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ORIGINAL ARTICLE

Yasuo Kawai · Yoshinori Kobayashi · Misato Norimoto

Hybrid drying with high-frequency heating and hot air under atmospheric pressure IV: water movement in *Cryptomeria japonica* wood during high-frequency heating

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Abstract The relations among internal temperature, internal pressure, and moisture content distribution in sugi square lumber during high-frequency (HF) heating were determined to clarify the mechanism of water movement during the combination of HF heating and hot air exposure. Green sugi square lumbers were subjected to HF heating under atmospheric pressure. The water movement and pathways in the lumber during HF heating were also investigated. Results showed that internal pressure is the driving force of water movement. HF heating causes a rise in the internal temperature and internal pressure in sugi square lumber. Ordinarily, water in lumber evaporates from the surfaces of lumber during hot air drying. However, with HF heating the internal pressure is generated by the increased temperature, and liquid water is driven not only parallel to the grain but also perpendicular to the grain of the lumber. The ratio of the amount of liquid flow in the parallel and perpendicular directions ranged from 2:3 to 1:3. When the movement of water in the lumber was traced with a 0.5% aqueous solution of acid fuchsin, water was found to move through the lumber in the longitudinal direction and then flow in a direction perpendicular to the grain or in the radial and tangential directions.

Key words Water movement · HF heating · Sugi (*Cryptomeria japonica* D. Don) · Internal pressure · Internal temperature

Y. Kawai (✉) · Y. Kobayashi
Institute of Wood Technology, Akita Prefectural University, 11-1 Kaieizaka, Noshiro, Akita 016-0876, Japan
Tel. +81-185-52-6985; Fax +81-185-52-6976
e-mail: kawai@iwt.akita-pu.ac.jp

M. Norimoto
Wood Research Institute, Kyoto University, Kyoto 611-0011, Japan

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Introduction

Drying of, or the removal of excess water from, lumber is an important requirement in wood products. During drying, water in liquid or vapor phase moves from high to low moisture content zones via capillary action or diffusion. Sugi (*Cryptomeria japonica* D. Don), an important plantation species in Japan, is refractory to drying because of its impermeability and the high moisture content in its heartwood. Various pretreatment methods have been recommended to improve the drying characteristics of sugi wood, including pond storage,[1,2] explosion treatment,[3] laser incising, and the utilization of fungi,[4] bacteria,[5] or enzymes.[6] Although their ability to improve the wood's drying characteristics have been confirmed, these methods have not yet been used in practical applications because they demand a long drying time, special equipment, and separate processes.

Various methods of drying have also been recommended for sugi square lumber, such as high-temperature drying, high-frequency vacuum drying, and so on. However, these methods also have some problems, such as large consumption of electrical energy and the resultant degradation of wood during industrial drying of sugi square lumber. We developed a new drying method that eliminates these problems. It is a combination of high-frequency (HF) heating and hot air drying under atmospheric pressure. We have already reported the results of the drying characteristics on laboratory-scale experiments[7] and the energy consumption and costs using an industrial-scale hybrid dry kiln.[8]

The mechanisms of wood drying using conventional methods have been studied by several researchers.[9] We previously reported the relations between the internal pressure and moisture condition,[10] internal temperature and internal pressure,[11] and internal pressure and water movement[12] for this combination drying method in sugi square lumber. This article aims to clarify the driving forces, water movement, and water pathways in sugi lumber to improve this drying method.

Materials and methods

HF heating method

A high-frequency generator (6.78MHz, 6kW) was used for HF heating. Each specimen was placed between a charged and a grounded electrode under atmospheric pressure. The moisture content of the green lumber ranged from 80% to 120%.

Measurement of water flow

Figure 1 shows the method for measuring water outflow from the two end cross sections of the lumber during HF heating. The total weight loss (A) of the specimens was monitored using a load cell. The water outflows (B) from the two cross sections were caught in plastic bags installed at the lumber ends and then weighed. The water outflows (C) from the four edge surfaces were computed from the total weight loss of each specimen and the amount of water outflow from the two cross sections.

Observation of water movement

Figure 2 shows the measurement of water pathways in the lumber. A hole (20mm diameter, 60mm depth) was bored at the midsection of each specimen, and stain (acid fuchsin 0.5% water solution) was driven into it by pressurized nitrogen gas. The gas pressures (200 and 360kPa) were chosen based on our previous experiments on internal pressures in lumber during HF heating.[10,11]
The lengths of the stained areas in the longitudinal, tangential, and radial directions were measured to determine water movement in the lumber caused by the applied pressures.

Results and discussion

Relations among temperature, pressure, and moisture gradient

Two behavioral patterns of the internal temperature and internal pressure of the lumber during HF heating were observed.[10,11] One pattern showed a low moisture content near the core of the lumber that maintained a longer period of internal pressure over 160kPa. The other pattern showed a higher moisture content than the former but it could not keep the internal pressure over 160kPa.

Based on these results, it could be concluded that the internal pressure drove the water around the core to the surface zones of the lumber. When the internal pressure was higher than 160kPa, it had a significant effect on the amount of water flow.

Water pathways

Based on the driving force of the water movement, it was confirmed that the water around the core was moved to the surface zones by the internal pressure generated during HF heating. Figure 3 shows the amount of water outflow of the lumber from the two cross sections and four edge surfaces during heating at 101°C for 30min. The total water outflow was measured as weight loss. As previously mentioned, water outflow from cross sections was initially observed when the temperature of the lumber reached 60°C. The specimen continued to lose weight as the temperature rose from 60°C to 101°C. After the temperature of the lumber reached 101°C, the internal pressure decreased gradually and the weight loss stopped. The ratio of water outflow from cross sections to that from the surfaces was 2:3 at this point.

There was much more water outflow and the internal pressure was higher when the specimens were heated to 120°C than when they were heated to a maximum of 101°C (Fig. 4). The internal pressure also dropped but stayed over 160kPa, and the weight loss continued even after HF heating was stopped at 120°C. When the internal pressure dropped to 160kPa, the cross section/surface water outflow

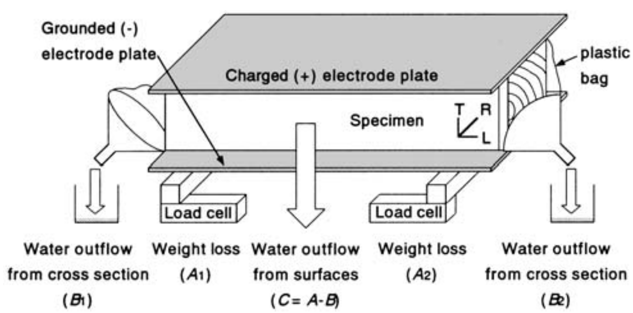

Fig. 1. Measurement of water outflow during high-frequency (HF) heating. Total weight loss (A) = $A_1 + A_2$. Water outflow from cross section (B) = $B_1 + B_2$. Water outflow from surfaces (C) = $A - B$. L, logitudinal direction; T, tangential direction; R, radial direction. Specimen size: 120 (T) × 120 (R) × 1000 (L) mm

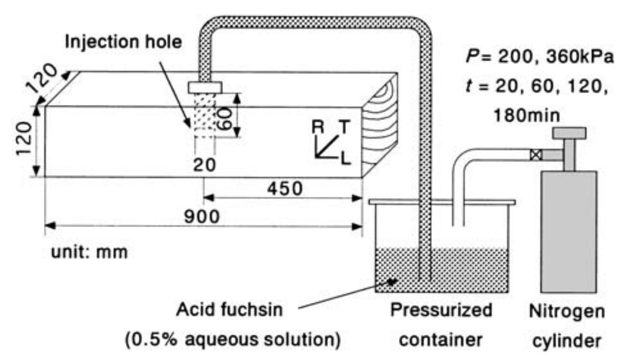

Fig. 2. Measurement of the water pathway in lumber under nitrogen gas pressure

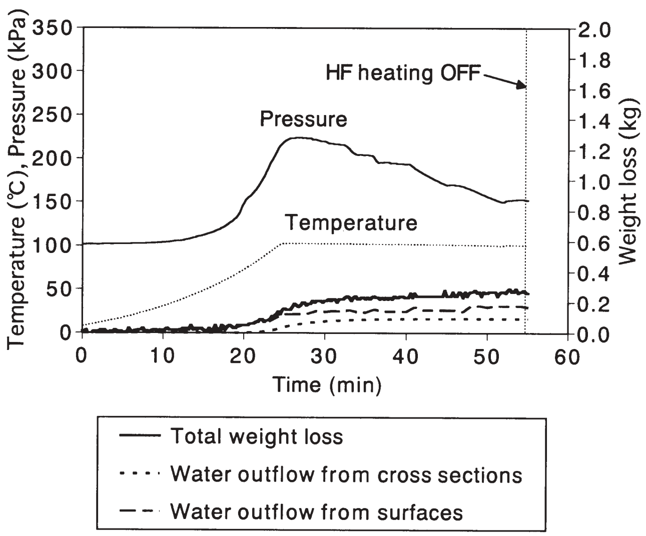

Fig. 3. Relations among internal temperature/pressure and weight losses. HF heating temperature and time are 101°C and 30 min, respectively

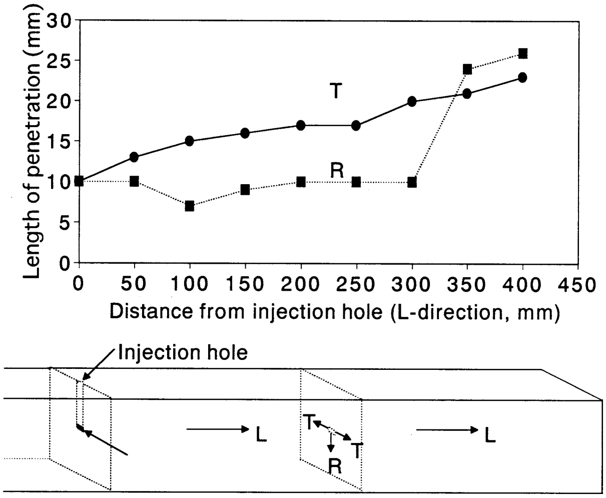

Fig. 5. Relation between penetration length of stain and distance from injection hole at 200 kPa. Manner of penetration. *Arrows* indicate the penetration direction

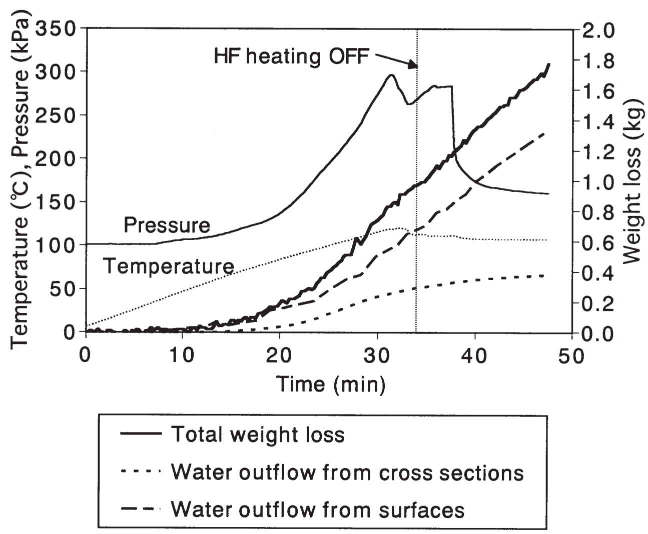

Fig. 4. Relations among internal temperature/pressure and weight losses. HF heating was turned off at 120°C

ratio was 1 : 3. Based on the amount of water outflow at the two cross sections and the four edge surfaces (Figs. 3, 4), it became evident that water moves in two directions during HF heating of lumber: the longitudinal direction and perpendicular to the grain.

To measure the distance of water movement and determine the water pathways, 0.5% aqueous solution of acid fuchsin was impregnated into the lumber under 200 or 360 kPa of nitrogen gas pressure. The water pathways could be easily observed as traces stained by acid fuchsin.

The aqueous solution of the stain ran through the lumber in the longitudinal direction and then flowed out of the cross sections. There was also evidence of penetration of the stain solution perpendicular to the grain. Figure 5 shows the relation between the length of stain penetration perpendicular to the grain (i.e., in the radial R and tangential T directions) and its distance from the injection hole at 200 kPa for 20 min in lumber with a moisture content of 20.0%. After the increasing the distance, penetration of the stain in the R and T directions also increased, which can be explained as follows: In wood, the liquid flows more easily in the longitudinal (L) direction than in the radial or tangential direction. Near the injection hole the pressure was high such that there was smooth flow parallel to the grain (L) because liquid flow parallel to the grain is easier than that the perpendicular to the grain. As the distance from the injection hole increased, the pressure decreased and the stain accumulated in an amount sufficient to allow penetration perpendicular to the grain, especially 350 mm distant from the injection hole. Therefore, some flow of the stain in the R and T directions were observed. This phenomenon suggests that the stain flowed parallel to the grain mainly due to gas pressure in the range of 300 mm from the injection hole. The flow was then driven by two forces: internal pressure and penetration perpendicular to the grain 300 mm from the injection hole.

This phenomenon was often observed in lumber with a low moisture content around the fiber saturation point. Penetration of a stain or preservative is affected by the moisture content of the lumber.[13] Figure 6 shows the penetrating length of the stain in the case of high moisture content (96.2%) at 360 kPa for 60, 120, and 180 min. Penetration of the stain in the T direction increased with the treatment time and slightly increased following the increases in the distance from the injection hole. On the other hand, penetration of the stain in the R direction decreased following the increase in distance. As the treatment time increased, the distance the stain reached was longer, as was the penetration length. This result shows that liquid flow perpendicular to the grain is difficult especially in the R direction in high moisture content lumber, but long periods

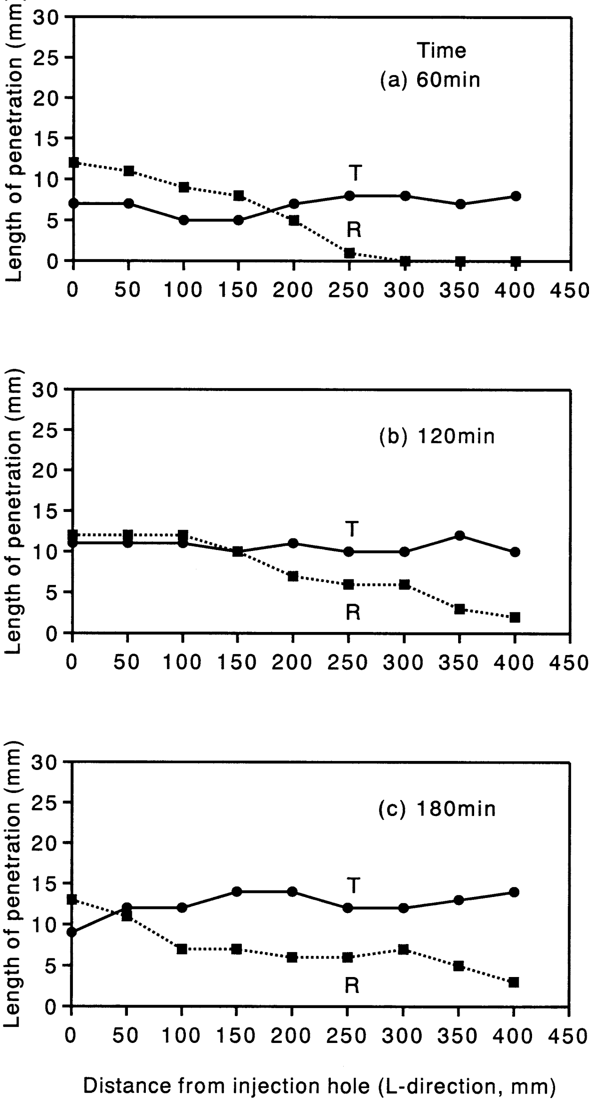

Fig. 6. Relation between penetration length of stain and distance from injection hole at 360kPa

of pressurization can make liquid flow perpendicular to the grain.

These results suggest that liquid water can move not only in the L direction but also in the T and R directions by internal pressure. The manner of water movement depended on the moisture content. The flow of water in the R direction becomes more difficult as the moisture content increases, especially to the fiber saturation point.

Conclusions

To clarify the movement of water in sugi square lumber during HF heating, the driving force, the direction of movement, and the pathways were investigated. The results are as follows. (1) During HF heating of sugi square lumber, there is a gradual build-up of internal pressure starting at around 60°C, and at the same time liquid water flowed out of the cross sections. At around 80°C the internal pressure rose drastically. Maximum pressure was reached at the maximum temperature. (2) Water movement from the core to surfaces was accelerated when the internal pressure reached above 160kPa. Internal pressure was shown to be the driving force of water movement during HF heating of sugi square lumber. (3) Water moves in two directions: parallel to the grain toward the end cross sections and perpendicular to the grain toward the surface. The cross section/surface liquid flow ratio ranged from 2:3 to 1:3, depending on the period and intensity of internal pressure and the moisture content of the lumber. (4) These results suggest that water moves not only in the longitudinal direction but also in the tangential and radial directions with HF heating.

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