Simulation of drying using a kiln model

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ABSTRACT

A mathematical and then a numerical model were developed for simulating a convective batch lumber drying process. The model incorporates mass and heat transfer relationships within the lumber stack, as well as thermodynamic properties of the wood and drying air. It takes into account a change of air properties along the stack and its effect on the mass and heat transfer parameters. Kiln and individual board properties as well as a drying schedule are the input parameters that are defined and entered by a user. The model relies on the drying rate functions which are empirical correlations based on single-board tests.

The drying rate function for hemlock was obtained based on experiment results from 23 small charges dried over a range of conditions used in industry. Three large batches of hemlock were also dried using three different industrial schedules. The change of average moisture content with time predicted by model was verified by weighing a kiln charge with load cells during drying. The change of board temperatures and temperature drop along the stack were verified by measuring the actual temperatures in the kiln during drying.

The model was first validated against data available in the literature. Then the experimentally-determined drying function for hemlock was used as the model input and the model output was compared to the larger hemlock batches. Validated variables for both cases were board temperatures, temperature drop through the package and average moisture content of the package.

INTRODUCTION

Simulation of a process can reduce the need for experiments or trials. Simulations can also test things that are very difficult to measure. For example, a kiln operator could try to determine when to reduce fan speed by changing the fan speed at times during the drying cycle and observing the results. However, it is likely that during these tests the weather would change, the log supply would change, and other factors associated with kiln operation would cause difficulty in interpreting the results. In a simulation, the fan speed could be changed while all other variables are held constant. The operator would have the results in a few hours instead of weeks.

The purpose of this work was to create and validate a model that simulates the processes taking place within a lumber stack during kiln drying and predicts the values of the main drying variables such as temperature of the wood and air, moisture content of the wood, humidity of the air, and the temperature drop along the stack. A further purpose of the work was to develop a drying rate function so the model can be applied to western hemlock lumber. Based on the steps necessary to create and validate the model, the objectives of this work are:

1) Make a valid mathematical model that describes the heat and mass transfer processes occurring in a stack of lumber during drying.

2) Develop drying rate function for hemlock which will be used in the mathematical model to describe how fast moisture moves through wood.

3) Validate the model by comparing the experimental results obtained by drying of stack of hemlock boards to the results obtained from the simulation.

Description of the simulation

A kiln simulation consists of two parts. The first part is a drying rate function that describes how fast an individual board dries. This rate depends on its moisture content and the air temperature, humidity, and velocity. This part of the simulation is species-dependent. The second part of the simulation is the kiln model. This part simulates the moisture change for every board in the kiln. It is independent of the species and handles the material end energy balance so that the air temperature decreases across the stack of lumber and the boards on the entering-air side of the pile dry faster. The kiln model applies the drying rate function to each board using the board's moisture content and the air temperature humidity and air velocity above and below the board.

Drying rate function

A drying rate function was developed for hemlock from approximately 500, 4-foot-long, 2-inch nominal (42 mm in thickness), pieces of dimension lumber dried in 23 kiln charges. Each charge was dried using commercial schedules. Each piece was weighed before and after drying, then oven-dried to determine the initial and final moisture content. The moisture content at any time was determined from the dry-bulb, wet-bulb, and vent rate of the kiln. Average conditions were determined for each hour of drying. The conditions included the drying rate, dry-bulb temperature, wet-bulb temperature, and wood moisture content.

A table was created with the data for each hour of drying for all charges. Hours that occurred during the initial warm-up period were deleted from the data set. The data set was then sorted by moisture content

The data was divided into two parts – above 80% moisture content and below. This appeared, based on a visual inspection of a rate versus moisture content graph, to be the critical moisture content, the moisture content at which drying changed from constant rate to falling rate.

At high moisture content, the drying flux was found to be a function of wet-bulb depression (Figure 1) in accordance with drying theory. For hemlock above 80% moisture content the drying flux from a board surface was expressed as

$$Flux = 0.0157 \bullet (T_{db} - T_{wb}) + 0.0663$$

where

T_{db} = Dry-bulb temperature, °C
T_{wb} = Wet-bulb temperature, °C

This relationship was not affected by the dry-bulb temperature. The relation should be affected by air velocity; however, all experiments were done at 3.8 m/s. Therefore theory must be relied on to include the effect of air velocity during the constant rate period. The rate should vary with the square root of velocity. A factor of $\sqrt{v}/\sqrt{3.81}$ was used to increase the drying rate as air velocity increases.

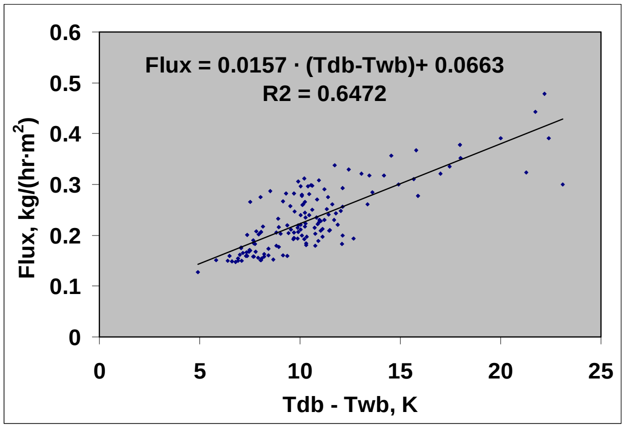

FIGURE 1. Flux of moisture from a board as a function of the wet-bulb depression. Data is for all boards when greater than 80% moisture content.

At low moisture contents, the drying rate was found to be a function of moisture content minus equilibrium moisture content and the dry-bulb temperature, also in accordance with drying theory.

The table of data for drying rate below 80% moisture content was divided into 10°C temperature ranges. For each temperature range the data was fit to

$$Flux = Slope \bullet (MC - EMC)$$

where

MC = Current moisture content of the wood, %/100

EMC = Equilibrium moisture content of the air stream, %/100

Thus a slope was obtained for each temperature as shown in Figure 2.

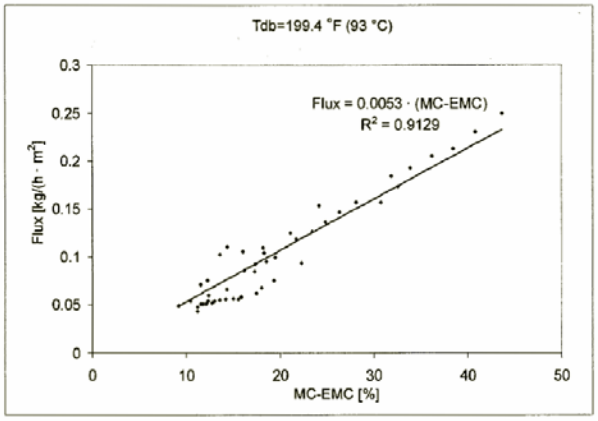

FIGURE 2. Flux of moisture from a board as a function of MC-EMC for one-hour periods when the kiln temperature was near 200°C. Data points are from several different charges of lumber.

The slope at each temperature was then fit to the absolute temperature using and Arrhenius-type function:

$$Slope = A \bullet \exp(B / T_{db})$$

The equation for slope was then substituted into the equation for flux at moisture content less than 80% to obtain:

$$Flux = (MC - EMC) \bullet 3.6 \bullet \exp(-2404.2 / T_{db})$$

The flux predicted by this equation versus the measured flux is shown in Figure 3 for all data below 80% moisture content. The fit is very good at low flux. Low flux is most likely to occur below the fiber saturation point of wood where the moisture movement is by diffusion and equation is best applied. Hemlock is a species with wet pockets. Free water is trapped in the wet pockets. The higher MC-EMC in these cases would cause the equation to predict too high a flux. The relationship is more scattered at higher flux because the equation is strictly applicable at low moisture contents which correspond to low flux.

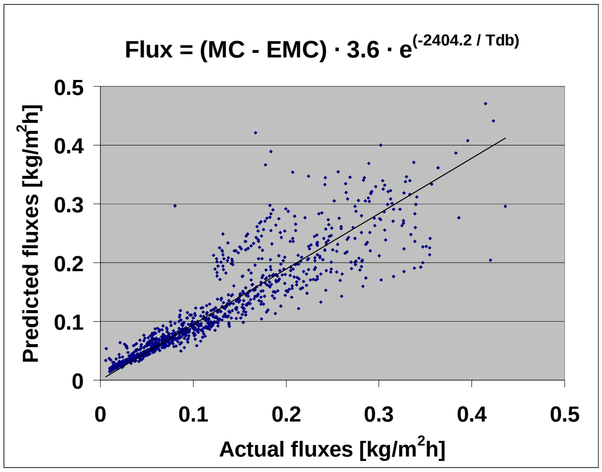

FIGURE 3. Flux of moisture from a board as a function of temperature and the difference between the board moisture content and the EMC. Data is for all time intervals for all boards when less than 80% moisture content.

These relations for drying at high and low moisture content were combined into the following equation

$$Flux = \{[(3.6033 \bullet e^{-2404.2/T_{db}}) \bullet (MC - EMC)]^{-16.64} + \sqrt{\frac{V}{3.81}} \bullet (0.0157 \bullet (T_{db} - T_{wb}) + 0.0663)^{-16.64}\}^{-1/16.64}$$

where

Flux = Moisture loss rate, kg/hr/m²

V = Air velocity, m/s

Tdb Dry-bulb temperature, K

Twb Wet-bulb temperature, K

MC = Moisture content of the board, %/100

EMC = Equilibrium moisture content of the air, %/100

This equation describes how a hemlock board will dry in a kiln at the conditions input to the equation. It is valid in the range of dry-bulb temperature between 60°C and 105°C and wet-bulb temperature between 50°C and 80°C. These are the typical conditions under which hemlock is dried industrially if one neglects the first few hours when the kiln is coming up to operating temperature.

Kiln Model

The kiln model inputs include the initial moisture content, specific gravity, and thickness of each board. Thus the user can put in a distribution of board properties. All boards must be of the same the same width. The kiln schedule is input including the dry-bulb temperature, wet-bulb temperature, air velocity, and fan reversal times. The kiln schedule variables can vary at any time increment, but are restricted to the valid range of the drying rate function. Other inputs include the sticker thickness and number of boards wide and high for a package.

At any time during drying the simulation will predict the average moisture content of the charge and the variability in moisture content. It also produces graphical displays of the board moisture contents versus location in the kiln, the board temperatures versus location in the kiln, the air temperature versus position, and the air relative humidity versus position.

The calculations are done using standard engineering equations for mass balances, energy balances, and the rates of mass and energy transfer. Details can be found in Berberović, 2007. Condensation occurs if the board surface is below the dew point temperature of the air. Condensation is allowed to run off the board. This is consistent with observations on the exiting-air side of a hemlock charge during the warm up period of a kiln.

Model validation

The model was first compared to information in the literature (Milota and Tschernitz, 1994). This was done so that the model could be tested independently of the hemlock drying rate function. The predicted versus measured results for moisture content, temperature drop across the load, and board temperature are shown in Figure 4. The agreement was very good.

The next step in verification of the model was to use it with the hemlock data. Three packages, each containing 168 pieces of 4.9-m-long 2x6 hemlock (42x147 mm), were dried to validate the model. The weight of each board was recorded before and after drying. The moisture content of each board was measured in two places with a Wagner L612 hand-held moisture meter. A third measurement was made if the first two differed by more than five percent. The charge was continually weighed during drying using in-kiln load cells and the moisture content as a function of time was calculated. The specific gravity for each board was estimated from

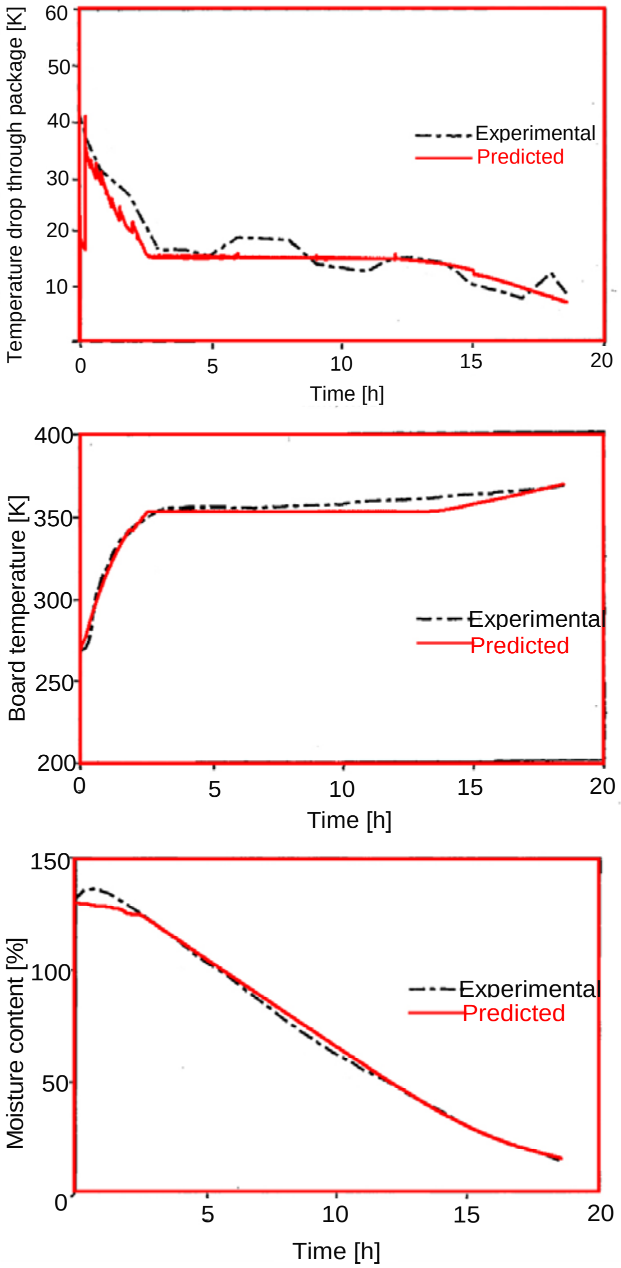

FIGURE 4. Moisture content, temperature drop across the load, and board temperature versus time predicted by the model and measured during drying. The measured data is from Milota and Tschernitz, 1994.

the board dimensions, weight, and moisture content. The internal temperature of selected boards in the charge were measured. The dry- and wet-bulb temperatures as measured during drying were input to the model. The air velocity was measured and introduced to the model.

The model was then run with the inputs matching the actual kiln operating conditions and board initial conditions.

The predicted moisture content versus time is compared to the actual in Figure 5. A good agreement can be seen. The model dries a little too slowly later in the cycle. When conditioning occurs at about 85 hours, the predicted moisture content does not increase because the EMC is not high enough to cause the model to simulate water vapor transferring to the wood. In the actual kiln, with a moisture content below the EMC, water vapor did transfer to the boards and increase their moisture content.

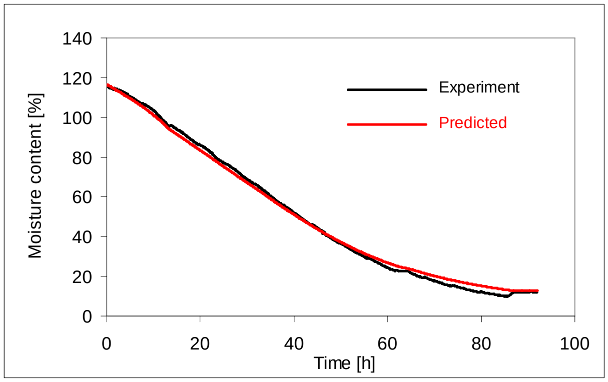

FIGURE 5. Moisture content versus time predicted by the model and measured during hemlock drying.

Figure 6 shows the temperature drop through the package as measured by thermocouples placed on the package and as predicted by the model. Again, the agreement is good. The predicted temperature drop is slightly less than the actual. This is because the drying was slightly slower in the model. The temperature drop will be lower when less water is removed. The upward spikes occur at fan reversals because the actual entering-air temperatures for the kiln were entered. The model captured the higher inlet temperature and predicted a greater temperature drop during the period immediately after fan reversal. The downward spikes in the measured temperature drop are when the fans are stopped between reversals and the temperature drop across the load approaches zero.

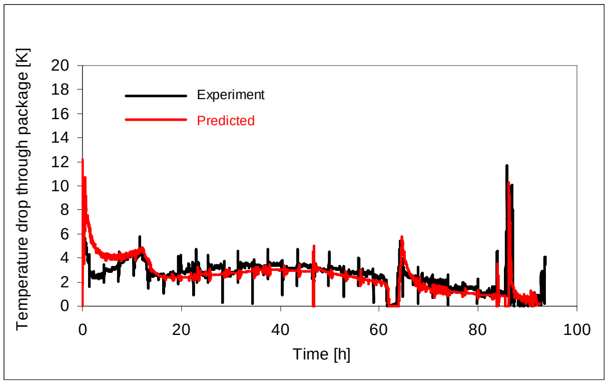

FIGURE 6. Model results compared to measured results for temperature drop across the load for hemlock drying.

Figure 7 shows the temperature inside of a board. It was the third board from the outside of a stack that was eight boards wide. Again, the agreement is good between the predicted and the experimental. The first dip in both the measured and the predicted temperatures occurred when no thermal energy was supplied to the kiln due to a steam failure. The second dip is when the wood was probed with a hand-held moisture meter to measure its moisture content. These anomalies are also apparent on the temperature drop graph in Figure 6 at 65 hours when the temperature drop is zero for both the predicted and actual. Also, the high predicted and actual temperature drop across the package at 85 to 90 hours is associated with the package reheating after the moisture content check.

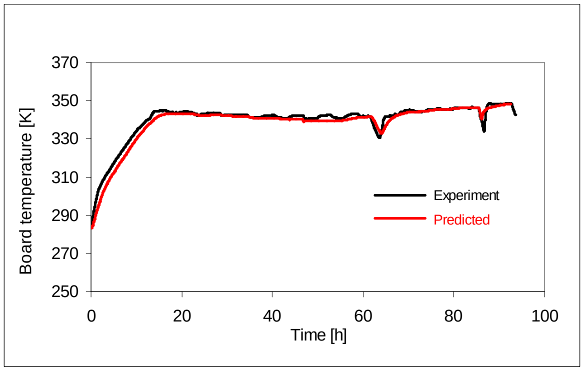

FIGURE 7. Measured and predicted internal board temperatures versus time during hemlock drying.

The model was tested on a full-sized package of lumber using the actual temperature, humidity, and air velocity experienced by the package. A full size-package in a large kiln and a small kiln will behave similarly; therefore there is no reason why the model should not work on a larger kiln for predicting general trends in the drying as a function of kiln conditions.

The drying rate function developed represented the average drying rate for the hemlock lumber quite well resulting in good agreement between the average predicted moisture contents and the average measured board moisture contents. However, as Figure 8 shows, the board by board agreement is lacking.

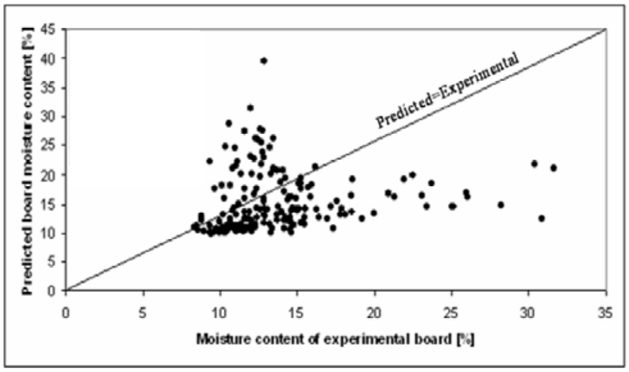

FIGURE 8. Predicted versus measured board moisture content at the end of the drying cycle.

In some respects, the differences in the drying behavior of different boards is accounted for. For example, the model would predict that a board with a higher specific gravity would take a longer time to undergo a given moisture content change. However, there is a lot more affecting the drying behavior of an individual board at a given temperature, humidity, and air velocity than just specific gravity. A drying rate function in needed that captures that variability and allows two seemingly identical boards to dry differently.

The model will be useful for answering what-if questions. For example, what would be the effect on drying time and moisture uniformity if the package was made one board wider? Or, what would be the effect of reducing the fan speed earlier in the cycle? Further development of the model is in progress. Much of this work will be focused on developing a drying rate function that better captures the variability in the drying behavior of the boards.

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