

A review of computational and experimental analysis of high temperature thermal treatment of wood based on thermowood technology.

Mohammad Azarshab^{1,*}, Ali Khoshnam², Seyed Karim Sharifi³

1-Damoon choob mandegar-Mechanical engineer (manufacturing engineering)

2-independent researcher-Mechanical expert (fixed and rotating equipment)

3- Independent researcher – Turbomachinery and automotive expert

*Corresponding Author: info@dmoonchoob.com

ABSTRACT

This article talks about a way to make wood better by heating it at high temperatures between 180-240 °C. By doing this, the wood becomes more stable and lasts longer. The article focuses on a specific method called ThermoWood technology.

Scientists made a 3D computer model to understand how heat and moisture move inside the wood during the heating process. They used special equations to describe these changes and made sure their model worked by comparing it with real-life experiments.

The article explains that the model and the ThermoWood heating method could help create better wood products, and the scientists hope to do more research on this in the future.

Keywords: Heat and moisture transfer, ThermoWood technology, High-temperature wood treatment, CFD, Mathematical modelling, Validation, Thermally modified wood,

1. INTRODUCTION

This introduction talks about how wood, which is made up of different parts like cellulose and lignin, can get damaged when it's outside because of sunlight, rain, and other things. To protect wood and make it last longer, people use a process called heat treatment. This makes wood stronger and more stable, and it's better for the environment than using chemicals.

There are different ways to do heat treatment, but they all involve heating wood to high temperatures, around 160-260 °C. One method, called ThermoWood, uses water vapor to protect the wood while it's being heated.

Understanding heat treatment also means understanding how heat and moisture move through the wood. To do this, scientists make computer models and use special equations. By solving these equations, they can figure out how to make wood even stronger and more durable during the heat treatment process.

2. MATHEMATICAL FORMULATION

This section talks about the math used to understand the heat treatment process. The problem is like a batch of wood being heated up in a special environment, as shown in Figure 1.

2.1. Solving the problem of how fluids move (called hydrodynamics)

Based on the average velocities measured in the furnace, the flow regime is expected to be turbulent. The three-dimensional Navier–Stokes, energy and concentration equations are considered as follows:

Continuity:

$$\frac{\partial(\rho_f u)}{\partial x} + \frac{\partial(\rho_f v)}{\partial y} + \frac{\partial(\rho_f w)}{\partial z} = 0 \quad (1)$$

Momentum

X-momentum

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_f u) + \frac{\partial}{\partial x}(\rho_f uu) + \frac{\partial}{\partial y}(\rho_f uv) + \frac{\partial}{\partial z}(\rho_f uw) \\ = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}[(\mu_{eff}) \frac{\partial u}{\partial x}] + \frac{\partial}{\partial y}[(\mu_{eff}) \frac{\partial u}{\partial y}] + \frac{\partial}{\partial z}[(\mu_{eff}) \frac{\partial u}{\partial z}] \end{aligned} \quad (2)$$

Y-momentum

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_f v) + \frac{\partial}{\partial x}(\rho_f uv) + \frac{\partial}{\partial y}(\rho_f vv) + \frac{\partial}{\partial z}(\rho_f vw) \\ = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}[(\mu_{eff}) \frac{\partial v}{\partial x}] + \frac{\partial}{\partial y}[(\mu_{eff}) \frac{\partial v}{\partial y}] + \frac{\partial}{\partial z}[(\mu_{eff}) \frac{\partial v}{\partial z}] \end{aligned} \quad (3)$$

Z-momentum

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_f w) + \frac{\partial}{\partial x}(\rho_f u w) + \frac{\partial}{\partial y}(\rho_f v w) + \frac{\partial}{\partial z}(\rho_f w w) \\ = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left[(\mu_{eff})\frac{\partial w}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\mu_{eff})\frac{\partial w}{\partial y}\right] + \frac{\partial}{\partial z}\left[(\mu_{eff})\frac{\partial w}{\partial z}\right] \end{aligned} \quad (4)$$

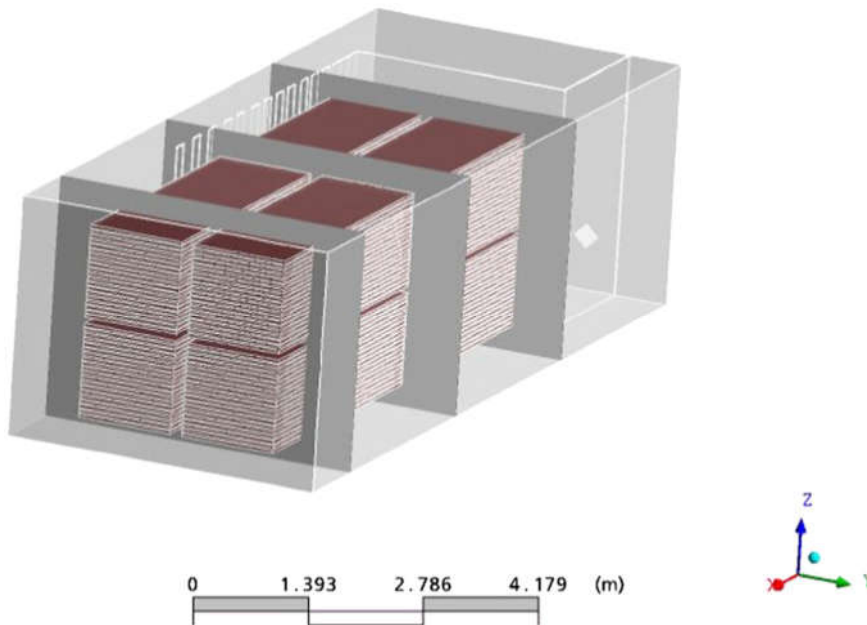


Fig. 1. Global schematic of the physical model.[21]

Energy equation

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_f c_{pf} T) + \frac{\partial}{\partial x}(\rho_f u c_{pf} T) + \frac{\partial}{\partial y}(\rho_f v c_{pf} T) + \frac{\partial}{\partial z}(\rho_f w c_{pf} T) = \\ \frac{\partial}{\partial x}\left[K_{eff}\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_{eff}\frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_{eff}\frac{\partial T}{\partial z}\right] \end{aligned} \quad (5)$$

Concentration equation

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_f C) + \frac{\partial}{\partial x}(\rho_f u C) + \frac{\partial}{\partial y}(\rho_f v C) + \frac{\partial}{\partial z}(\rho_f w C) = \frac{\partial}{\partial x}\left[D_{eff}\frac{\partial C}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_{eff}\frac{\partial C}{\partial y}\right] + \\ \frac{\partial}{\partial z}\left[D_{eff}\frac{\partial C}{\partial z}\right] \end{aligned} \quad (6)$$

he Standard k-ε Model
 k-Eddy kinetic energy

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho_f K) + \frac{\partial}{\partial x}(\rho_f uK) + \frac{\partial}{\partial y}(\rho_f vK) + \frac{\partial}{\partial z}(\rho_f wK) \\ & = \frac{\partial}{\partial x} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x} \right] + \frac{\partial}{\partial y} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial y} \right] + \frac{\partial}{\partial z} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial z} \right] + P_k - \rho_f \varepsilon \end{aligned} \quad (7)$$

ε-Rate of dissipation of turbulence energy

$$\begin{aligned} & \frac{\partial}{\partial t}(\rho_f \varepsilon) + \frac{\partial}{\partial x}(\rho_f u\varepsilon) + \frac{\partial}{\partial y}(\rho_f v\varepsilon) + \frac{\partial}{\partial z}(\rho_f w\varepsilon) \\ & = \frac{\partial}{\partial x} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x} \right] + \frac{\partial}{\partial y} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial y} \right] + \frac{\partial}{\partial z} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial z} \right] \\ & + \frac{\varepsilon}{k} (C_1 P_k - C_2 \rho_f \varepsilon) \end{aligned} \quad (8)$$

$$\mu_{eff} = \mu + \mu_t \cdot k_{eff} = k_q + \frac{\mu_t C_{pf}}{\sigma_T} \cdot D_{eff} = D + \frac{\mu_t}{\sigma_T} \cdot \mu_t = \frac{C_\mu \rho_f k^2}{\varepsilon}$$

In the above equations μ_t is turbulent dynamic viscosity, P_k is the production of turbulent kinetic energy due to shearing, σ_k , σ_ε , σ_T and σ_C are turbulent Prandtl numbers defined for the relevant variable. The values of the model constants for all models considered are $\sigma_k=1.0$, $\sigma_\varepsilon=1.4$, $\sigma_T=1.0$, $\sigma_C=1.0$, $C_1=1.44$, $C_2=1.92$, $C_\mu=0.09$. The turbulence model presented above is valid only in the effects, due to the small local Reynolds number of turbulence. To account for these regions for computing turbulent flows, the classical wall function method [16] is retained. The wall functions are used to bridge the near-solid-wall region in the case of the standard k-ε model.

The integration of k and ε equations from fully turbulent region to the wall results in this equation for the wall shear stress:

$$\tau_w = \frac{\rho_f C_\mu^{\frac{1}{4}} k^{\frac{1}{2}}}{\ln(y^+)} u \quad (9)$$

where u is the average velocity component parallel to the wall (u for the wall in x direction, v for the wall in y direction and w for the wall in z direction). Similarly, the following expression is

obtained for the ε near the wall region:

$$\varepsilon = \frac{C_{\mu}^{\frac{3}{4}} k^{\frac{3}{2}}}{C_{\mu} y} \ln(C_k y^+) \quad (10)$$

2.2 Using that information to understand how heat and moisture move through the wood (called heat and mass transfer)

.Heat transfer

$$\rho_m \frac{\partial h_m}{\partial t} = \frac{\partial}{\partial x} \left(k_{qx} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{qy} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_{qz} \frac{\partial T}{\partial z} \right) \quad (11)$$

.Moisture transfer

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left(D_x \frac{\partial M}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial M}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_z \frac{\partial M}{\partial z} \right) \quad (12)$$

2.3. Initial and boundary conditions

The initial conditions are given by the uniform distribution of temperature and moisture content in the wood board at reference time zero:

$$T(x, y, z, 0) = T_0, M(x, y, z, 0) = M_0 \quad (13)$$

The equations expressing the continuity of the state variables and their respective fluxes at the interface were used as boundary conditions for both problems and are given by:

Temperature continuity:

$$T_f = T_s \quad (14)$$

Concentration continuity:

$$C_f = C(T, M)_s \quad (15)$$

Heat balance:

$$\left[k_q \frac{\partial T}{\partial n} \right] = \Delta H_{lv} D \frac{\partial C_f}{\partial n} + k_f \frac{\partial T}{\partial n} \quad (16)$$

Species flux balance:

$$\left[\rho_s D_s \frac{\partial M}{\partial n} \right] = D \frac{\partial C_f}{\partial n} \quad (17)$$

The inflow and outflow conditions for the flow field are given as follows:

$$\begin{aligned} \text{Inflow} \Rightarrow \{ U = U_g, v = 0, w = 0, T = T_g, C = C_g, k = k_{in}, \varepsilon = \varepsilon_{in} \\ \text{Outflow} \Rightarrow \{ P = 0, \frac{\partial T}{\partial X} = 0, \frac{\partial C}{\partial X} = 0, \frac{\partial K}{\partial X} = 0, \frac{\partial \varepsilon}{\partial X} = 0 \end{aligned} \quad (18)$$

2.4. Thermophysical properties of wood

The accuracy of this model depends on the accuracy of the thermophysical properties of wood. The density (ρ), specific gravity (G_m), specific heat (cp), and thermal conductivities (k_{qx} , k_{qy} , k_{qz}) of moist wood were calculated using relations proposed by Simpson and Tenwold [17] and Siau [18].

$$\rho = 1000 * G_m \left(1 + \frac{M}{100} \right) \quad (19)$$

The heat capacity and thermal conductivity of moist wood are functions of both moisture content and temperature:

$$C_p = \frac{C_{p0} + 0.01 C_{pw} M}{1 + 0.01 M} + A_c \quad (20)$$

where M is moisture content in (%), cp_w is the heat capacity of water, and cp_0 is the heat capacity of dry wood, and A_c is a parameter which is a function of moisture content and temperature. cp_0 and A_c are given below:

$$c_{p0} = 0.1031 + 0.003867T \quad (21)$$

$$A_c = M(-0.06191 + 2.36 * 10^{-4}T - 1.33 * 10^{-4}M) \quad (22)$$

The thermal conductivity of wood in longitudinal direction is approximately two times higher than that in transversal or radial directions as reported in the literature [19]. The thermal conductivities in different directions are:

$$k_{qz} = k_{qy} = G_m(0.1941 + 0.004064M) + 0.01864(k_{qx} = 2k_{qy} = 2k_{qz}) \quad (23)$$

Heat of vapourization data from steam tables was fitted to a polynomial as a function of temperature and given as [19]:

$$\Delta H_{lv} = 2.792 * 10^6 - 160T - 3.43T^2 \quad (24)$$

The other transport and physical properties and flow conditions used are summarized in Table 1

3. NUMERICAL SOLUTION

To understand the heat treatment process, scientists used special computer software called ANSYS-CFX10. This software helps solve complex equations that describe how heat and moisture move through the wood.

They made sure their computer model gave accurate results by testing different grid sizes. After finding the best grid size, they used it for all their calculations. It took 6 hours on a computer to simulate 60 hours of the heat treatment process.

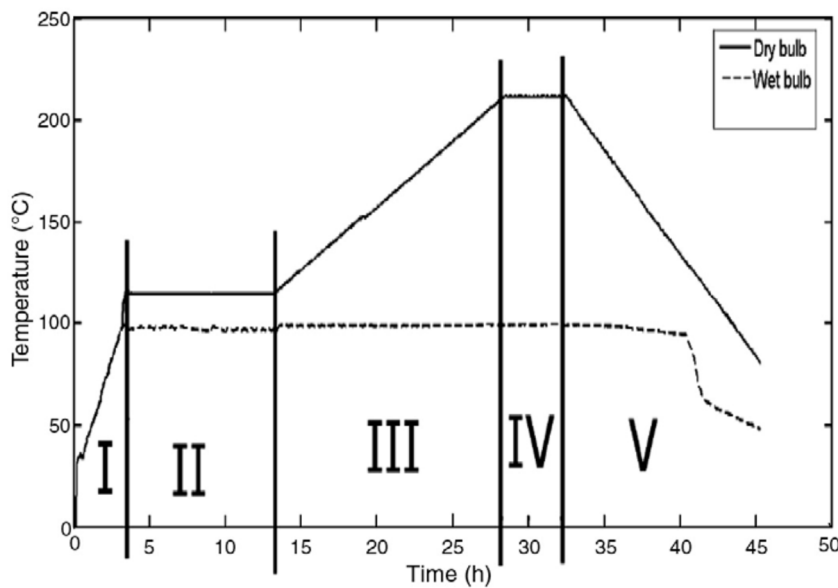


Fig. 2. Typical ThermoWood heat treatment schedule (ThermoWood Handbook [9]).

Table 1 Parameters used in the simulations[21]

Property	Expression	Reference
G _m	0.660	19
γ	$\gamma = 1 - G_m(0.667 + M)$	18

$\rho_d(kgm^{-3})$	660	17
$D_s(m^2s^{-1})$	$D_s = \frac{\sqrt{\gamma}D_{bt}D_v}{(1-\gamma)(\sqrt{\gamma}D_{bt}+(1-\sqrt{\gamma})D_v)}$	18
$D_v(m^2s^{-1})$	$D_v = \frac{1.29*10^{-13}(1.0+1.54M)P_sT_k^{1.5}}{(T_k+245.18)}$	18
$D_{bt}(m^2s^{-1})$	$D_{bt} = \exp(-9.9 + 9.8M - \frac{4300}{T_k})$	18
$D(m^2s^{-1})$	$D = 9.2 * 10^{-9}T_k^{2.5}/(T_k + 245.18)$	18
$p_s(pa)$	$P_s = 3390\exp(-1.74 + 0.0759T_c - 0.000424T_c^2 + 2.44 * 10^{-6}T_c^3)$	18
$C_{pW}(Jkg^{-1}K)$	4185	
$M_0(\%)$	15-17%	
$T_0(K)$	280-298	
$U_g(ms^{-1})$	15	

4. EXPERIMENTAL APPARATUS

In this study, they used a method called ThermoWood technology. It uses superheated steam at 130°C and normal air pressure as a protective gas during the heat treatment. The experiments were done in an industrial oven with temperatures below 220°C.

The wood they used was jack pine boards with an initial moisture content of 17%. They measured the moisture content with a special tool called a wand moisture meter. They also measured the temperatures inside the wood every 60 seconds using thermocouples connected to a data collection system. This section explains how scientists used computer software to model the heat treatment process and how they conducted their experiments in an industrial oven using the ThermoWood technology.

5. RESULT AND DISCUSSION

This section discusses the results of the study and how well the computer model matches the real-life experiments. Scientists compared temperature and moisture content changes over time using three different schedules with varying amounts of vapor and duration. Overall, the model predictions matched the experimental data quite well.

There were some small differences in moisture content predictions due to vapor amounts and wood properties. During the heat treatment, temperature increased and moisture content decreased almost in a straight line over time, except at the beginning because of steam and condensation.

The airflow inside the furnace was complex, with high speed near the fan. Airflow moved around the wood, providing heat and removing moisture. The temperature was highest near the furnace walls and decreased towards the center of the wood. As time went on, temperature increased, and moisture content reduced, because the surrounding gas temperature was higher than the wood temperature.

Temperature and moisture levels inside the wood varied, so the time needed to reduce moisture content by half differed in various parts of the wood.

In conclusion, the computer model successfully predicts how temperature and moisture change during the heat treatment process, which can help control wood quality more effectively.

In this article, a coupled high temperature heat treatment of wood based on ThermoWood technology was studied numerically. The mathematical formulation consists of modelling simultaneously the hydrodynamics in the fluid domain and heat and mass transfer in the porous domain. The developed model is effective to evaluate the moisture and temperature profiles during wood thermal treatment. Simulations of wood thermal treatments for the schedules at high temperatures show that the model adequately reproduces the main features of the heat treatment of wood. It could be used in future developments of industrial furnaces. By achieving good control of the process parameters, as represented by the model, better control of the final quality of thermally modified wood could be achieved.

The model needs to be validated at more extreme operating conditions, such as the higher treatment temperatures of 260 °C, and expanded to three-dimensional treatment kilns. The computational fluid dynamics model used can also be used to design optimised kilns for heat treatment which yield an improved and uniform quality product.

Furthermore, the three-dimensional coupled model presented in this work can be extended to include a correlation of internal stress and strain calculations as a function of temperature and moisture content. This would facilitate the development of measures to prevent cracks formation, as well as to ensure that the product has reduced shrinkage and swelling properties. This article studied the heat treatment process for wood using ThermoWood technology and made a computer model to better understand it. The model looked at both the flow of fluids and the transfer of heat and moisture in the wood. The results showed that the model could predict what happens during the heat treatment process, which could help improve wood quality control.

In the future, the model should be tested under more extreme conditions, like higher temperatures, and expanded to include more complex three-dimensional situations. The model can also help design better kilns for heat treatment that produce a more consistent and high-quality product.

Finally, the model could be improved by adding information about how wood changes shape and stress when heated and how that affects cracks and shrinking.

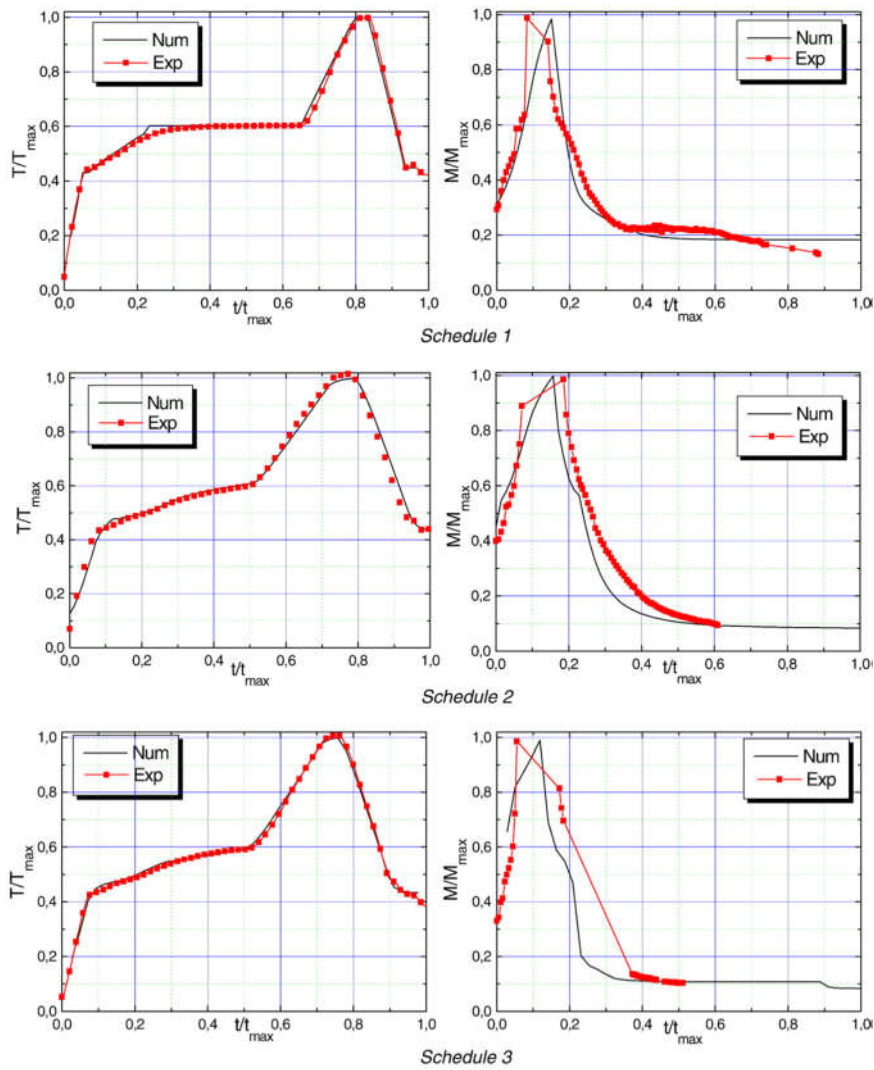


Fig. 3. Comparison of predicted and experimental normalized temperature evolution (left) and normalized moisture content evolution (right) during heat treatment for different schedules (final temperature $T_{g,final}=210$ °C) [21]

CFX

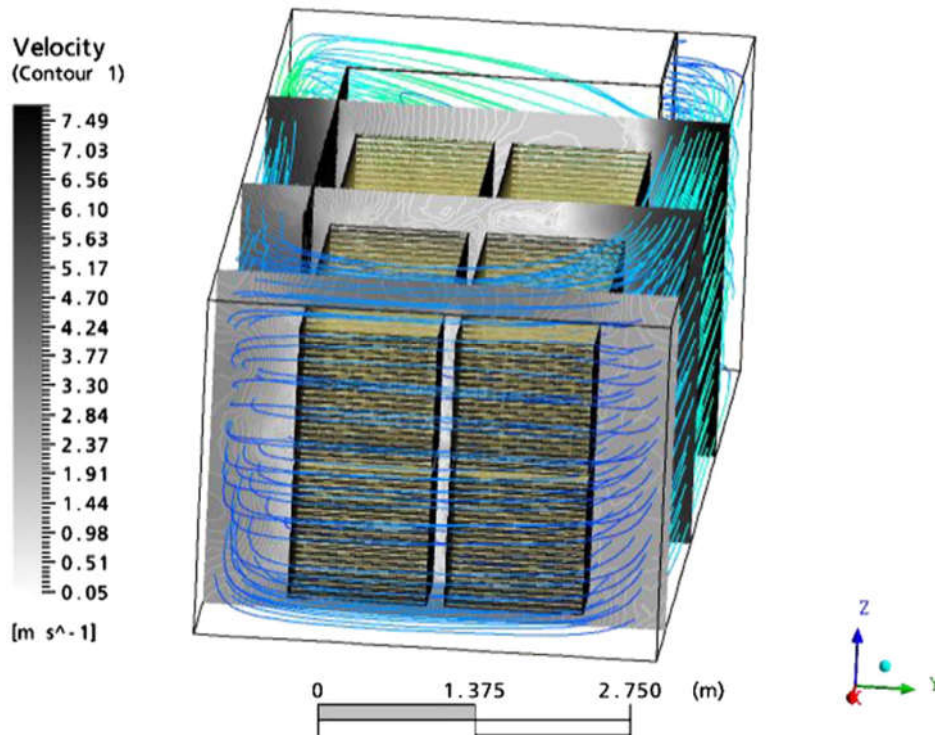


Fig. 4. Velocity contours for three positions ($X=3$ m, 6 m, 9 m) during heat treatment ($T_{g,final}=210$ °C, $M_0=17\%$).[21]

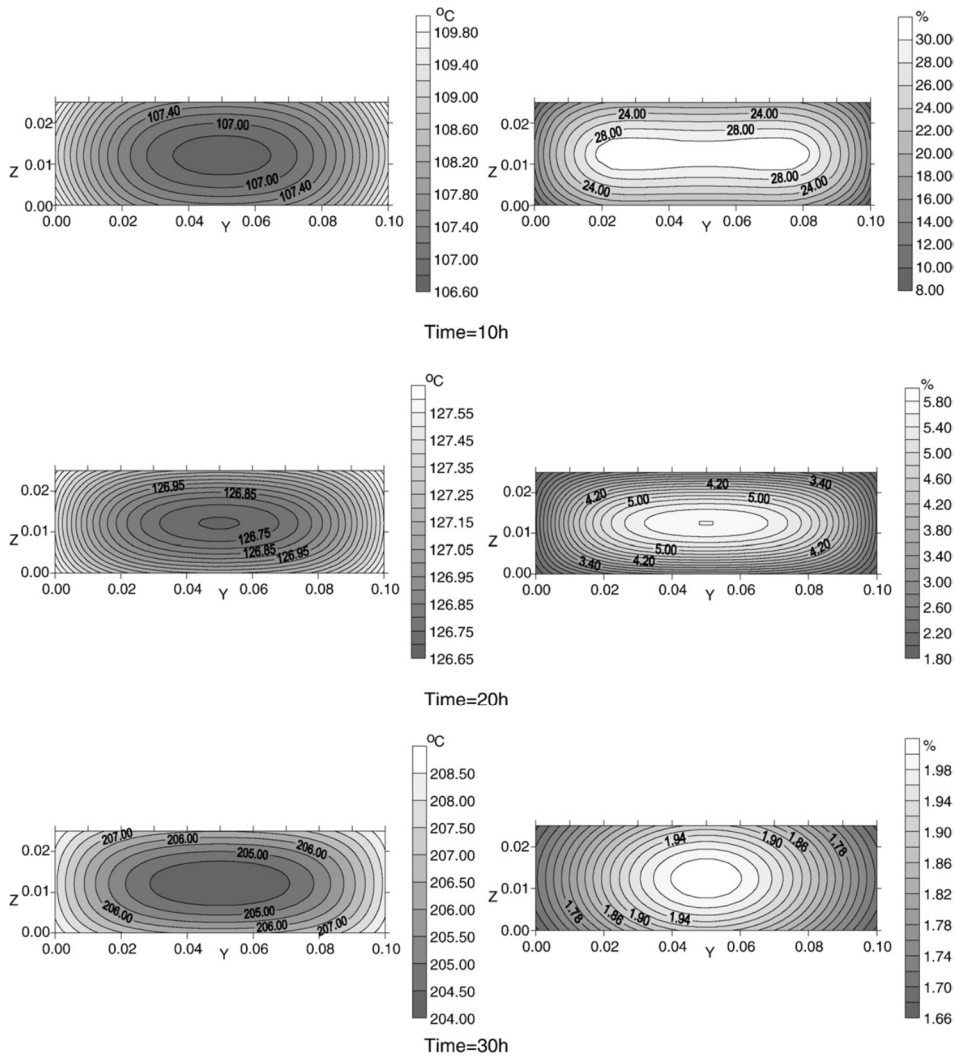


Fig. 5. Spatial profiles of temperature and moisture content during heat treatment ($X=1m$, $T_{g,final}=210\text{ }^{\circ}C$, $M_0=17\%$).[21]

6. CONCLUSION

The study of the heat treatment process for wood using ThermoWood technology. Scientists created a computer model and tested it against real-life experiments, finding good agreement between the two. Any differences between the model and experiments might be because of chemical reactions in the wood that weren't considered in the model.

The model successfully simulated what happens inside the industrial furnace during the heat treatment process. It can be a helpful tool for designing new furnaces, solving problems in existing ones, and making them work more efficiently. By using this model, researchers can see what's happening inside the furnace and the wood without having to do as many experiments, saving time and money.

In the future, the model could be made even better by studying the specific properties of different types of wood and learning more about the chemical reactions that happen during the

heat treatment process. This information can be used to improve the model and make it more accurate.

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