THE INFLUENCE OF STICKER THICKNESS ON HYBRID DRYING OF *LARIX GMELINII* COMBINED WITH RADIO-FREQUENCY AND HOT-AIR HEATING

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In this study, sawn pieces of *Larix gmelinii* lumber were dried, and the specimens were divided into six piles with the use of stickers having two thicknesses. The convection conditions were kept the same throughout the high-frequency heating in order to maintain the core surface temperature difference, while the high-frequency time was adjusted in order to meet the temperature difference requirements. Meanwhile, the variables of drying rate, energy consumption, and drying quality were compared for the 15- and 20 mm-thick stickers. The result was that the drying rate of the piles with 15 mm stickers was lower above the FSP (fiber saturation point), but began to converge near to the point of reaching the FSP. Moreover, at the end of the drying process, the drying rate of the piles with 15 mm thickness stickers was higher than, and the energy consumption and drying quality superior to, those with 20 mm thickness stickers.

Keywords: Hybrid drying; Radio-frequency drying; Drying rate; Energy consumption; Drying quality; Wood sticker

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INTRODUCTION

Rajeev (2001) and Xia (2010) have improved the drying method by combining radio-frequency (RF) heating technology with the traditional heating technology to reduce the long drying process and the possibility of the appearance of drying defects due to HA (hot-air) heating. Compared with HA heating, the advantages of hybrid heating are as follows: greater heating uniformity, better control of the temperature gradient, fewer drying defects, and utilization of the easy-built drying kiln that can be made by adding a high-frequency generator to an HA heating kiln.

It was proved conclusively in a previous study (Poulin and Dostie 1997) that the values of the heat and mass transfer coefficients increase when the evaporation rate caused by RF energy decrease. The experiments have also shown that non-uniform drying is dependant on the initial moisture distribution and the relative intensity of the heat transfer by RF and convection, that the maximum drying rate occurs at high level average moisture content (MC>50%), and that the total drying time increases with the non-uniformity of the initial moisture distribution.

Yayoi (1999) investigated the effects of the combined dryer using the end matched columns of Sugi. The drying results were compared with those of a steam-heated dryer. The results showed that the drying time of the Sugi columns using the combined dryer was one-fourth to one-fifth of the drying time using the steam-heated dryer. Furthermore, fewer surface checks and end checks appeared in the combined sample than in the steam sample. Rajeev and Perrv (2001) carried out Non-isothermal RF drying on red oak, incorporating a pre-drying step at the start of the process, and found that the drying times were significantly shorter than those of the same moisture content (MC) range when using the conventional kiln-drying method.

An iinvestigation by Kawai and Kobayashi (2003) showed that internal pressure is the driving force behind water movement during hybrid drying combined with RF and connective heating, and that RF heating causes a rise in the both internal temperature and the pressure in Sugi square lumber. With RF heating, the internal pressure is generated by the increased temperature, and the water is driven not only parallel to the grain but also perpendicular to it. Jin and Fujimoto (2007) has researched the heating system of the Sugi boxed heart timber based on the RF heating drying system, showing that it is better to use conventional drying before the MC decreases to 20% and to shorten the drying time and reduce the energy consumption after the RF heating.

When this hybrid drying technology was introduced by Japan into Chinese production, it was necessary to research the technology and parameters of the drying process. For the RF heating, thinner stickers have been adopted to achieve better efficiency, but for the HA heating, the relatively smaller airflow channels affect the rate of drying. Therefore, reasonable thickness on the part of the stickers turns out to be an important factor that affects hybrid drying. In an overall consideration of drying rate, quality, and energy consumption, this study attempts to determine the appropriate thickness of stickers to use in the hybrid drying method for sawn Russia larch lumber. Remond and Perre (2008) found that, using RF heating combined with convective hot and moist air, it is possible to dry a 50 mm-thick board from 150% to 5% in about 10 hours while maintaining good final quality.

EXPERIMENTAL

Materials

48 specimens (900 × 150 × 50 mm), which were free of any visual defects, were extracted from *Larix gmelinii*. The sample boards were end-coated with epoxy resin to restrain the moisture movement in the longitudinal (fiber) direction for the simulation of the drying of long-length wood. A pile was made of 16 specimens, from which 4 specimens were selected as sample boards that would be used to measure MC distribution and stress variation (Figure 1b).

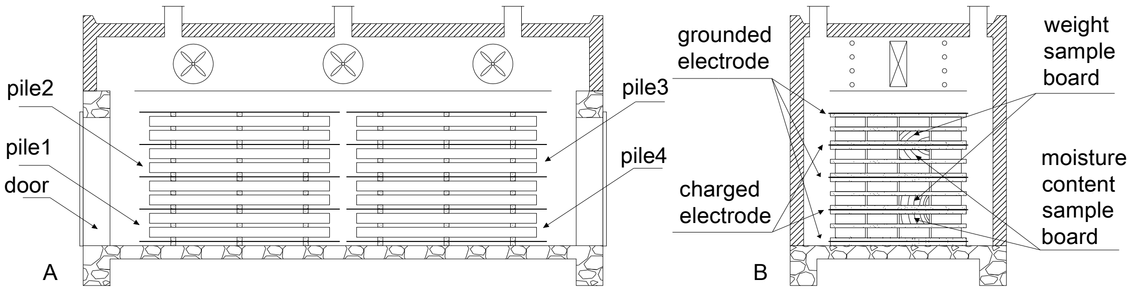


Fig. 1. Placement of kiln samples in side view, A; right view, B; end view

A radio-frequency generator (13.56 MHz, 20 kW) was used for the RF heating. The drying kiln (of volume 2 × 1.8 × 1.6 m) had a capacity of about 3.456 m^3. Eight specimens were placed between a charged and a grounded electrode under atmospheric pressure. The MC of green lumber ranged from 70 to 80%. A MGZK-V drying controller was used to control the temperature and relative humidity. The air speed was 2 m/s. The energy consumptions of HA heating and RF heating were measured using two digital watt meters. An XJY-160 temperature recorder and T type thermocouples adopted EMC screen were used to measure the inner temperature distribution of the lumber and the kiln at the moment that the RF generator stopped.

Experimental Methods

During connective drying, sticker thickness contributed to the uniformity of the air velocity and the final moisture content in the kiln package. However, the drying medium that existed among stacks would cause dielectric loss during hybrid drying, which would decrease the heating efficiency of the RF. Bassett (1974) investigated the air circulation using 2×4's stacked with stickers of 10 mm, 13 mm, 15 mm, and 20 mm sticker thicknesses. The results showed that the air flow in a kiln is very sensitive to the size of openings within and between loads of lumber.

The present study included two experiments. There were four piles in each (Fig. 1a). The stickers were made of dried hardwood. The first experiment adopted stickers whose cross-section was 15 mm × 25 mm and whose length was 1000 mm. The second experiment adopted stickers whose cross-section was 20 mm × 25 mm and whose length was 1000 mm. The drying schedule for the two experiments, as seen in Table 1, was as follows: condition 1 was hot-air heating, which applied to pile 1; conditions 2 and 3 were hybrid drying, which applied to piles 2 and 3, respectively; pile 4 consisted of dried pieces of lumber whose purpose was to ensure the uniformity of air circulation in the kiln. Two measurements of the temperature difference, $\triangle t_1$ and $\triangle t_2$, between the inner layer and the surface layer were evaluated by turning the RF generator on or off.

The drying schedule can be described as follows: during the first period, the MC ranged from 50% to 30%, and the dry-bulb temperature (T_d) was 60 ℃; during the second period, the MC ranged from 30% to 20%, and the T_d was 65 ℃; during the third period, the MC remained below 20%, and the T_d equaled 75 ℃. During the experiments, the sample boards were taken out from sliding doors that were installed on the kiln. The HIOKI3286-20 clamp on the power hit ester was used to modify the value of total energy consumption. Every 24 hours, an MC sample board was taken out, and two small specimens were cut and quickly sliced into 7 pieces. The moisture distribution at a specified time in the thickness direction was measured using a gravimetric method. Immediately after being cut, the ends of each sample were coated with asphaltic paint.

The per unit energy consumption was defined as the HA heating energy consumption, which was measured by a wattmeter, divided by drying time. The RF heating energy consumption consisted of two parts. One part was generated when the RF generator worked during standby time. The other part was generated when the RF generator came into use. The total energy consumption was calculated from the HA heating energy consumption plus the energy consumption generated during the working hours of the RF generator.

According to Chinese drying quality standards for sawn lumber, quality indicators included MC deviation in the thickness direction, stress indicators, and visible drying defects. The drying quality was divided into four levels based on these indicators. Layered MC was used to detect moisture distribution and movement in the thickness direction. In the thickness direction, a cross section of the sample board was divided into the surface layer, subsurface, and core layer. To measure the residual stress of the sawn lumber, stress sections were cut from the stress sample board, and the prong method was adopted. The difference between the surface layer and the inner layer was defined as MC deviation. The uniformity of the piles was described by standard deviation (SD) σ.

$$\sigma = \sqrt{\frac{\sum_{n=1}^{n}(M_2 - \bar{M})^2}{n-1}}$$

Where, M_2 is final MC.

Table 1. Drying Schedule

Condition 1				Condition 2	Condition 3
				$T_d + \Delta t_1$	$T_d + \Delta t_2$
MC %	T_d	Δt	EMC	Δt_1	Δt_2
Above 40	60	3	15.5	6-10	1-5
40-30	62	4	13.5	6-10	1-5
30-25	65	6	11.5	6-10	1-5
25-20	70	8	9.5	6-10	1-5
20-15	75	14	6.5	6-10	1-5
Below 15	85	25	3.8	6-10	1-5

1, T_d, dry bulb (℃); 2, Δt, difference, wet-dry (℃); 3, Δt_1 and Δt_2, difference, inner layer-surface layer.

RESULTS AND DISCUSSION

The drying performance was evaluated on the basis of an overall consideration of the drying rate, energy consumption, and drying quality.

Drying Rate

Moisture distributions in the thickness direction were obtained at specified times during the drying by means of the slicing method. The drying rate for HA heating decreased gradually with the decrease in the MC, as shown in Figure 2a. This indicated that in the third period (T_d = 75℃), the HA heating was inefficient. As shown in Figures 2b and c, compared with the drying rate for the HA heating at the same period (Fig. 2a), the drying rate for the hybrid was greater. A reduction in the kiln drying time was achieved with hybrid drying. The reason for this result was that the temperature gradient and pressure gradient caused by the RF heating favored the discharge of water from the inner layer to the surface layers.

The improvements in drying time as a result of the hybrid drying method were not as obvious for the Russian Larch boards as they were for the Sugi columns. The relatively slow drying rate of the Russian Larch boards was attributable to many factors, such as the size of specimens, the much lower final MC, and the shorter RF heating time.

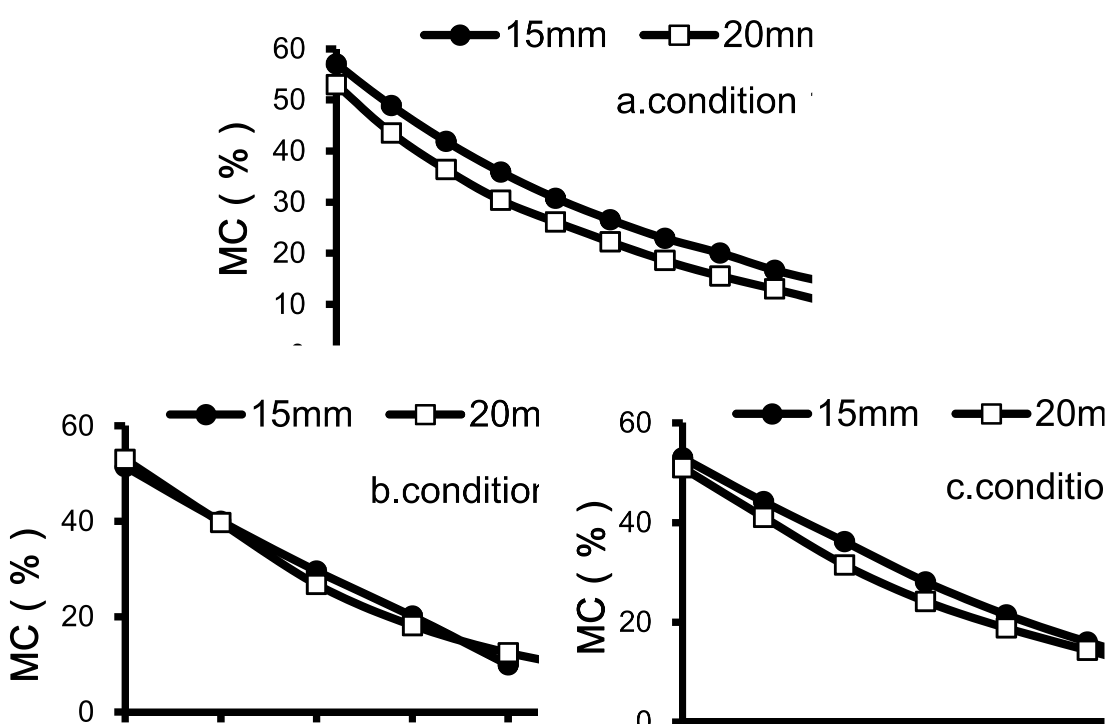


Fig. 2. MC as a function of time with two kinds of thickness stickers.

In order to compare the drying rates of the piles with stickers of different thicknesses under different conditions, the change tendencies of the drying rates were plotted as in Fig. 3.

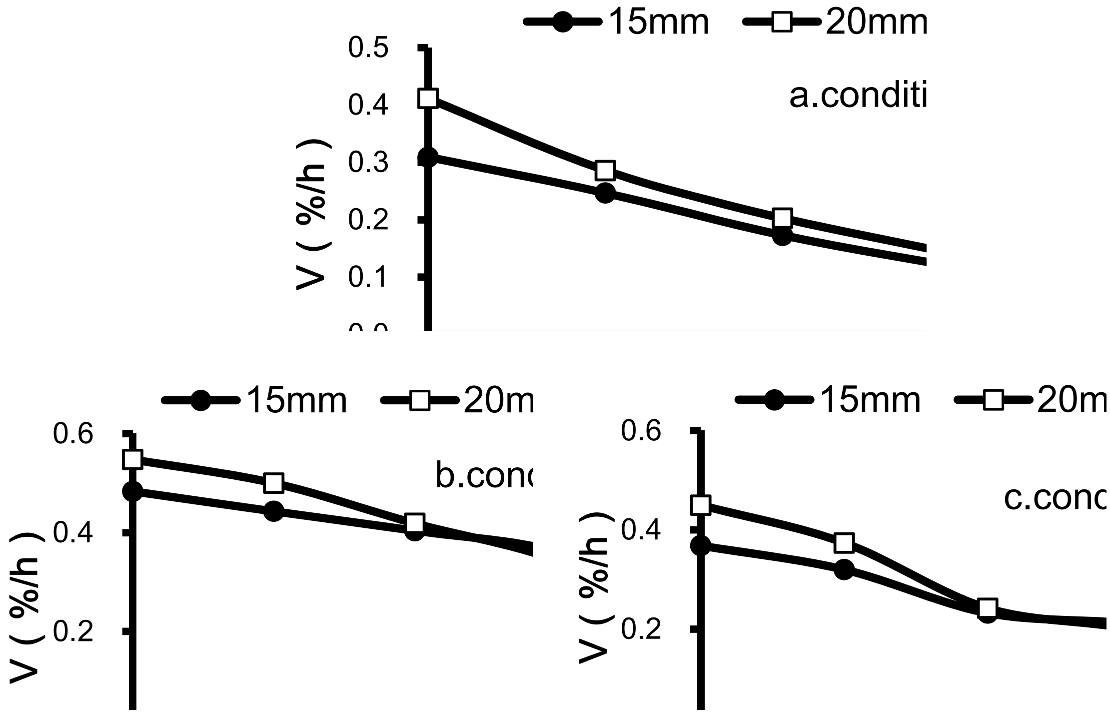


Fig. 3. Drying rate as a function of time with two kinds of thickness stickers.

Under the same HA heating condition (condition 1, Fig. 2a), the drying rate of the pile with 15 mm-thick stickers was slower than that of the pile with 20 mm-thick stickers. This led to the difference in kiln-drying times. The drying time of the pile with 15 mm-thick stickers was 260 hours. This was 20 percent higher than the drying time of the pile with 20 mm-thick stickers (210 hours). This phenomenon suggested that the rate of air circulation decreased with the decrease in sticker thickness, by which mode the drying rate was reduced.

Under the same hybrid heating condition (conditions 2 and 3, Figures 2b and c), above FSP, the drying rate of the piles with 15 mm-thick stickers was lower than that of the piles with 20 mm-thick stickers. As the MC decreased, the differences between the drying rates of the four piles started to decrease. Around the FSP, the drying rates were reaching unanimity. The drying rate of the piles with 20 mm-thick stickers dropped down much faster in comparison to the drying rate of the piles with 15 mm-thick stickers. Thus, in the third period, the drying rate of the piles with 15 mm-thick stickers was becoming higher.

Throughout the drying process, the piles with 15 mm-thick stickers possessed a higher average drying rate. During the period that the MC dropped from 50% (T_d=60 ℃) to 10% (T_d=85 ℃), the drying time of the piles under condition 2 was the lowest. Specifically, the pile with 15 mm stickers took 100 hours, which was 13% less than the 115 hours of drying time for the pile with 20 mm stickers. With condition 3, the pile with 15 mm stickers cost 170 hours, which was 8% less than the 185 hours for the pile with 20 mm stickers. This considerable reduction of kiln drying time indicated that the RF heating was efficient, because the period of RF heating was longer and the cross section of sticker was smaller in the experiment conducted under condition 2.

Drying Consumption

According to the previously defined drying schedule, the statistical data of energy consumption and kiln drying time were shown as below:

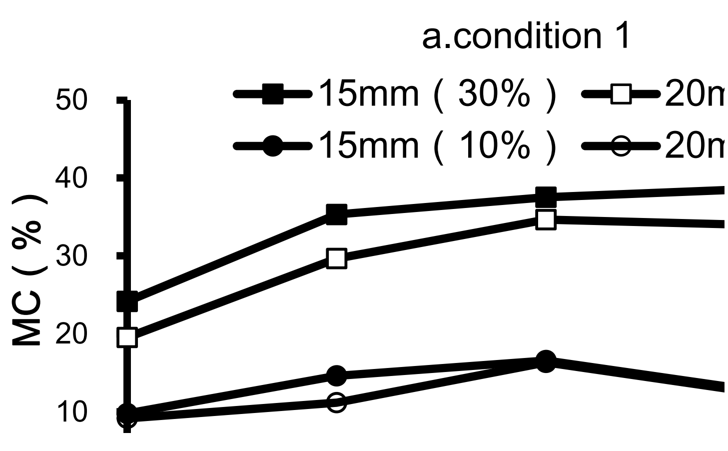
Table 2. Energy Consumption and Drying Time of Different Drying Periods with Different Thickness Stickers

Condition	sticker (mm)	50% - 30%		30% - 20%		20% - 10%	
		energy (kwh)	time (h)	energy (kwh)	time (h)	energy (kwh)	time (h)
Condition 1	15	8.28	84.5	8.46	70.5	20.41	97.2
	20	6.08	73.3	6.55	59.5	17.05	81.2
Condition 2	15	42.31	46.1	24.83	26.2	34.17	33.1
	20	35.47	42.1	22.53	25.9	46.9	49.5
Condition 3	15	51.24	64	45.12	50	57.09	53.9
	20	42.67	56.3	39.17	44.8	85.32	81.5

For HA heating under condition 1, both energy consumption and kiln drying time were much greater for the piles with 15 mm-thick stickers. For the hybrid heating under conditions 2 and 3, both energy consumption and kiln drying time for the piles with 15 mm-thick stickers were much greater during the periods that the MC dropped from its initial green lumber value to 20%. During the third period, however, both drying time and energy consumption showed the opposite tendencies. The total energy consumption of the piles with 15 mm-thick stickers was lower than that of the piles with 20 mm-thick stickers. Specifically, total energy consumption was reduced by 3.5% and 9% under conditions 2 and 3, respectively.

Drying Quality

Layered MC



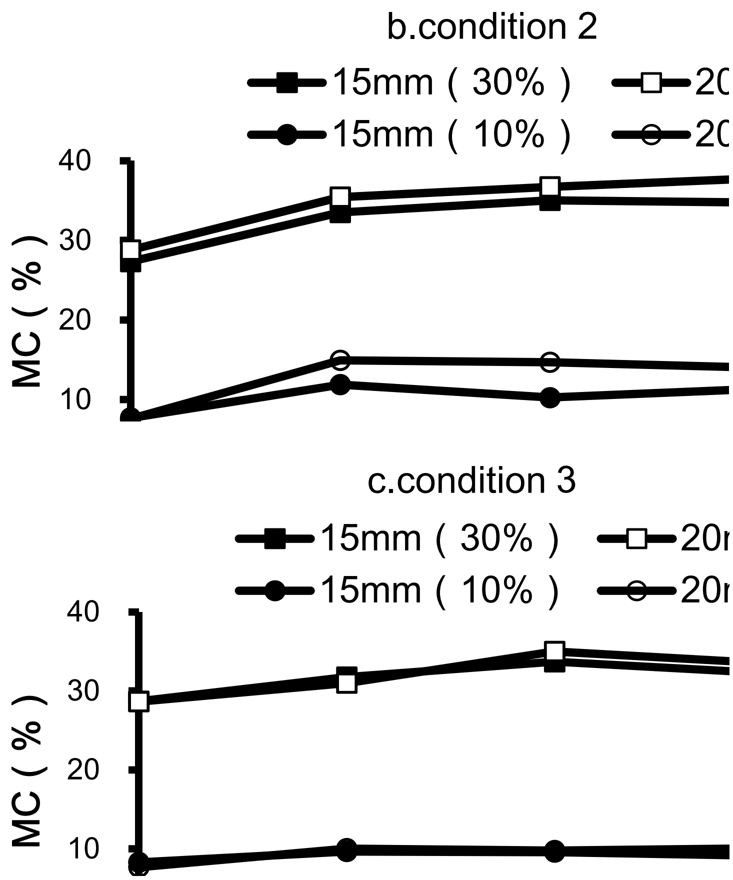


Fig. 4. MC distribution in the thickness direction of sawn lumber (a, b, and c correspond to conditions 1, 2, and 3, respectively) .

Table 3. SD of MC

Thickness (mm)	Condition	SD
15	1	3.605
	2	1.901
	3	1.732
20	1	2.81
	2	3.996
	3	2.064

The values of SD stand for the drying uniformity of the piles, which corresponded to the MC deviation cures in the thickness direction (Fig. 4). The smoother the MC deviation cures were, the smaller the SD became. This meant more drying uniformity of piles.

Figure 4 shows that when 15 mm-thick stickers were adopted, the MC distribution in the thickness direction decreased to some extent during the experiments conducted with three conditions. The influence of sticker thickness on MC distribution in the first period was more significant than it was in other periods, because the air circulation was affected by lateral spaces between boards. In the first period, the air speed for the piles with 20 mm-thick stickers was faster, which led to intensive heat and moisture exchange on the surface layer. This situation caused faster water evaporation on the surface layer. The inner moisture migration velocity could not keep pace with the rate of evaporation on surface layer and thus resulted in a greater MC gradient. In the third period, the RF heating lasted for a longer time in the experiments under condition 2. The longer the RF heating lasted, the greater the temperature difference that was created between the inner layer and the surfaces layer. The water movement from the inner layer to the surface layer was accelerated by this temperature difference, which was shown to be the driving force behind water movement during HF heating. Due to the acceleration of water movement, more and more water evaporated from the surface layer. All of this resulted in the stable influence of sticker thickness on MC gradient. As for the experiments conducted under conditions 2 and 3, the influence of sticker thickness on MC gradient was lower in comparison because the water moved from the inner layer to the surface layer at a slower speed.

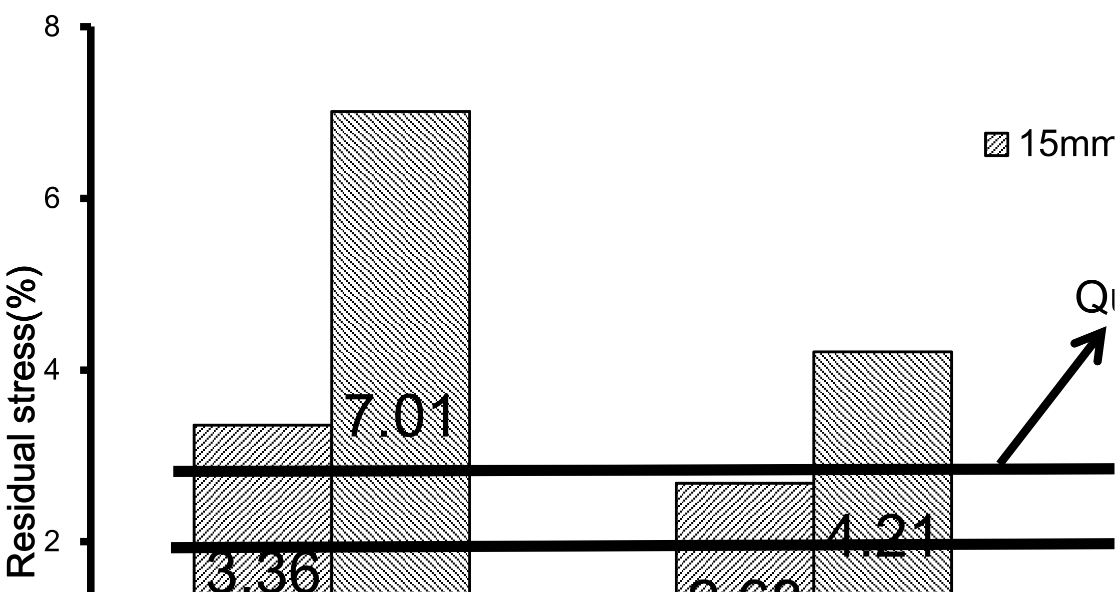


Fig. 5. Residual stress in three conditions with different thickness stickers.

Fig. 5 shows that under all three kinds of drying conditions, the sticker thickness had a significant influence on the residual stress during HA heating and hybrid drying. In the case of the 15mm sticker, the surface evaporation was slower and the MC gradient less, because the air speed in the piles with 15 mm-thick stickers was slower. This situation resulted in lower residual stress. The figure also shows that the hybrid drying conducted under condition 2 (Figure 5) resulted in significantly less residual stress than did the HA heating, although it did result in a fast drying rate.

Drying Defects

During the experiments, specimens in every pile displayed checking, but there was no evidence to prove that the thickness of stickers had any effect on the emergence of defects. After a period of placement, specimens of all piles, with the exception of the experiment with condition 3, displayed obvious checking. More specifically, both the length and quantity of the checking in the piles with 15 mm-thick stickers were much less than the length and quantity in the piles with 20 mm-thick stickers. This showed that the 15 mm-thick stickers could reduce the appearance of drying defects.

To clarify the influence of the thickness of stickers during the hybrid drying process, 15 and 20 mm thickness stickers were selected for experiments with 50 mm-thick pieces of sawn lumber. However, in practical wood drying, 10 mm- and 25 mm-thick stickers also have been widely adopted according to the different thicknesses of sawn lumber. Additionally, the available thickness of the stickers varied according to when and for how long the RF was put into use. Further research will be needed to provide a fuller understanding of the topics just mentioned.

CONCLUSIONS

1. During the heating process, there was a gradual decline in the drying rate. The piles with 15 mm-thick stickers exhibited a higher average drying rate.
2. The piles with stickers of different thicknesses possessed nearly the same drying rate around the FSP. With the decrease in MC, the drying rate of piles with 15 mm stickers dropped more slowly. Compared to that of connective drying, the drying rate of hybrid drying improved significantly at the final stage of drying.
3. Throughout the drying process, the energy consumption of the piles with 15 mm-thick stickers was lower. During the decrease of MC from its initial value to about 20%, the energy consumption of the piles with 15 mm-thick stickers was higher; however, an opposite trend was shown when the MC continued to decline from 20% to 10%.
4. The piles with 15 mm-thick stickers resulted in a lower MC gradient, less residual stress, and less drying defects such as checking and warping after 60 days placement.

ACKNOWLEDGMENTS

This project was supported by the National Natural Science Fund of China (No. 30972306) and Program 948 of the State Forestry Bureau (N0. 2006-4-105). The authors express their sincere gratitude for these funders.

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Article submitted: February 9, 2012; Peer review completed: March 10, 2012; Revised version received and accepted: May 8, 2012; Published: July 25, 2012.