressed in terms of a diffusion phenomenon below the fiber saturation point. The mechanism of free water movement in the void structure is still not well understood.

The diffusion coefficient for water in wood has been determined from drying data at fixed boundary conditions by numerous researchers (Skaar 1954; Biggerstaff 1965; Stamm and Nelson 1961; Choong 1963; McNamara and Hart 1971; Bui et al. 1980) using the general solution of Fick's second law given by Newman (1931). These studies, however, have not considered the effect of surface resistance, which was reported by Ogura (1950) and by Choong and Skaar (1972) to be significant for samples less than 1.2 in. in thickness. Surface resistance can also be expected to be pronounced when there is inadequate air circulation, especially during the beginning of drying.

This study was undertaken to investigate the wood drying process as a mass transfer problem. Drying of wood is modeled by the equation for unsteady-state diffusion. For the solution of the equation, boundary conditions were chosen to resemble those existing in a dry kiln, with several important variables taken into consideration in order to simulate various drying conditions.

Several drying simulations have been reported in the literature. Peck and Kauh (1969) report average values of concentration based on a uniform mass diffusivity, with vapor pressure on the surface as the surface boundary condition. Ashworth (1980) uses a temperature-dependent diffusivity and a surface boundary condition based on heat transfer analogies. Spolek and Plumb (1980) base their model on capillary action above fiber saturation and diffusion below fiber saturation. In this study, we assumed the surface concentration of vapor is given by the adsorption equilibrium relationship. We also assumed an isothermal condition in the wood and a two-part diffusion coefficient.

DEVELOPMENT OF THE MODEL

Fick's second law,

$$\frac{\partial C_{H_2O}}{\partial t} = D\frac{\partial^2 C_{H_2O}}{\partial Z^2}, \tag{1}$$

has often been used to describe the unsteady-state, one-dimensional movement of moisture through wood. In this equation, C_{H_2O} is the concentration of water in the wood (mass water/volume green wood), D is the diffusion coefficient (area/time), t is the time, and Z is the distance from the center of the board.

We concur with the literature (Bateman et al. 1939; Stamm 1964; Hart 1964) that diffusion controls the entire range of moisture content during the drying of wood below the boiling point of water. Thus drying can be accurately modeled as a diffusion phenomenon. This is applicable whether the movement of moisture involves only the bound water and water vapor forms, or includes the free water form as well. It is especially true in a moderately impermeable hardwood, where the mass flow of free water is restricted. We have chosen to use Fick's law to model moisture movement both above and below the fiber saturation point and have done so by the incorporation of a two-part diffusion coefficient. The diffusion