Journal of Heat and Mass Transfer Research 11 (2024), Serial Number 21, 33 – 42

Journal of Heat and Mass Transfer Research

Journal homepage: https://jhmtr.semnan.ac.ir

Semnan University

ISSN: 2383-3068

Research Article

Mathematical Modeling for Vacuum Infrared Radiation Drying of Pyinkado (*Xylia Xylocarpa*)

Duc Le Anh [a], Kim Bui Thi Thien [b*], Huong Hoang Thi Thanh [b]

[a] *Faculty of Mechanical Engineering, Nong Lam University, Ho Chi Minh city, Vietnam*

[b] *Faculty of Forestry, Nong Lam University, Ho Chi Minh city, Vietnam*

ARTICLE INFO

Article history:

Received: 2023-05-29

Revised: 2024-01-07

Accepted: 2024-01-09

Keywords:

Heat and mass transfer;
Vacuum drying;
Pyinkado;
Mathematical model.

ABSTRACT

The main goal is to build a mathematical model to describe the heat and moisture transfer process and experiment to determine the appropriate vacuum drying mode for Pyinkado wood material. According to the objective above, research has been conducted using the infrared vacuum drying method for Pyinkado, and a mathematical model has been developed to represent the heat and moisture transfer processes during the drying process. Solve mathematical models using the finite element method. Comsol Multiphysics software is used to simulate the drying process. Results are shown through images and temperature and humidity distribution charts. Experimental results recorded the distribution of temperature and humidity during the vacuum drying process of Pyinkado, compared with results calculated from a mathematical model with profiles and trends consistent with the drying experiment. The largest average error when drying using the infrared radiation vacuum method is less than 5%. Determine the appropriate technological parameters for the vacuum drying process of wood with a thickness of 50 mm. The parameters are as follows: drying temperature Ts = 58.9 °C, pressure p = 0.2 bar, and infrared radiation intensity Phn = 625–641 W/m2.

1. Introduction

The important thing in drying wood is the drying time and the quality of the wood after drying, especially for woods with resin like Pyinkado (Xylia Xylocarpa). This substance hinders moisture evaporation, prolongs the drying time, and causes many defects. Wood cracks and warps after drying. Therefore, it is necessary to have a solution to shorten the drying time and reduce the rate of wood defects after drying. Therefore, the drying method is one of the most effective solutions because this is a factor that directly affects the drying process. Researching drying methods suitable for drying materials to shorten drying time while reducing wood defects after drying, which contributes to improving the quality and value of wood materials, which need to be quickly resolved.

Vacuum drying is based on the pressure difference, which is the main driving force of the drying process. The principle of lowering the boiling point of water under low pressure has been studied as one of the effective solutions to the above problem. Research results by scientists have proven that vacuum wood drying technology is a technique that brings great efficiency to the wood drying industry through recent studies such as Chen et al. [1], Deliiski, Syuleymanov [2], He et al. [3], Defo et al. [4],

* **Corresponding author.**
E-mail address: thienkim@hcmuaf.edu.vn

Cite this article as:
Le Anh, D., Bui Thi Thien, K., Hoang Thi Thanh, H., 2024. Mathematical Modeling for Vacuum Infrared Radiation Drying of Pyinkado (Xylia Xylocarpa). *Journal of Heat and Mass Transfer Research*, 11(1), pp. 33-42.
https://doi.org/10.22075/JHMTR.2024.30781.1448

Koumoutsakos et al. [5], Torres et al. [6], He Zhengbin et al. [7], Fu et al. [8], Guler, Dilek [9], Scott Lyon et al. [10]. Of the three heat transfer methods: conduction, convection, and radiation, only heat transfer by radiation is effective in a vacuum environment (Aniesrani Delfiya [11], Sachin Gupta1, Kishan Kum [12], Gunduz, Aydemir, Karakas [13], Allegretti et al. [14], Surini et al. [15], Jae-Woong Han et al. [16], Xuan-Quang Nguyen et al. [17], Rautkari et al. [18], Sahin et al. [19], Sattho et al. [20]). The project chose heat transfer using infrared radiation because this method of heating dried materials by volumetric heating has many advantages compared to other heating methods. From there, the drying method combining vacuum with radiant heating brings great advantages in greatly promoting the process of moisture evaporation in wood. It helps significantly shorten drying time due to the simultaneous use of many types of driving forces during the drying process, such as moisture flow, heat flow, and pressure differences. With many energy sources being maximized for the moisture removal process, this method is a suitable solution for wood that is difficult to dry and contains a lot of resin, like Pyinkado.

Vacuum drying shows that the application of vacuum-drying technology has been around the world for a long time and is still widely used today [1,8,9]. From the initial studies of low-pressure drying, vacuum wood drying technology was gradually formed. Experimental results of vacuum drying wood showed practical benefits when applied to wood materials, especially hard-to-dry wood [3,5,9].

Through the results of research by scientists worldwide, vacuum wood drying technology has proven to be a highly efficient technology in the wood-drying industry. The studies were applied to timber materials from the Americas and Europe, such as oak, pine, alder, and beech, with high efficiency. It is recommended to apply this drying technology to tropical timber from Asia, especially hard-to-dry timber such as Pyinkado timber, to help improve the quality of the timber and shorten the drying time. In Vietnam, vacuum drying works for rubber wood and Eucalyptus wood are available, but not for others. This is one of the hard-to-dry woods with structural characteristics containing a lot of resin that restricts the drainage process and water when drying at high temperatures, and this draination directly affects the drying time and wood defects occurring during drying.

A technical solution is required for tropical wood that contains a lot of resin, reducing drying time and increasing wood quality, increasing the value of wood products. This is an innovative move for the wood drying industry, helping solve the following three main factors: Infrared radiation heating, vacuum drying technologies, and Pyinkado wood, which is suitable for low-temperature drying because it is difficult to dry at high temperatures.

The study has been conducted to understand the authors' theoretical research results in heat transfer and moisture transfer when drying wood and other porous materials to reach the research objective. Simultaneously, applying mathematical and physical theory to build a physical model of the Pyinkado wood vacuum drying process, a mathematical model describing the nature of heat transfer and moisture transfer in wood materials, solving the mathematical model by the finite element method and finding the solution of the heat and moisture transfer mathematical model, and using the experimental method to determine the thermo-physical properties of Pyinkado wood through which to verify the theoretical model by experiment Based on the experimental results, the appropriate vacuum drying technology parameters contributed to the construction of steps in the Pyinkado wood drying process by the vacuum drying method.

In conclusion, the main objective of research on the drying technology of Pyinkado by vacuum drying was to build a mathematical model of heat and moisture transfer along with experiments to determine the suitable vacuum drying schedules for Pyinkado wood.

2. Materials and Methods

Pyinkado *(Xylia Xylocarpa)* provided by Cuu Long Wood Product Ltd. Samples without dead knots, collapses, or cracks were randomly selected from the board and cut into the dimensions is 500 x 50 x 50 mm with 500 mm length, 50 mm width and 50mm thickness. Its initial moisture ranges from 40 ± 2%.

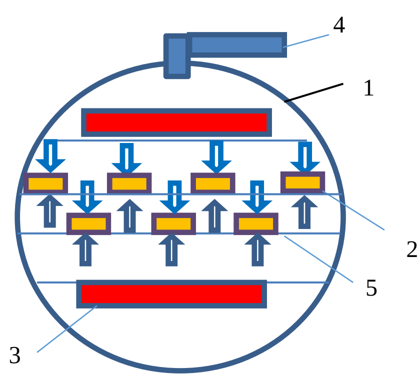


Fig. 1. Vacuum drying chamber model; 1. Drying chamber, 2. Pyinkado, 3. Infrared light, 4. Vacuum, 5. wooden bar

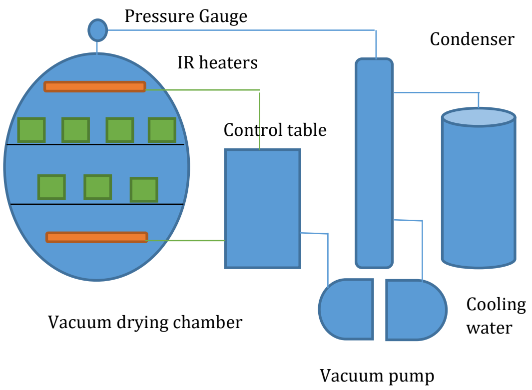


Fig. 2. Vacuum Drying chamber

Pyinkado was dried at a pressure of 0.12 - 0.217 bar and temperature at 45 - 59^{0}C in an infrared vacuum drying chamber, two IR heaters with dimensions 15 x 300 mm were installed on the top and the bottom of the drying chamber. ASIT sensor scale –20^{0}C - 750^{0}C, error ± 0.5^{0}C, the thermal sensor is installed at the hole on the surface of wood samples which displays and regulates the wood temperature. A vogel moisture meter with a scale of 2 - 70%, error ± 0.5 - 1% was used to measure the moisture contents of wood.

Pyinkado wood (2) initial humidity W_{woIN} = 40 ± 2% put into the drying chamber (1), set the temperature of the heating system (3), wood is heated with the support of infrared radiation. The pressure of the vacuum pump is set according to the drying temperature to reach the boiling point of the water in the wood. The system operates under low pressure conditions that match the boiling point of water. The water in the wood evaporates to the wood surface and diffuses in the drying chamber. This process occurs continuously until the wood moisture decreases by 10 ± 1% to meet the requirement after drying.

Mathematical model

Assumptions

The following assumptions were imposed for the heat and mass transfer model during wood vacuum drying:

- The Initial temperature is distributed uniformly in wood, and the biological structure of materials is solid.
- The gas phase and water vapor are considered ideal gases.
- Bonded and free water have the same physical properties.
- The physical heat and latent heat of vaporization are averaged by temperature.
- Heat and moisture transfer is considered 3-dimensional in the x, y, and z directions (based on the cross section: z; radial direction: y; longitudinal direction: x).
- The initial temperature and humidity distribution in wood are uniform.
- The drying chamber is equipped with insulation to ensure that heat loss to the outside environment is limited and almost negligible.
- To simplify the process, ignore the change in volume and shape of the wood during the vacuum drying process.
- The drying process is when the wood receives energy, mainly heat, from a heat source (infrared radiation).

The wood received energy from the heat source, and the moisture from the interior moved to the surface in the vacuum drying. Therefore, the drying process was a process of heat transfer and mass transfer occurring simultaneously. The process of heat and mass transfer occur both inside the wood and between the wood surface and the environment of vacuum drying. Inside the wood was a mix of heat transfer and moisture diffusion. The heat-mass exchange at the wood surface Analyzing the problem of heat and mass transfer in the drying process, includes the heat and mass transfer inside and outside the vacuum drying wood.

The Geometry of the samples:

The geometry of the sample wood was presented in Fig. 1. Heat and mass transfer in the 3D direction were considered in terms of length, width, and thickness. Thus, the heat and mass transfer for wood were simplified as a 3D model.

Governing equations of heat and mass transfer

The heat and mass coupling transfer process in vacuum drying is shown in Fig. 3. The pressure gradient and volume fraction gradient are the primary components of the drying force and operate under the assumptions above. The general heat and mass transfer equations and the initial conditions are shown in the 3D direction as follows:

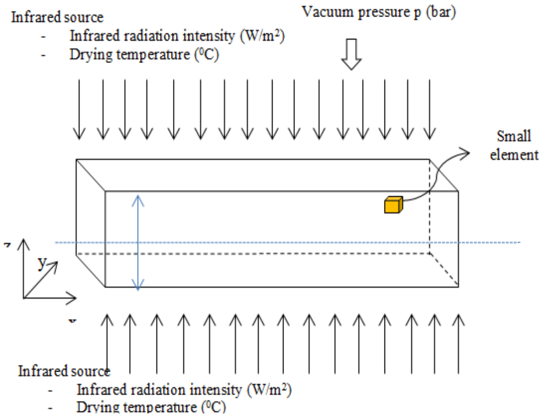


Fig. 3. The geometry of the sample wood

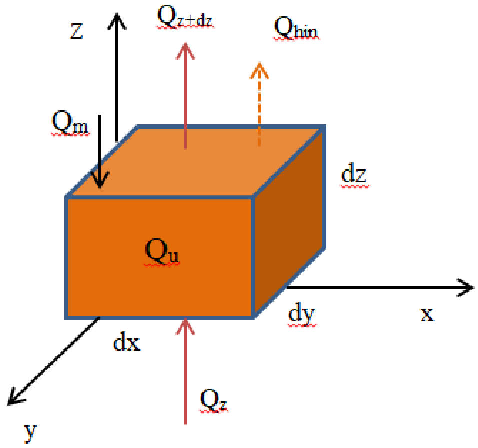


Fig. 4. Heat balance in small element

Heat transfer

Based on the law of conservation of energy, heat balance equation for the small element of the wood drying (Fig. 4) in terms of the z-direction as follows

$$\sum E_g = \sum E_{in} - \sum E_{out} \tag{1}$$

$$Q_u = Q_z + Q_m + Q_{inf} - Q_{x+dx} \tag{2}$$

In there:

+Q_z and Q_{z+dz} were the heat flux in and out of the infinitesimal element at positions z and z + dz, according to Fourier's law calculated as follows (Fu et al., [8], Scott Lyon et al.,[10], Yan Yang et al., [21])

$$Q_z = -k_p \frac{\partial T}{\partial z} dydx \tag{3}$$

$$Q_{z+dz} = Q_z + dQ_z = \left[-k_p \frac{\partial T}{\partial z} + \frac{\partial}{\partial z}\left(-k_p \frac{\partial T}{\partial z}\right) dz\right] dydx \tag{4}$$

+Q_m is the amount of heat required for moisture to change the phase from liquid to vapor in the wood sample

In the researched heat transfer equation, the phenomenon of moisture diffusion affects the temperature field through the amount of heat required to provide moisture to transform the phase from liquid to vapor in the wood sample, and Q_m is calculated by the following (Yan Yang et al., [21])

$$Q_m = D\rho_{wodry} C_p \frac{\partial W}{\partial z}\frac{\partial T}{\partial z} dxdydz \tag{5}$$

+Q_{hin} was the energy provided for the vaporization process called latent heat of vaporization (Yan Yang et al., [21])

$$Q_{hin} = -m_v \Delta h dxdydz \tag{6}$$

+Q_u was the change in internal energy in the element after time dt and was calculated by the formula.

$$Q_u = C_p \rho_{wo} \frac{\partial T}{\partial t} dxdydz \tag{7}$$

Substituting the equations from (3) ÷ (7) into (2), the heat transfer equation written as follows (Yan Yang et al., [21]):

$$C_p \rho_{wo} \frac{\partial T}{\partial t} dxdydz = -k_p \frac{\partial T}{\partial z} dydx + D\rho_{wodry} C_p \frac{\partial W}{\partial z}\frac{\partial T}{\partial z} dxdydx - m_v \Delta h dxdydz - \left(\left[-k_p \frac{\partial T}{\partial z} + \frac{\partial}{\partial z}\left(-k_p \frac{\partial T}{\partial z}\right) dz\right] dydx\right) \tag{8}$$

Simplifying equation (8) (Yan Yang et al., [21]):

$$C_p \rho_{wo} \frac{\partial T}{\partial t} = k_p \frac{\partial^2 T}{\partial^2 z} + D\rho_{wodry} C_p \frac{\partial W}{\partial z}\frac{\partial T}{\partial z} - m_v \Delta h \tag{9}$$

On 3 directions x, y, z equation (9) to (10)

$$\rho_{wo} C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_l \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_r \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_r \frac{\partial T}{\partial z}\right) + D\,\rho_{wodry} C_{wa}\left(\frac{\partial W}{\partial z}\frac{\partial T}{\partial z} + \frac{\partial W}{\partial y}\frac{\partial T}{\partial y} + \frac{\partial W}{\partial x}\frac{\partial T}{\partial x}\right) - m_v \Delta h \tag{10}$$

Mass transfer

The temperature gradient will cause moisture diffusion in the wood sample.

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial W}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial W}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial W}{\partial z}\right) - \frac{\dot{m}_v}{\rho_{wodry}} \tag{11}$$

Initial conditions

$$T = T_0 \text{ when } t = 0 \tag{12}$$

$$W = W_{woIN} \text{ when } t = 0 \tag{13}$$

Boundary conditions

Applying the equation of conservation of energy at the boundary of the wood sample, the equation as follows (Yan Yang et al., [21]):

Surface layer:

$$-\left(k_r \frac{\partial T}{\partial z}\right)_{z=H} = h_R (T_R - T_S)_{z=H} + h\ (T_R - T_S)_{z=H}$$
$$= \varepsilon\sigma_0 \left(T_s + T_R\right)\left(T^2_s + T^2_R\right)\left(T_R - T_s\right) + h\left(T_R - T_s\right) \quad (14)$$
$$= \varepsilon\sigma_0 \left(T_R^4 - T_S^4\right) + h\left(T_R - T_S\right)$$

$$-\left(k_r \frac{\partial T}{\partial y}\right)_{y=B} = h\left(T_R - T_S\right) \quad (15)$$

$$-\left(k_l \frac{\partial T}{\partial x}\right)_{x=L} = h\left(T_R - T_S\right) \quad (16)$$

Center layer:

$$\left(k_l \frac{\partial T}{\partial x}\right) = 0,\ \left(k_r \frac{\partial T}{\partial y}\right) = 0,\ \left(k_r \frac{\partial T}{\partial z}\right) = 0 \quad (17)$$

$$D\left(\frac{\partial W}{\partial z}\right) = h_m W_s,\ D\left(\frac{\partial W}{\partial y}\right) = h_m W_s,\ D\left(\frac{\partial W}{\partial x}\right) = h_m W_s \quad (18)$$

$$D\left(\frac{\partial W}{\partial z}\right) = 0,\ D\left(\frac{\partial W}{\partial y}\right) = 0,\ D\left(\frac{\partial W}{\partial x}\right) = 0 \quad (19)$$

Numerical solution

The experiment model can be controlled [22] and had more measured output responses. The data was used to derive an empirical model linking the outputs and inputs factors. The research used the experiment planning method, which was indicated in Figure 5.

The experimental matrix design was summarized in Table. 1.

The solution of the above governing equations was difficult to obtain by analytical methods. Therefore, the mathematical model represented was solved numerically. To solve the above partial differential equations, the partial derivatives in the equations were, They are approximated by the finite element method (FEM) using COMSOL Multiphysics software. The parameters were calculated based on wood, water, and vapor characteristics. The parameter values are listed in Table 2.

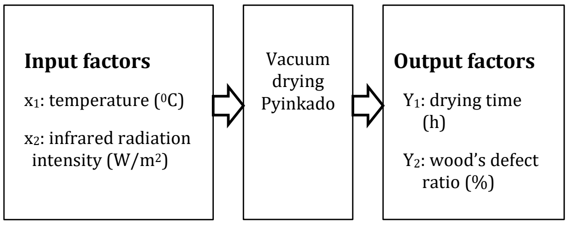


Fig. 5. The experiment model

Table 1. Experimental matrix

	Encode form		Real form	
No.	x_1	x_2	Temperature drying (^{0}C)	Infrared radiation intensity (W/m2)
1	-1	1	47	700
2	1	1	57	700
3	0	-1.414	52	459
4	-1	-1	47	500
5	-1.414	0	45	600
6	1	-1	57	500
7	0	0	52	600
8	1.414	0	59	600
9	0	0	52	600
10	0	1.414	52	741
11	0	0	52	600
12	0	0	52	600
13	0	0	52	600

Table 2. Thermo-physical properties of Pyinkado and other parameters

No.	Parameters	Equations	Reference source
01	Thermal conductivity coefficient	k_l = 0.0122.W + 0.267 (W/m.K) k_r = 0.0043.W + 0.1096 (W/m.K) $k_l = 0.733$ (W/m.K) when W = 40% $k_r = 0.304$ (W/m.K) when W = 40%	Measured by experiment

02	Specific heat of wood	c_{wop} = 8.082.W + 1567.2 (J/kg.K) c_{wop} = 1884.05 (J/kg.K) when W = 40%	Measured by experiment
03	Density of wood	ρ_{wo} = 0.0068.W + 0.7875 (g/cm^3) ρ_{wo} = 1.084 (g/cm^3), W = 40%	Measured by experiment
04	Density of dry wood	ρ_{wodry} = 0.788 g/cm^3	Measured by experiment
06	Diffusion coefficient	$D = 7.10^{-6}\exp\left(-\frac{9200-70.W}{RT}\right)$ (m^2/s)	Siau J.F [23]
07	Latent heat of vaporization	$\Delta h = 2.792.10^6 - 160.T - 3.43.T^2$ (J/kg) $\Delta h = 2382115.086 J/kg = 2382.115 kJ/kg$	Stanish, M.A.; Schajer, G.S.; Kayihan, F. A [24]
08	Mass transfer coefficient	$h_m = \frac{h_{bx}}{\rho_k.c_k.Le^{1-n}} = \frac{h_{bx}.D_{lkbm}.Le^n}{k_k}$ (m/s) $= \frac{h_{bx}.D_{lkbm}}{k_k}.\left(\frac{\frac{k_{bm}}{c_{bm}.\rho_{bm}}}{D_{lkbm}}\right)^n$	Yan Yang, [21], Torres S. S. [25], Zhengbin He [26]
09	Lewis number	$Le = \frac{\alpha_{df}}{D} = \frac{\lambda_{df}}{\rho.D_{aver}.c_p}$	Yan Yang, [21], Torres S. S. [25], Zhengbin He [26]
10	Heat transfer coefficient	$h = 3209{,}07 - 15{,}38T + 2893{,}23lnP + 0{,}392T^2 + 905{,}34(lnP)^2 - 3{,}713TlnP - 2{,}62, 10^{-3}T^3 + 91{,}885(lnP)^2 + 1{,}7, 10^{-3}T^2 lnP$ $h = \frac{m\Delta h}{A(T-T_s)}$	Zhengbin He, Zijian Zhao, Yu Zhang, Huan Lv, Songlin Yi [26]
11	Density of air	$\rho_a = 1.1614 kg / m^3 \approx 1 kg / m^3$ $\rho_a = 4.06.10^{-14}T + 6.86.10^{-12}$ $\rho_k = 19.9738.10^{-12}$	Chen [1]
12	Saturation pressure	$P_0 = 8.75.10^8.e^{\frac{-43472}{RT}}$	Chen [1]
13	Density of saturated steam (temperature from 27 to 200^{0}C)	$\rho_{varser} = 10^6.\exp(-46.49 + 0.26179T$ $-5.0104.10^{-4}T^2 + 3.4712.10^{-7}T^3)$	Stanish et al. [24]
14	Volume evaporation rate of the liquid phase of water in wood	$m_v = 0.04075.v^{0.8}.(p_m - p).A$ $= 0.04075.0{,}5^{0.8}(0.015 - 0.012).0.81$ m_v = 3.588e^{-4} (kg/m^3.s)	Chen [1]
15	System emissivity between radiant panel and wood	$\varepsilon_s = \frac{1}{\frac{1-\varepsilon_R}{\varepsilon_R.A_R} + \frac{1}{F_{ij}.A_R} + \frac{1-\varepsilon_s}{\varepsilon_s.A_s}}$	Yan Yang, [21]
16	Temperature drying	T = T^{0}C + 273.15 = T(K) T = 323.15 K	Measured by experiment
17	Stephen Boltzman number	σ_0 = 5.67.10^{-8} W/m^{2}K^4	
18	Universal gas constant	R = 8.314 kJ/kmol.K	

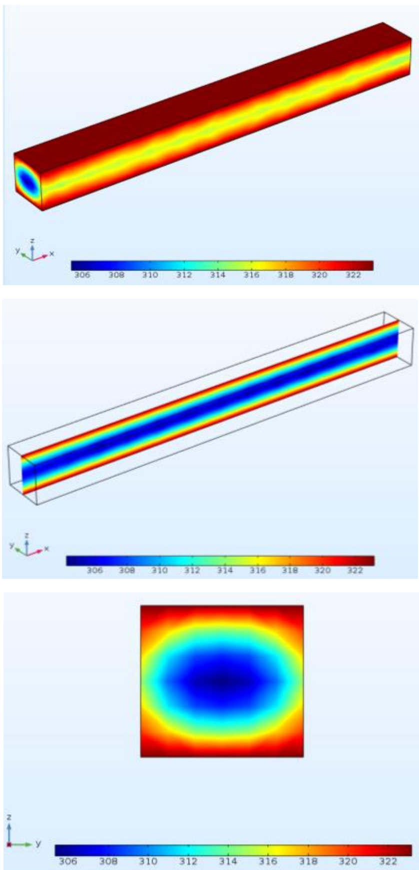
3. Results and Discussion

The heat and moisture transfer equation describes the process of changing temperature and humidity during the vacuum drying process of Pyinkado wood. The results of solving the heat and moisture transfer problem through

simulation will contribute to theoretically predicting the Changes in heat and moisture in wood that occur during the drying process. Besides, to test the compatibility of the math equation with experimentation, the experimental results were compared with the theory to verify the mathematical model and establish a suitable drying mode for the Pyinkado when applying the infrared vacuum drying method.

The results of solving the heat and moisture transfer problem through simulation will contribute to theoretically predicting the changes in heat and moisture in wood (Pyinkado 50x50x500mm) occurring during the drying process.

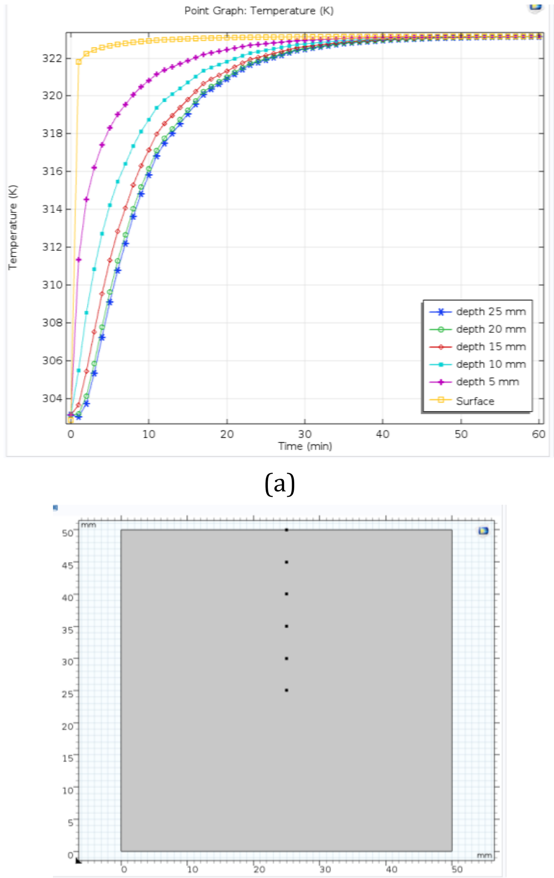
Using numerical methods, solve the system of heat and moisture transfer equations. From the results obtained, determine the heat and moisture distribution during the vacuum drying process of Pyinkado wood. The results of the simulation are displayed via graph.



(a) (b) (c)

Fig. 6. Simulation temperature of Pyinkado 50 x 50 x 500 mm showing the wood (a) longitudinal section, (b) cross-section, (c) at time t = 15 minutes

Figure 6 simulates the temperature on the longitudinal section, cross section, and wood sample (50 x 50 x 500 mm). The simulation graph shows that the temperature appears on the wood surface first; in the heartwood, there is still no appearance. increased temperature. Simulations were conducted on the Oyz cross-section (Figure 6. c) to show the temperature changes along the wood thickness. The temperature on the wood sample was on the surface and inside the wood sample and changed after 15 minutes of drying.



(a)

(b)

Fig. 7. The graph was shown the heat (a) inside the Pyinkado 50 x 50 x 500 mm, (b) six points from surface to center of wood sample

Figure 7 shows the drying temperature curve at 6 points from the wood surface to the center, with a distance of 5 mm between positions on a wood sample 50 x 50 x 500 mm. The graph shows that temperatures increase fastest on the top of the wood, the first surface exposed to heat, then inside the heartwood. The temperature curve is closer to the center, and the smaller the distance, the closer the position, the larger the distance. At the wood surface, the temperature increases faster to reach the drying temperature in a few minutes. The further away from the wood surface, the longer the drying time, especially in the heartwood position, about 60 minutes after reaching the drying temperature. Calculation results from the model show the temperature increase process at locations in the wood and contribute to predicting the temperature change during the vacuum wood drying process. The mathematical model's temperature change value on the surface and center layers of wood matched the test value. The result corresponded with the findings of Yan Yang et al. [21].

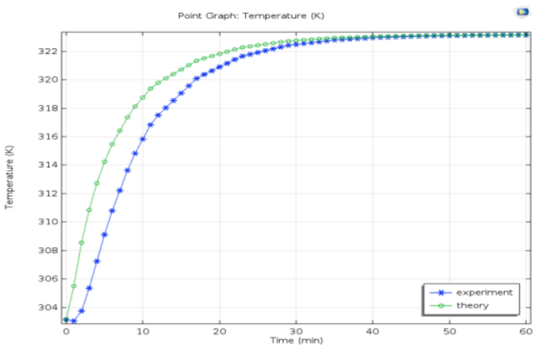


Fig. 8. Comparisons of predicted (theory) and experiment heat values during the vacuum drying.

In Fig. 8, the model can predict the changes in heat with time. However, some discrepancies were observed between the values of the mathematical model (theory) and the experiment. First, the extractives were extracted during the heat treatment; the release of extractable components and the chemical reactions were not considered in the present mathematical model. Second, some errors existed in the actual experiment process, such as heat loss through the wall of the drying chamber, the vacuum stability of the vacuum drying chamber during heat treatment, and so on. Finally, the wood was a heterogeneous material, so the basic densities and moisture content (MC) of different samples or positions of the same sample were virtually different, leading to an uneven heat distribution during the temperature rise process. The value of the mathematical model agreed well with the test value of the temperature changes of the center layer of the dry wood under the heat treatment temperature of 50°C and pressure of 0.2 bar.

The results are illustrated in Fig. 9, where to verify the accuracy of the mathematical model, the experimental values of MC (wet basis) were compared with those of the mathematical model at the center layer of the samples under heat drying. The model-predicted values were in line with the experimental values. During the vacuum drying process, due to the radiation heat used to evaporate moisture and heat wood, the temperature increased, and the moisture decreased with the drying time. Through the action of the heat, the moisture of the interior wood was vaporized and migrated toward the wood surfaces.

Table 3. Experiment and predicted MC

Nu.	Hours (h)	Experiment MC (%)	Predicted MC (%)
1	0	40,4	40,0
2	3	35,5	37,1
3	6	32,3	34,2
4	9	28,7	31,1
5	12	26,4	28,2
6	15	23,5	25,1
7	18	21,1	22,2
8	21	19,7	20,1
9	24	19,1	19,0
10	27	18,9	18,2
11	30	18,6	17,7
12	33	17,7	17,3
13	36	17,0	16,7
14	39	16,8	16,2
15	42	16,5	15,7
16	45	15,9	15,2
17	48	15,2	14,8
18	51	14,9	14,3
19	54	13,9	13,8
20	57	13,8	13,3
21	60	13,5	12,9
22	63	12,9	12,3
23	66	12,3	11,7
24	69	11,7	11,1
25	72	11,1	10,5
26	75	10,3	10,0

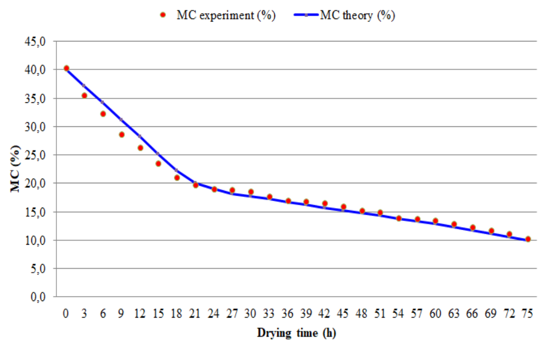


Fig. 9. Comparisons of predicted and experiment MC (wet basis) values during the vacuum drying

Table 3 and Figure 9 show that the predicted results from the theoretical model are consistent and compatible with the experimental wood moisture reduction process. The difference between theoretical and experimental results is that when vacuum drying wood, the heat and moisture values of the material change unevenly in different locations because wood is such a natural material. Many factors further influence the diffusion of moisture. During theoretical research, the complexity of materials and phenomena is ignored. Therefore, the results of the theoretical model show a difference from the experimental results. However, the comparison results show that the drying curves calculated from the theoretical mathematical model have profiles and trends in directions similar to the experimental curve. Therefore, using the developed theoretical mathematical model to predict the moisture reduction process when drying wood using the vacuum drying method is possible. The longer it took for moisture migration to begin, the greater the initial MC. The first MC significantly impacted the lowering of MCs on the inside and outside of the wood. This result was similar to the findings of Yan Yang et al. [21].

Fig. 9 shows that wood moisture content and drying rate decrease as time progresses. It took about 75 hours for the wood to dry at 0.4%/h during drying. The average drying rate was 1.75102/min above FSP. The wood took about 54 hours to dry, and the average drying rate was 0.3102/min below FSP. The drying rate above FSP was about five times that below FSP.

There are two kinds of water in the wood: free water in the cell cavities and bound water in the cell walls. The free water is mainly diffused by capillary tension with a high drying rate, while the bound water is mainly diffused as a gas with a low drying rate. The drying properties of free water and bound water markedly differ. The critical point between free and bound water is the fiber saturation point (FSP), which decreases linearly as temperature increases. FSP is reduced by 0.1% when the temperature increases by 1°C, and the FSP of Pyinkado wood is 20%. The differences in the moisture content of materials between the experimental data and theoretical calculations when considering external resistance factors are less than the differences when no external resistance factors apply.

Experiments show that the process of reducing moisture depends on the thickness of the wood. When drying wood 50 x 50 x 500 mm, it takes 72 hours for the wood's moisture content to decrease from 40% to 10%, while with the same dimension, it only takes 36 hours less than 30 mm thick. The thickness of the wood is reduced by more than half, and the drying time is reduced by half. This relationship shows that the choice of material dimension has an important influence on the vacuum drying time of wood.

The thickness of the samples had a significant influence on their MC. The reduction in the MC of the sample with 40 mm thickness was the slowest for both the surface layer and the core layer, while the drop in the MC of the sample with 20 mm thickness was the fastest, which was similar to the study results of Yan Yang et al. [21]. Thus, the internal moisture must be distributed to the wood's surface to push out the moisture in the wood. The moisture in the wood traveled quickly as the thickness of the wood decreased. As a result, the MC decreased rapidly. When the thickness of the wood rose, it took longer for the moisture to disperse.

4. Conclusions

A mathematical model based on the Navier-Stokes equation has been developed to study the heat and moisture transport phenomena inside wood. These key equations include heat and mass transfer in wood during infrared radiation drying. The model displays moisture content and temperature details as a function of time. The results predicted by the present model are further confirmed with reasonable accuracy against data derived from experimental results. Therefore, numerical modeling is considered a positive tool to explain the heat and moisture transport phenomena inside the wooden slats, and this is ideal for parametric studies that can lead to optimization of the wood drying process. To demonstrate its usefulness, this model is used to study the effects of temperature and radiation power on wood drying time and quality. The results show that drying heat affects the time and quality of wood after drying.

The appropriate technological parameters for the vacuum drying process of Pyinkado wood with a thickness of 50 mm were determined as follows: drying temperature Ts = 58,9°C, pressure p = 0,2 bar, and infrared radiation intensity Phn = 641 W/m2, time drying: 64.29 hours and wood defect rate 5.6%.

Acknowledgements

The authors would particularly like to thank the Nong Lam University laboratory for carrying out the samples presented in our work.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

References

[1] Chen, Z., 1997.Primary Driving Force in Wood Vacuum Drying, (Doctor of Philosophy in Wood Science and Forest Products, Faculty of the Virginia Polytechnic Institute and State University).

[2] Deliiski, N., Syuleymanov1, A., 2006. Influence of molar ransfer coefficient on pressure distribution in beech lumber during its convective-vacuum drying, Original scientific paper, UDK: 630*847.31; 630*847.8. https://hrcak.srce.hr/10847

[3] He, Z., Yao, X., Chen, L., Yi, S., 2010. Theoretic discussion on the way and driving forces of moisture migration in wood during vacuum

drying", The international research group on wood protection. https://www.iufro.org/download/file/6524/1999/iwc10-seoul-IRG_10-40538_pdf

[4] Defo, M., Cloutier, A., Fortin, Y., 2000. Modeling vacuum contact drying of wood the water potential approach. Drying technology, International journal, Vol 18, No. 8, pp. 1737 - 1778.

[5] Koumoutsakos, A., Avramidis, S., Hatzikiriakos, Savvas, G., 2003. Radio Frequency Vacuum Drying of Wood. III. Two-Dimensional Model, Optimization, and Validation. Drying technology, Vol 21, No 8, pp. 1399 - 1410.

[6] Torres, S. S., Jomaa, W., Puiggali, J. R., Avramidis, S., 2011. Multiphysics modeling of vacuum drying of wood, Applied Mathematical Modelling, Vol 35 (2011) 5006–5016. DOI: 10.1016/j.apm.2011.04.011

[7] He Zhengbin, Zijian Zhao, Yu Zhang, Huan Lv, Songlin Yi, 2015. Convective heat and mass transfer during vacuum drying process, Wood Research, Vol 60, No. 6, pp. 929 – 938,. http://www.woodresearch.sk/wr/201506/09.pdf

[8] Fu, Z., Avramidis, S., Weng, X., Cai, Y., Zhou, Y., 2019. Influence mechanism ofradio frequency heating on moisture transfer and drying stress in larch boxed-heartsquare timber, Drying Technology, 1625 – 1632, https://doi.org/10.1080/07373937.2018.1526191

[9] Guler, C., Dilek, B., 2020. Investigation of high-frequency vacuum drying on physical and mechanical properties of common oak (Quercus robur) and common walnut (Juglans regia) lumber", Bio Research. Vol 15, No 4, 7861 – 7871.

[10] Scott Lyon, Scott Bowe, Michael Wiemann, 2021. Comparing Vacuum Drying and Conventional Drying Effects on the Coloration of Hard Maple Lumber. Research Paper FPL-RP-708. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

[11] Aniesrani, D. S, Delfiya, K. Prashob, S. Murali, P. V. Alfiya, Manoj P. Samuel, R. Pandiselvam, 2012. Drying kinetics of food materials in infrared radiation drying: A review, Journal of Food process Engineering

[12] Sachin Gupta1, V. S. Kishan Kumar, 2017. An easy drying schedule for Tectona grandis through vacuum press drying, Ciência da Madeira (Brazilian Journal of Wood Science).

[13] Gunduz, G.; Aydemir, D.; Karakas, G. 2009. The effects of thermal treatment on the mechanical properties of wild pear (*Pyrus elaeagnifolia* Pall.) wood and changes in physical properties. Materials and Design , 30(10), 4391–4395

[14] Allegretti, O.; Brunetti, M.; Cuccui, I.; Ferrari, S.; Nocetti, M.; Terziev, N.,2012.Thermo-vacuum modification of spruce (Picea abies Karst.) and fir (Abies alba Mill.) wood. BioResources , 7(3), pp. 3656–3669.

[15] Surini, T.; Charrier, F.; Malvestio, J.; Charrier, B.; Moubarik, A.; Castéra, P.; Grelier, S,2012. Physical properties and termite durability of maritime pine Pinus pinaster Ait heat-treated under vacuum pressure. Wood Science and Technology , 46, 487–501.

[16] Jae-Woong Han, Dong-Hyuk Keum, Woong Kim, Le Anh Duc, Sung-Ho Cho, Hoon Kim, 2010. Circulating concurrent-flow drying simulation of rapeseed, Journal of Biosystems Engineering, Korean Society for Agricultural Machinery, Vol. 35, No.6, 401 – 407. https://doi.org/10.5307/JBE.2010.35.6.401

[17] Xuan-Quang Nguyen, Anh-Duc Le, Ngoc-Phuong Nguyen, Hay Nguyen, 2019. Thermal diffusivity, moisture diffusivity, and color change of Codonopsis javanica with the support of the Ultrasound for drying, Journal of Food Quality, Vol.2019, Article ID 2623404,13. https://doi.org/10.1155/2019/2623404

[18] Rautkari, L.; Honkanen, J.; Hill, C.A.S.; Ellis, D.R.; Hughes, M. 2014. Mechanical and physical properties of thermally modified Scots pine wood in high pressure reactor under saturated steam at 120, 150 and 180°C. European Journal of Wood and Wood Products 2014, 72, pp. 33–41.

[19] Sahin, H.T.; Arslan, M.B.; Korkut, S.; Sahin, C. 2011. Colour changes of heat-treated woods of red-bud maple, European hophornbeam and oak. Color Research & Application, 36(6), 462–466.

[20] Sattho, T., Yamsaengsung, R., 2005. Vacuum drying of rubberwood. PSU-UNS International Conference on Engineering and Environment - ICEE-2005, Novi Sad 19-21, University of Novi Sad, Faculty of Technical Sciences Trg D. Obradovića 6, 21000 Novi Sad, Serbia & Montenegro.

[21] Yan Yang, Jianxiong Lu, Chunlei Dong, Tianyi Zhan, Jinghui Jiang and Bei Luo, 2016. Mathematical model of heat and moisture transfer in Alder Birch wood during the thermo-vacuum treatment and its application in the quantitative control of the wood color, Drying Technology, Vol 34, No.13, 1567-1582, https://doi.org/10.1080/07373937.2015.1137308

[22] Safary, M. and Amiri Chayjan, R., 2016. Optimization of Almond Kernels Drying under Infrared-vacuum Condition with Microwave Pretreatment using Response Surface Method and Genetic Algorithm, Journal of Agricultural Science and Technology 18:1543-1556.

[23] J. Siau F, 1984. Transport Processes in Wood. Springer-Verlag: Berlin, Heidelberg, New York, 1984.

[24] Stanish, M.A, Schajer, G.S, Kayihan, F. A, 1986. Mathematical model of drying for hygroscopic porous media, AICHE Journal 1986, 32(8), 1301–1311. https://doi.org/10.1002/aic.690320808

[25] Torres. S. S., Jomaa. W. , Puiggali. J. R. , Avramidis. S., 2011. Multiphysics modeling of vacuum drying of wood. Applied Mathematical Modelling, Vol 35 (2011) pp. 5006–5016.

[26] Zhengbin He, Yu Zhang, Zhenyu Wang, Zijian Zhao, and Songlin Yi, 2016. Reducing wood drying time by application of ultrasound pretreatment, Drying technology, Vol. 34, No.10, pp. 1141 – 1146. https://doi.org/10.1080/07373937.2015.1099107