목재공학 27(4) : 38~42
Mokchae Konghak 27(4) : 38~42, 1999

Nondestructive Estimation of Average Wood Moisture Content Using Surface Temperature Rise by Radiation Heating and Moisture Gradient[*1]

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ABSTRACT

Average moisture content of 30mm-thick Korean red pine(*Pinus densiflora)* was estimated nondestructively and continuously using surface temperature rise by radiation heating and moisture gradient profile in wood. The surface temperature rises increased as surface moisture contents decreased and good relationships were found between surface moisture contents and surface temperature rises at three different feed speeds of 10, 20 and 30 m/min. Average moisture content could be described as a function of surface moisture content and wood thickness.

Key words : nondestructive testing, moisture content, moisture gradient, radiation heating

INTRODUCTION

The importance of moisture content control of lumber and other wood products for various uses cannot be over emphasized. An accurate method to measure wood moisture content(MC) continuously is needed to properly sort lumber or other wood products into several ranges, which will reduce overdry, degrade, and energy waste.

Various methods, including electrical(Milota, 1996), microwave(James *et al.,* 1985), ultrasound (Mishiro, 1996), and computer tomography (Wiberg and Moren, 1999) have been used to measure wood MC nondestructively. In general, these methods are limited since they require extensive calibration data. In the case of computer tomoraphy, the equipment is very expensive.

It has been observed by several authors(Kotok *et al.,* 1969; Troughton and Clarke, 1987) that there is a relationship between wood surface temperature and moisture content. A method using surface temperature as an indicator of moisture content has the advantage that it does not require lots of data for expensive equipment. However, low thermal conductivity of wood limits the application of this method only to thin

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[*1] Received September 27, 1999
This work was conducted with support from the Korea Science and Engineering Foundation (981-0606-027-2).

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material, such as veneers. Therefore, it is required to investigate moisture gradient profile in wood at certain surface moisture content to estimate the average moisture content of board or lumber.

The objectives of this study are to develop a new method to estimate average moisture content nondestructively and continuously using surface temperature rise by radiation heating and moisture gradient profile in wood.

MATERIALS AND METHODS

Unseasoned 30- by 150-mm Korean red pine (*Pinus densiflora*) boards, 2,400mm in length, were cut into 400mm-long sample boards with a 25mm section adjacent to each sample board removed for moisture content(MC) determination by the ovendry method. Experiment was conducted during air-drying of sample boards with the interval of 10% MC over the MC ranges of approximately 20 to 150%.

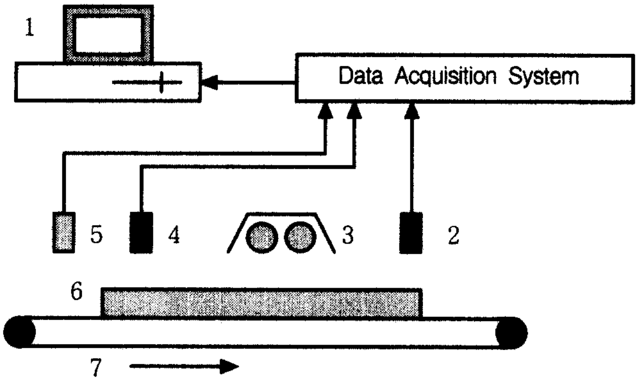
Unseasoned 30mm-thick sample boards were conveyed underneath an infrared temperature sensor to measure the surface temperature before radiation heating. The infrared temperature sensor was K-thermocouple type. Radiation heater was composed of two 850 watt halogen heaters lined one directly behind the other, each having a heating element 365mm in length. The distance between the wood surface and the heaters was fixed at 5mm. Another infrared temperature sensor measured the surface temperature after radiation heating and surface temperature difference between before and after heating was calculated and recorded by data acquisition system. This test was repeated at three different feed speeds of 10, 20, and 30m/min. with same sample board.

A nondestructive wood moisture content estimating system in Figure 1. As shown in Figure 1, the distance between the center of radiation heater and each infrared temperature sensor, which was located 200mm above wood surface, was 300mm. Target spot diameter of infrared temperature sensor was 40mm at distance of 200mm to wood surface.

After the experiment ten 30mm-long blocks were cut out from each sample boards. Any blocks containing defects were discarded. The blocks were then sectioned by blade into five 3mm-thick and one 15mm-thick slices from the heated side of each block to measure the moisture gradient by ovendry method.

RESULTS AND DISCUSSION

Figure 2 shows the relationships between



1. Personal computer
2. Infrared outlet temperature sensor
3. Halogen heater
4. Infrared inlet temperature sensor
5. Laser displacement sensor
6. Wood specimen
7. Conveyor

Fig. 1. Schematic diagram of nondestructive wood moisture content estimating system.

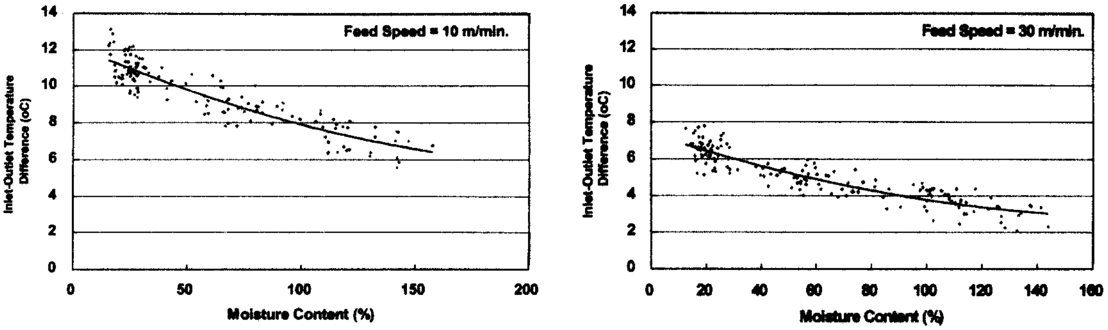


Fig. 2. Relations between surface moisture contents and inlet-outlet surface temperature differences at two feed speeds of 10 m/min. and 30 m/min.

surface MC and inlet-outlet surface temperature differences for three different feed speeds, 10m/min., 20m/min. and 30m/min. Temperatures of surface at green condition were raised by about 6, 4 and 3℃ at 10, 20 and 30m/min., respectively. Then the surface temperature rises increased as surface MC decreased. The temperature rises of surfaces at final air-dried condition(about 15% MC) were about 12, 8 and 7℃ at 10, 20 and 30m/min., respectively. Room temperature ranged from 13 to 15℃ at test time. This result means that the higher the feed speed, the less the heat energy input to wood and the lower the surface temperature rise. There were good correlations (r^2 = 0.81~0.82) between surface MC and surface temperature rises over the MC range of about 15% to green MC at any feed speeds.

The following equation evaluates the amount of heat required to produce a given change in temperature of a given volume of wood which contains water(Brown *et al.*, 1952):

$$Q = w_o c(t_f - t_i) + w_o M(t_f - t_i)/100 \qquad [1]$$

where:

Q = the total heat required
w_o = the ovendry weight of the wood
c = the average specific heat of wood substance for the temperature range $(t_f - t_i)$
t_f = final temperature
t_i = initial temperature
M = percent MC

Since Q was constant for this experiment at each feed speed, MC can be expressed as a function of temperature rise $(t_f - t_i)$.

$$M = 100(Q - w_o c(t_f - t_i))/(w_o(t_f - t_i)) \qquad [2]$$

Therefore, the higher the surface temperature rise, the lower the surface MC as shown in Figure 2. The surface temperature rise decreased at higher feed speed because higher feed speed causes the reduction of heating time which

Table 1. Equations for estimating surface moisture content(Ms) of Korean red pine as a function of surface temperature rise(dT) at three different feed speeds

Feed speed (m/min.)	Regression equation	r^2 coefficient
10	$Ms = 1.3464\ dT^2 + 49.224\ dT + 402.13$	0.81
20	$Ms = 1.5922\ dT^2 + 46.615\ dT + 298.69$	0.81
30	$Ms = 2.0950\ dT^2 + 48.266\ dT + 243.46$	0.82

results in decrease of heat amount from heat source. Table 1 shows the equations to estimate surface MC(Ms) as a function of temperature rise(dT).

The equations on Table 1 could estimate only the surface MC because very short heating time and low thermal conductivity of wood limited the depth from the wood surface which could beheated simultaneously. Kikuchi and Komazawa (3) studied the internal temperature change of wood by radiation heating and found that more than 2 minutes were taken to raise the temperature of the center of 30mm-thick ponderosa pine at 1.75kW heating output. However, the width of heater slot was only 56mm and the heating time was less than 0.3 seconds even at feed speed of 10m/min. in this experiment. Therefore, the analysis of moisture gradients from the surface to the center of sample blocks was conducted during air-drying to estimate average MC.

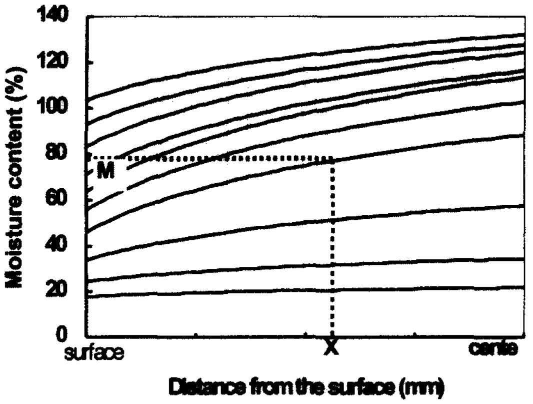


Fig. 3. Moisture distributions of 30mm-thick Korean red pine during air-drying (Ma : average moisture content ; Xa : the X-coordinate that divides the area below moisture gradient profile into two same area sections).

Regression lines were made for each moisture gradient profile with the interval of 10% surface MC over the MC ranges of approximately 20 to 100%(Fig. 3). Average green MC of Korean red pine was over 150% and there was no moisture gradient above 150% MC. It was assumed that similar moisture gradient profile existed at surface MC ranging from 100% to 150% MC. The regression equations from each moisture gradient profile were shown in Table 2. Correlations between average MC and surface MC were very good because any blocks which

Table 2. Regression equations for each moisture gradient profile of 30mm-thick Korean red pine during air-drying

Surface moisture content range (%)	Regression equation	r^2 coefficient
<20	Y = 2.499 Ln(X) + Ms	0.970
20 ~ 30	Y = 6.223 Ln(X) + Ms	0.922
30 ~ 40	Y = 14.814 Ln(X) + Ms	0.997
40 ~ 50	Y = 26.443 Ln(X) + Ms	0.985
50 ~ 60	Y = 29.485 Ln(X) + Ms	0.993
60 ~ 70	Y = 31.054 Ln(X) + Ms	0.990
70 ~ 80	Y = 28.056 Ln(X) + Ms	0.997
80 ~ 90	Y = 25.500 Ln(X) + Ms	0.993
90 ~ 100	Y = 21.446 Ln(X) + Ms	0.980
100 ~ 150	Y = 17.667 Ln(X) + Ms	0.951

(Ms = surface moisture content ; X ranges from 0 to 15mm ; Y means MC) contained defects such as knots were discarded before the analysis of moisture gradient. These equations contain surface MC(Ms) as an intercept on Y-axis.

For the estimation of average MC from the moisture gradient profile it is necessary to find the X-coordinate(Xa) that divides the area below moisture gradient profile into two same area sections.

$$Ms = A\ dT^2 + B\ dT + C \qquad [3]$$

$$Y = D\ Ln(X) + Ms \qquad [4]$$

$$\int_{surface}^{Xa} YdX = \int_{Xa}^{center} YdX \qquad [5]$$

where:

A, B, C, D = constants

Xa = the X-coordinate that divides the area below moisture gradient profile into two same area sections

Average MC will be obtained by substituting this X-coordinate into the regression equation for moisture gradient profile, assuming the same condition on both half-thicknesses. Therefore, if the thickness and surface MC are known, the average MC(Ma) can be estimated.

CONCLUSION

Good relationships were found between surface MC and surface temperature rises of the radiation-heated Korean red pine boards at three different feed speeds of 10, 20 and 30 m/min. The surface temperature rises increased as surface MC decreased. Therefore, surface MC could be estimated by surface temperature rise by radiation heating. Regression lines were also made for moisture gradient profiles and good correlations were obtained. Using moisture gradient profile at a given surface MC level, a new method was developed to estimate average MC of board. The results show that this new MC estimating method has good potential for sorting unseasoned wood into several MC ranges for more effective drying or secondary processing.

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