Mechanism of heat transfer using water in wood pores during wood densification

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Abstract. Heat treatment was used for softening purposes during wood compression. Water was impregnated into wood pore to study heat transfer of wet wood along the process. Heat treatment of 3 hours before compression were measured at the center-side of compressed wood pores that perpendicular to compression direction. Temperature measurement of experimental results and simulation model were compared and discussed.

1. Introduction
Compressed wood is properties enhancement of a wood by reduces void part that increased bulk density [1] and improved its mechanical properties utilizing hydrogen bonding. Wood compression steps are: first vapor-heating (plasticization); pressing (deformation); second vapor-heating (permanent fixation) [3, 4, 5, 6] and cooling [7]. Water in form of vapor was used in every steps of wood compression. Study of water in a compressed wood at liquid, vapor and super-heated phases is necessary to understand mechanism of permanent fixation, plastic deformation and wood softening.

Principle of wood softening or plasticization [8] are to reduce required force [9] and to prevent cell wall damage in process of wood compression [10]. Heat or steam treatment could be use for this purpose [11]. The important consideration is that heat could be transferred in form of conduction, convection [12] or radiation by hot plate, steam or microwave, respectively and should exceed glass transition temperature of lignin [13]. Comparison on heat transfer of dry and wet wood is required to study mechanism of thermal conduction in a wood.

Wood temperature is influence amount of compression deformation force parallel to its direction. This force magnitude should not exceed limit of compression stress to prevent cell wall damage. The two parameters of temperature and force is an important consideration in deformation step of wood compression. Therefore, viscoelastic properties of wood is necessary for a formulation of wood compression methods.

Final important steps in wood compression is permanent fixation. There are three proposed mechanism to achieve permanent fixation such as stress relaxation, cross linking materials, and water resistance application [14]. Internal materials stress relieving considered as an effective methods to achieve permanent fixation [15]. This stress is depend to amount of heat transferred to final product of compressed wood, and heat conduction is one of methods for permanent fixation.
Heat conduction in a wood with impregnated water into its pores was investigated to learn effect of water in wood compression process. Beside higher heat capacity, water also have cooling properties and interesting molecular interaction with wood materials. This study discussed about comparison between heat transfer modeling and experimental results of temperature measurement in wood compression. With a main aim to improves theoretical approach in thermodynamic process of compressed wood.

2. Materials and Methods

2.1. Experiment condition

A 50 mm x 50 mm x 120 mm (Paraserianthes falcataria (L.) I.C. Nielsen) respectively in radial, tangential and longitudinal direction, was used as a sample and dried in a oven with 100°C for 24 hours prior densification. Water was impregnated into the sample by dipped in a water container inside a pressure vessel, then supplied with 7 kg/cm² compressed-air. Then, the sample was put between 176°C hot press plates (Compression Molding Machine, NF- 50-HH, Shinto Metal Industries Ltd., Osaka, Japan) for 3 hours, prior densification. The hot press plate temperature was chosen based on lignin melting point range from 124 to 176°C [16]. Sample temperature was measured using a type K thermocouple and read by a panel meter (Omega, DP462, Omega Engineering, Inc., Norwalk CT, USA) and illustrated in Fig. 1. After 3 hours of preheating the sample then compressed until compression ratio \( CR = 0.87 \) [9].

![Figure 1](image)

**Figure 1.** Measurement of preheating and compression temperature at the center side of compressed wood perpendicular to compression direction.

2.2. Modeling condition

The modeling framework were used following steps [17]. **Step 0:** Set up as precisely as possible the reasons for constructing the model and its objectives. Heat treatment is use in wood densification processes of preheating for wood softening or plasticization followed by compression and deformation, finished with fixation until cooling [5, 7]. Fastest heating duration and fewer processing sequences is desirable to reduce energy requirement that implied manufacturing cost. This mathematical model was simulated in order to know constitutive equations for achieve optimum wood densification duration and heat treatment condition.

**Step 1:** Study the problem as it is in real life. Heat transfer of dry and wet wood was observed by measuring sample temperature during preheating and compression steps as illustrated in Fig. 1. Temperature and time of preheating and each compression strokes were measured then compared with modeling results. **Step 2:** Data collection and analysis in real life. Temperature data of hot press plates and sample during preheating and compression were collected in experiments. Time stamps and temperature were measured during 3 hours preheating and at each compression strokes. Temperature were measured by thermocouple in a center hole at the side compressed wood perpendicular to
compression direction. Modeling and simulation was used Energy2D software [18] with parameters that represented experimental condition were presented in Table 1.

| Parameters                        | Dry sample | Wet sample | Unit  |
|-----------------------------------|------------|------------|-------|
| Background temperature            | 36         | 36         | °C    |
| Thermal boundary condition        | Dirichlet  | Dirichlet  | (constant temperature) |
| Upper boundary temperature        | 176        | 176        | °C    |
| Right boundary temperature        | 80         | 80         | °C    |
| Lower boundary temperature        | 176        | 176        | °C    |
| Left boundary temperature         | 80         | 80         | °C    |
| Conductivity                      | 0.025      | 2.3        | W / (m °C) |
| Specific heat                     | 1012       | 2.3        | J / (kg °C) |
| Kinematic viscosity               | 0.00001568 | 0.00001568 | M² / s |
| Thermal expansion coefficient     | 0.00025    | 0.00025    | m/(s² °C) |

3. Results and discussion

Step 3: Controlled laboratory studies and simulations. Results were presented as a comparison between temperature measurement of experiment and simulation model of dry and wet wood at preheating and compression steps. Three hours time frame was shown for preheating results. However, temperature measurement and simulation model during densification process were presented as function of the compression ratio (CR). Convergence temperature distribution of simulation model during preheating and compression also presented for dry and wet wood condition.

3.1. Preheating temperature of oven-dried condition

Result in Fig. 2 is shown that experimental and simulation temperature of sample during 3 hours preheating relatively has similar curve shape. Temperature difference between experimental and simulation was happened at pre-convergence within 1 hour time frame. The difference might indicated that heat transfer efficiency of experimental apparatus was lower than modeling condition. Heat insulation on compression punch and dies might improve rate of heat flux transferred to the sample.

Temperature distribution of simulation model shown on Fig. 3 that high temperature was concentrated around top and bottom plates. Stream of heat as indicated by white lines on Fig. 3 shown that heat flux was flown from vertical to horizontal direction. The distribution might improved by supplying heat sources on every side of samples. Therefore, temperature homogeneity and wood softening / plasticization process could reached within shorter time period.
3.2. Temperature of oven-dried sample during compression

Temperature of oven-dried sample during compression was shown in Fig. 4. Results were indicated that sample temperature was increased proportionally with increased of compression ratio (CR). This results is in good agreement with Asako et. al research that thermal conductivity of compressed wood increased proportionally to its density [5]. However, there was temperature difference between simulation model and experimental results from CR about 0.5. This difference might caused by lower temperature fluid (water vapor) from center location at longitudinal direction [12]. This in-homogeneity temperature might reduced by supplying heat at longitudinal direction in form of conduction or forced convection. On the other hand, temperature distribution at left and right side of compressed wood was shown slight cooler temperature. This phenomena is a possible caused of internal stress [15] that implied strain recovery of a compressed wood.

3.3. Preheating temperature of water-impregnated

Result in Fig. 6 is shown that a big gap between experimental and simulation temperature of sample during 3 hours preheating. This difference might caused by higher heat capacity of water compared to wood, in brief wood impregnated with water required additional heat to increase its temperature.
Beside heat insulation, supply of heat from every side of samples, additional potential room for improvement is to reduced water or moisture content of wood prior compression process. Hopefully, temperature in-homogeneity in wood as illustrated in Fig. 7 could reduced significantly.

3.4. Temperature of impregnated sample during compression

Temperature of wet sample during compression were compared between experiment and simulation model is shown on Fig. 8. Experimental results of wet samples was have a big temperature difference compared to simulation results. Possible caused, beside water has high heat capacity also it has latent heat during transformation from liquid to vapor. On condition of $CR < 0.8$ some water spill over the wood pores and results were indicated that sample temperature was not exceed 100°C until $CR > 0.8$. Followed that condition heat added to compressed wood could increased the temperature passed 100°C. In summary, heat treatment begin to transform residual water in the wood into vapor. Beside beneficial of lower required force in wood compression [9] water impregnated wood has limitation on the transfer of heat. On the other hand, temperature distribution pattern of wet wood as shown in Fig. 9 is not different with dry wood compressed wood that shown in Fig. 5.

Step 4: Construction of a conceptual qualitative model. The qualitative model that constructed from comparison between experiment and simulation results is describe in the following. Sample
temperature and heat transfer efficiency are depended on heat insulation; compression ratio (CR); heat coverage from every direction (radial, tangential and longitudinal); heat flux / rate; heat amount to increase temperature (specific heat) and for phase transformation (latent heat); heat type (conduction, convection and radiation); and water or moisture content of a wood. Further modeling steps of 5, 6, and 7, that required for a mathematical model is will be future works of this study.

**Step 5:** Conclusions, predictions, and recommendations that follow for the qualitative model. Qualitative model presented in step 4 considered as enough for followup improvement on heat transfer efficiency of wood compression apparatus. However, there are some limitation that may required quantitative model approach. Such as entalphy of water vaporation (latent heat); standard enthalphy of formation of cellulose form glucose, that was predicted may improve mechanical properties of compressed wood; and heat capacity of every wood chemical components. Another important consideration is required energy to form desirable hydrogen bonding [19] for improve mechanical properties of compressed wood [20, 21]. This model limitations and constraints that describe above are future agenda of this study. Including iteration process from step 5 to step 12 are future agenda to understand the thermodynamic system of compressed wood that describe at following list. **Step 6:** Abstraction and symbolic representation; **Step 7:** Derive the equations that govern the phenomena.; **Step 8:** Model testing.; **Step 9:** Model limitations and constraints.; **Step 10:** Predictions and sensitivity analysis.; **Step 11:** Extensions and refinements.; **Step 12:** Compounding.

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