Vol. 14, No. 3 (2025): 772 - 780 http://dx.doi.org/10.23960/jtep-l.v14i3.772-780

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Drying Characteristics of Pine Wood (*Pinus merkusii* Jungh. et de Vriese) Using Hot Air, Infrared, and Combined Infrared-Hot Air

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Article History:

Received : 06 January 2025
Revised : 07 February 2025
Accepted : 19 February 2025

Keywords:

Drying,
Hot air,
Infrared,
Temperature.

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ABSTRACT

This research aims to determine the drying characteristics of Merkusii pine wood (Pinus merkusii Jungh. et de Vriese) using three methods, including the hot air drying, infrared, and combined infrared-hot air. The drying characteristics included temperature distribution, reduction in moisture content, drying rate, wood surface temperature distribution, and specific energy consumption (SEC). The results show that the combined infrared-hot air drying method produces a faster drying time and the highest drying rate compared to the only hot air or only infrared drying method. The fastest drying time was 345 min at a treatment temperature of 90°C, air velocity of 3 m/s, and the greatest drying rate was 0.429 gr/min at a temperature of 80°C, air velocity of 3 m/s. Additionally, the combined infrared-hot air method produces a more uniform temperature distribution on the wood surface and lower specific energy consumption, specifically 1027.15 MJ/kg.

1. INTRODUCTION

Pinus merkusii (*Pinus merkusii* Jungh. et de Vriese) is the only type of pine that is native to Indonesia. This species belongs to the *Pinaceae* family, and is characterized by light brown-yellow heartwood with darker colored bands and patterns, as well as brown or dark brown resinous wood with needle-shaped leaves (Sallata, 2013). The sapwood is white or yellowish, with a thickness of 6-8 cm. Merkusii pine wood contains 54.10% cellulose, 23.05% hemicellulose, and 27.16% lignin (Karlinasari *et al*., 2010).

Wood drying aims to remove water from the wood until it reaches a moisture content that is balanced with the environment where the wood or wood products will be placed without reducing its quality (Fransiska *et al*., 2023). Wood drying can also eliminate attacks from fungi and wet wood powder, making the wood lighter, stabilizing its dimensions, increasing its strength, enhancing its color, and improving its acoustic properties (Putera & Listyanto, 2021). The factors of drying consist of temperature, relative humidity, and air circulation. Drying that does not regulate these factors is known as natural drying, while drying that regulates these factors is known as artificial drying (Purnawati & Arifudin, 2021: Basri *et al*., 2018). There are several methods of wood drying, including hot air, microwave, osmotic, infrared (IR), and various combined hybrid drying (Sakare *et al*., 2020).

The use of infrared for drying wood was first published by Kollmann *et al*. (1967), and it was used for drying spruce and beech wood. The drying rates with double-sided and one-sided radiation increase progressively with decreasing average water content. This can be explained by the fact that for the same average water content with single-sided irradiation, the fastest reduction in water content is achieved at air speeds of 0.2-0.3 m/s and a radiation intensity of 300 mW/cm^2 with 2 sides. Subsequently, illumination and temperature were observed to be about 150°C.

The rise of surface temperature in spruce wood is faster than that beech wood because of lower density (Kollmann *et al*., 1967). Infrared drying of wood occurs first on the surface exposed to infrared (IR) radiation, the wood surface absorbs 70–90% of all incoming IR radiation (Dupleix *et al*., 2013). Furthermore, the concentration of all solutes dissolved in the water vapor increases, causing water to move from the center of the cell through the semipermeable cell walls by osmosis (Cserta *et al*., 2011). The drying time for wood depends on the initial moisture content of the material. With a treatment temperature of 165°C, pine wood with initial moisture content of 45-65% decreased to below the fiber saturation point (FSP) of 25% after 800 min (Cserta *et al*., 2012; Cserta *et al*., 2013). When compared to hot air drying, infrared drying of wood at a temperature of 90°C produces better drying times (Straže *et al*., 2020).

Combined infrared-hot air drying for sengon wood samples (*Paraserianthes falcataria*) was reported by Chan *et al*. (2023). In the research, tests were carried out at temperatures of 70, 80, and 90°C with air velocities of 1, 2 and 3 m/s, respectively. The result shows that the fastest drying time for sengon wood to obtain a moisture content of 19% was 330 minutes at a temperature of 90°C and an air velocity of 3 m/s (Chan *et al*., 2023). The infrared method was compared with the combined infrared-hot air method in drying sengon wood, where the infrared method showed a faster drying time than the combined infrared-hot air method, with optimum conditions at a temperature of 90°C and an air velocity of 1 m/s (Chan *et al*., 2024).

This research aims to determine the output parameters of drying characteristics of pinus merkusii in the form of data on temperature, water content, drying rate, temperature distribution using a thermal imaging camera, and specific energy consumption (SEC). Furthermore, three drying methods were used, including the hot air method, infrared method and combined infrared-hot air method. To date, no previous investigation has compared these three methods for drying wood. Tests were carried out at temperatures of 70, 80, and 90°C with air velocity variations of 1 and 3 m/s. This research limits the drying time when the wood moisture content reaches 19% in accordance with ISPM standard no. 15 (FAO, 2009).

2. MATERIALS AND METHODS

2.1. Material

Samples were wood blocks of pinus merkusii obtained from newly felled pine wood with an estimated age of around ≤ 10 years. The sample size was 300 mm long, 50 mm wide, and 100 mm high, in line with ISO 6780 standards (International Organization for Standardization, 2003). These pine wood blocks were dried in the sun for 2 days to remove sap and to equalize the moisture content at intervals of 37% dry basis. Pine wood samples were stored in an airtight container before testing, and the number of wooden beam samples used was 18 units

2.2. Methods

A laboratory scale dryer with internal dimensions of 60 cm long, 60 cm wide, and 60 cm high was used as seen in Figure 1. The infrared heat energy source was produced by two halogen-type far infrared radiation (FIR) heaters with a power of 500 W, an intensity of 0.5 W /cm-2, wavelength from 1.5 to 8 μm, Additionally, the hot air energy source was produced from 2 electric heating elements with a power of 500 W, the hot air was blown using a centrifugal blower with valve settings for varying air velocity. An ORI GM16A brand anemometer was used to measure the velocity of air entering the oven, temperature measurements were carried out using a 12-channel Lutron BTM-4208SD temperature recorder with a type K thermocouple temperature sensor. The decrease in wood mass was measured using an Arduino ADC HX 711 digital scale and a thermal imaging camera. (TIC) resolution 160x120 Victor brand was used to visualize and analyze temperature distribution on wood surfaces.

Combined infrared and hot air dryer was experimentally analyzed during the drying of sengon wood and Merkusii pine wood pallets according to ISPM 15 standards as shown in Figure 1. The heat source comes from the heating elements (2) and infrared (3). Hot air was distributed into the oven chamber using a centrifugal blower (1), and the temperature inside the oven and the wood core temperature (5) were measured using a 12-channel Lutron BTM-4208SD temperature recorder with a type K thermocouple temperature sensor. Wood samples with a moisture content of 37% on a dry basis were placed on top of Arduino ADC HX 711 digital scale (4) to determine the decrease in mass.

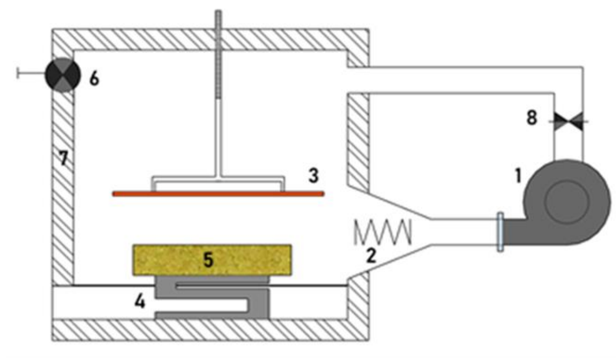


Figure 1. Schematic diagram of research tools. (1) Centrifugal Blower. (2) Heater Element. (3) Infrared. (4). Load Cell (5) Wood samples. (6) Exhaust. (7) Oven walls with heat insulation (8) Air circulation tunnel

The water vapor resulting from drying was released through the exhaust (6). This drying process uses a closed system where the air resulting from heating the wood is circulated through a pipe (8) which was sucked in by a centrifugal blower. Data on wood core temperature and wood mass reduction were recorded at 15 minute intervals, drying continued until the final moisture content of the pine wood samples was 19% on a dry basis. The wood block samples that had undergone the drying process were then placed in the oven again at a temperature of ± 103°C for 24 hours to obtain the equilibrium moisture content (ASTM D4442-92, 2003).

2.3. Determination of Moisture Content and Drying Rate

Changes in the moisture content of materials during drying was calculated as the following (Horák *et al*., 2012; Ondro *et al*., 2018).

$$M_t = \frac{m_t - m_d}{m_d} x100\% \quad (1)$$

where M_t is the dry basis moisture content, m_t is the mass of wood at time t, and m_d is the dry mass of wood.

The drying rate of wood was obtained by comparing the changes in wood weight that occur with the duration of the drying process. The drying rate was calculated using the following equation:

$$DR = \frac{m_{t2} - m_{t1}}{t_2 - t_1} \quad (2)$$

where m_{t2} and m_{t1} is the wood mass at times t_2 and t_1, and $t_2 - t_1$ is the time difference.

2.4. Specific Energy Consumption (SEC)

Specific energy consumption (SEC) refers to the ratio of the total energy supplied to the mass of water vapor evaporated. This serves as a very useful indicator in energy analysis and in the comparison of different dryers and types of dryers (Kaveh & Abbaspour-Gilandeh, 2020). SEC was calculated using the following equation (Ye *et al*., 2021; Nurmawati *et al*., 2022).

$$SEC = \frac{Q}{m} \quad (3)$$

where *SEC* is the specific energy consumption (kJ/kg), *Q* is the amount of energy needed to dry the material (kJ), and *m* is the amount of water evaporated from the material (kg).

2.5. Data Analysis

The influence of air velocity and temperature on drying time was analyzed using two-way ANOVA and Tukey-Fisher test to determine the impact of dominant parameters. Before conducting the ANOVA test and Tukey-Fisher test, prerequisite tests are performed, namely normality and homogeneity tests. The data was processed using Minitab 20.

3. RESULTS AND DISCUSSION

3.1. Survey of Bacterial Leaf Blight in Rice Fields

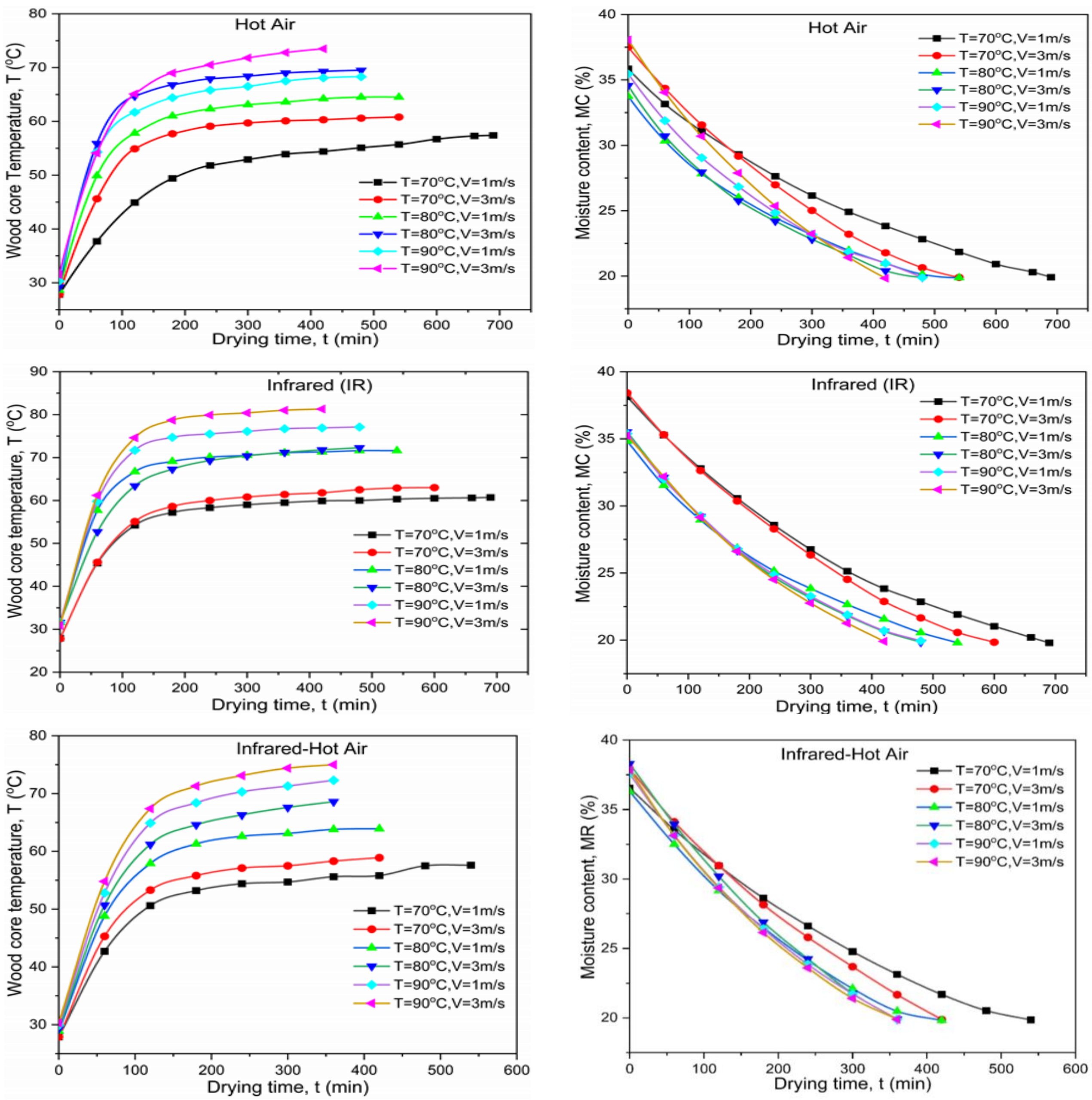
The results of drying pine wood using three drying methods are shown in Table 1. The effect of airspeed on all drying methods is very visible, where the higher the air velocity, the faster the drying process, in contrast to the results of drying sengon wood, especially for the infrared method. Subsequently, drying is more optimal in low air velocity conditions (Chan *et al*., 2023). The core temperature of pine wood produced from three drying methods used at different temperatures and air velocity meets the standards set by ISPM, namely a minimum of 56°C evenly across all wood profiles. The highest core temperature of pine wood was produced by the infrared drying method at 81.3°C at a temperature of 90°C, air velocity of 1 m/s and the lowest core temperature was 57.6°C during the drying process at a temperature of 70°C, air velocity of 1 m/s with the combined infrared-hot air drying method as shown in Figure 2a. Drying using the infrared method produces a higher average wood core temperature compared to the hot air and combined infrared-hot air methods. Infrared rays find it difficult to penetrate wood which has a high specific gravity, thereby air pressure is needed to allow the water vapor contained in the wood to escape.

The decrease in moisture content of pine wood during drying using the hot air method, infrared method, and combined infrared-hot air method is shown in Figure 2b. The increase in temperature and decreasing air humidity in the drying room lead to the formation of water vapor absorbed by hot air more easily and the pressure increases. This further pushes water out of the wood and the greater the air velocities in the drying chamber, the more quickly the wood drying process occurs. This is because the more hot air the wood receives and the more evenly the heat temperature is distributed, the lower the water content of the wood becomes, thereby the drying rate increases and the drying time becomes shorter (Elustondo *et al*., 2023).

The results of the Tukey-Fisher test show that the drying of pine wood is fastest using a combined infrared-hot air method, which requires an average drying time of 397.5 minutes. The optimal treatment temperature is 90°C, with an average drying time of 415 minutes, and the air velocity that results in the fastest drying time is at a velocity of 3 m/s, which is 443.3 minutes. Based on the two-way ANOVA test, parameters such as drying method, air speed, and temperature have an effect on drying time. When two parameters are combined, namely the drying method with air velocity, the drying method with temperature, and air velocity with temperature, only the air velocity with temperature significantly affects the drying time. It can be concluded that the drying of pine wood can be performed using two parameters, namely air velocity and temperature, even when using different drying methods.

Table 1. Drying results of pine wood using hot air, infrared, and combined infrared-hot air methods

Drying methods	Air velocity (m/s)	Temperature (°C)	Wood core temperature (°C)	Moisture content (%db)		Drying rate (g/min)	Drying time (min)
				m_o	m_t		
Infrared	1 m/s	70	60.7	38.135	19.801	0.221	690
		80	72	34.839	19.803	0.206	525
		90	81.3	35.389	19.943	0.258	465
	3 m/s	70	63	38.43	19.84	0.27	585
		80	72.3	35.521	19.841	0.263	465
		90	76.9	35.23	19.911	0.28	420
Hot Air	1 m/s	70	57.7	35.85	19.915	0.175	690
		80	64.5	33.751	19.88	0.177	495
		90	68.3	35.462	19.896	0.243	480
	3 m/s	70	60.8	37.497	19.898	0.27	525
		80	69.5	34.566	19.898	0.217	450
		90	73.5	38.062	19.836	0.355	420
Infrared-Hot Air	1 m/s	70	57.6	36.551	19.851	0.259	510
		80	63.9	36.308	19.814	0.327	390
		90	72.3	37.562	19.904	0.398	360
	3 m/s	70	58.9	37.937	19.872	0.35	420
		80	68.6	38.308	19.9	0.429	360
		90	75	37.857	19.896	0.422	345



(a) (b)

Figure 2. Effect of drying modes: (a) Temperature increase in the wood core, and (b) Moisture content decrease of pine wood

The drying rate of pine wood, as shown in Figure 3, is very fast at the beginning of the drying process. This is because the wood contains a significant amount of water on the surface, classified as free water. As the drying process continues, and the material becomes drier, the remaining is water bound to the cells of the material, which causes a decrease in the water content of the material (Avramidis *et al*., 2023). The highest drying rate for pine wood was 0.429 gr/minute using a combined infrared-hot air method at a drying temperature of 90°C with an air velocity of 3 m/s. In contrast, the lowest drying rate was 0.175 gr/minute, observed at a drying temperature of 70°C, an air velocity of 1 m/s using the hot air drying method. Drying with the combined infrared-hot air method provides a faster heat increase effect compared to the infrared and hot air methods. The combination of heat from infrared and heating elements leads to higher heat and mass transfer coefficients and increases the diffusion rate.

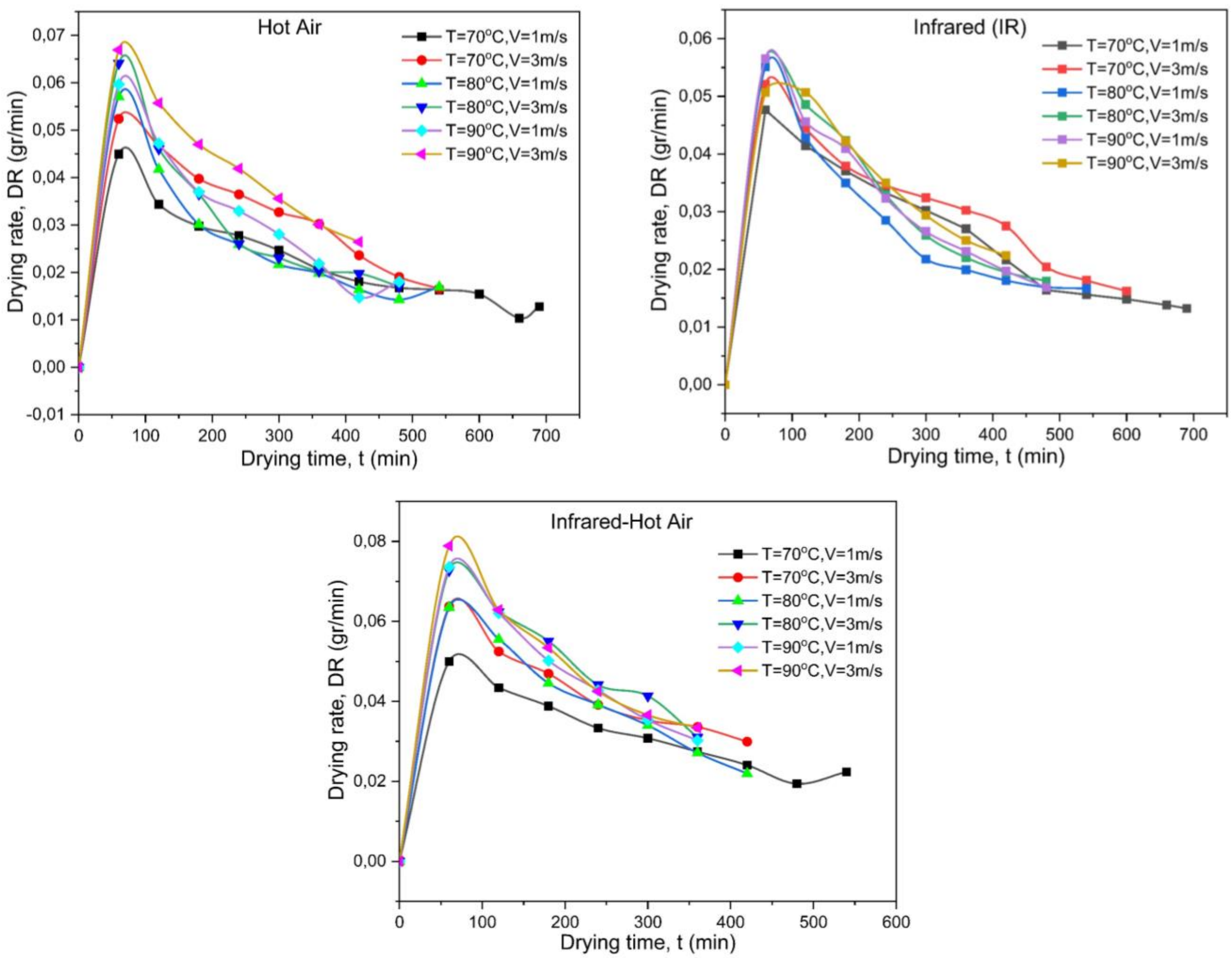


Figure 3. Drying rate of pine wood using different methods: hot air, infrared, and combined infrared-hot air

3.2. Temperature Distribution with Thermal Imaging Camera (TIC)

Thermal cameras use infrared energy to create thermal images, when the infrared radiation emitted by an object hits the infrared detector on the thermal camera, this radiation will be converted into electrical signals. These signals are sent to the signal processing unit to be decoded and displayed as a thermal image of the temperature distribution throughout the surface of the object (Conde *et al*., 2012; Jati & Rivai, 2020). In this research, a thermal camera was used to observe the temperature distribution on the surface of pine wood due to heating using infrared, hot air, and combined infrared-hot air methods. The thermal camera used has a resolution of 160 x 120 pixels, a wavelength, and 8~14 µm temperature measurement range of -15 – 600°C.

The surface temperature distribution of pine wood using the hot air, infrared, and combined infrared-hot air drying methods can be seen in Figure 4-6. Air velocity greatly influences the distribution of heat on the surface of pine wood (Lerman *et al*., 2022). Drying at an air velocity of 3m/s provides a more even temperature distribution effect than an air velocity of 1m/s. Drying using the hot air method produces a higher temperature distribution on the right side surface of pine wood, which is influenced by the air blast from the centrifugal blower. Drying using the infrared method produces a higher temperature on the top surface of the wood, this is due to the position of the infrared lamp, an air speed of 1m/s produces a higher temperature compared to an air velocity of 3m/s. The combined infrared-hot air method produces a more even temperature distribution compared to the hot air method and infrared method, at an air velocity of 1 m/s or an air velocity of 3m/s.

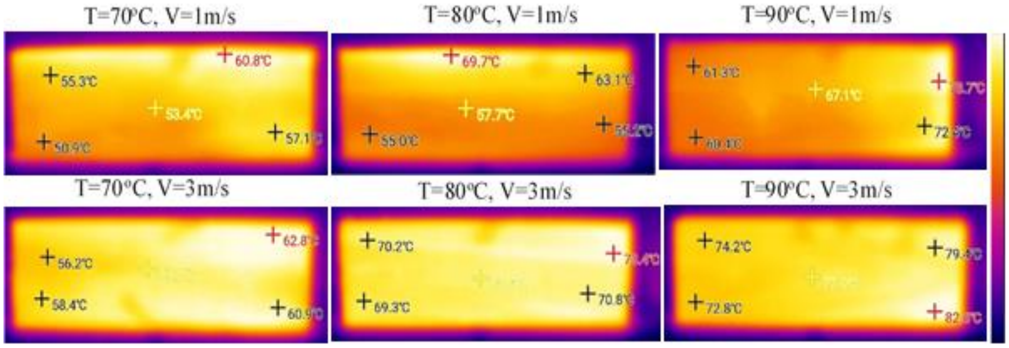


Figure 4. Surface temperature distribution of pine wood using the hot air method

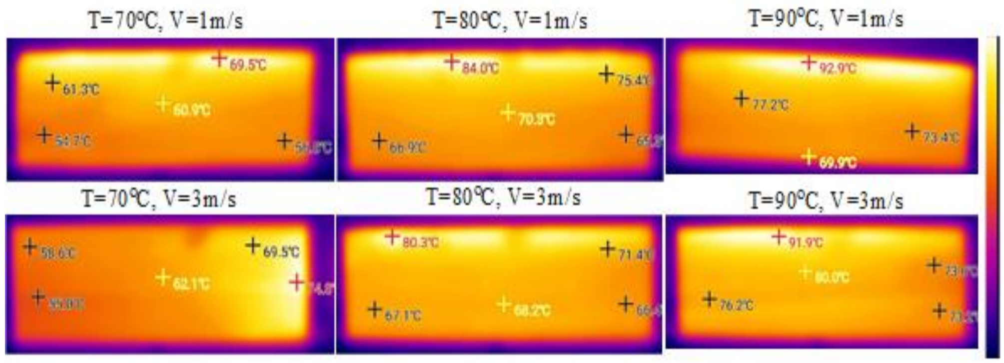


Figure 5. Surface temperature distribution of pine wood using the infrared method

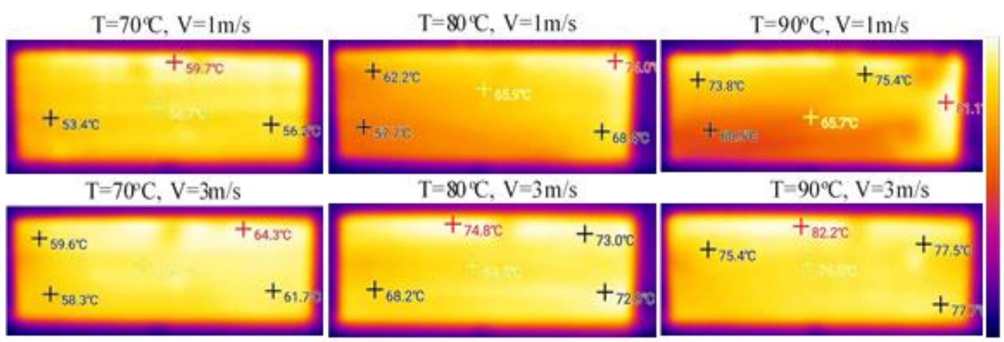


Figure 6. Surface temperature distribution of pine wood using the combined infrared-hot air method

3.3. Specific Energy Consumption (SEC)

The main energy consumption of the hot air drying method, infrared method, and combined infrared-hot air method is electrical energy from the use of infrared lamps, electric elements, and centrifugal blowers. The specific energy consumption for drying pine wood using the hot air drying method, infrared method, and combined infrared-hot air method is shown in Figure 8. The specific energy consumption in the drying process using the hot air method is 1480.95 MJ/kg, with a long drying time of 51 h and a total electrical power requirement of 47.26 kWh. The specific energy consumption of drying using infrared method is 1590.52 MJ/kg, with a drying time of 52.5 h and a total electrical power of 57.18 kWh. The specific energy consumption using the combined infrared-hot air method is 1027.15 MJ/kg, with a drying time of 39.75 h and a total electrical power of 40.04 kWh (Ye *et al*., 2021).

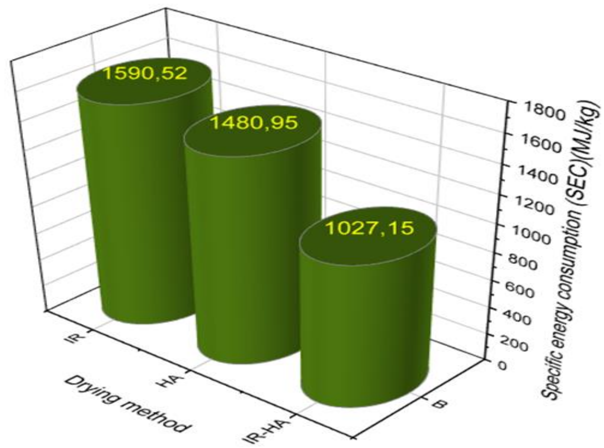


Figure 8. Specific energy consumption (SEC) for drying pine wood

4. CONCLUSION

In conclusion, pine wood with an initial moisture content of 30-40% was dried using the hot air method, infrared method, and combined infrared-hot air method until the final moisture content was 19% with various test temperatures of 70°C, 80°C, 90°C at an air velocity of 1 and 3 m/s. The optimum drying conditions used a combined infrared-hot air method with a long drying time of 345 minutes at a treatment temperature of 90°C, air velocity of 3 m/s and the highest drying rate was 0.429 gr/min at a temperature of 80°C, air velocity of 3 m/s. The combined infrared-hot air method produces a more even temperature distribution on the wood surface and a smaller specific energy consumption of 1027.15 MJ/kg.

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