

Heat Pump Drying of Arabica Coffee Beans: Influence of Inlet Air Conditions on Drying Rate Constant

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Abstract

Drying is a crucial step in agricultural processing as it reduces moisture content, extends shelf life, and preserves product quality. For heat-sensitive Arabica coffee beans, heat pump drying (HPD) is an efficient and energy-saving method. This study investigates the drying characteristics of wet Arabica coffee beans using an HPD system, focusing on determining the drying rate constant (k) at various inlet air temperatures and humidity conditions. The drying process was conducted for 30 minutes at a constant air mass flux rate of $0.69 \text{ kg/m}^2\text{-s}$ at temperatures of 45, 50, 55, 60, and 65 °C. Inlet air conditions were controlled with a cooling system at 10, 15, and 20 °C, compared to ambient air without cooling. The results showed that increasing drying temperature and decreasing inlet air humidity significantly enhanced the drying rate. Additionally, the study explored the relationship between the constant air mass flux and variable parameters, including air temperature and humidity, which directly affected the drying rate constant (k). The highest k value ($17.66 \times 10^{-5} \text{ s}^{-1}$) was observed at 65 °C with air from the cooling system at 10 °C, indicating that combining high temperature and dry air improves drying efficiency.

Keywords: arabica coffee; drying; drying constant; heat pump drying.

1. Introduction

Drying is a crucial post-harvest stage as it helps extend shelf life and enhance the market value of agricultural products. This process reduces moisture content to prevent rapid spoilage and maintain product quality [1, 2]. Although seemingly simple, drying involves complex heat and mass transfer processes [3]. The primary objective is to reduce moisture content to a safe level to prevent spoilage and maintain nutrient stability [4, 5]. Its effectiveness is influenced by temperature, humidity, air flow speed, and the physical and chemical properties of the material, such as size, thickness, initial moisture content, and internal structure [6].

Arabica coffee plays an important role in Indonesian agriculture and exports. Its distinctive flavor makes it popular in international markets and a source of income for millions of farmers. As one of the country's flagship commodities, Arabica coffee contributes significantly to the national economy. Indonesia ranks fourth globally in coffee production, accounting for approximately 11% of total global production with an average of 683 million kilograms per year [7]. Drying is a critical stage in coffee processing as it directly affects the physical quality and flavor. After washing, wet coffee beans have a moisture content of around 50–55%, which must be reduced to 10–12.5% to ensure longevity and safe storage. If the moisture content is too high, coffee can spoil due to microorganisms or chemical reactions during storage and distribution [8-13].

Generally, coffee drying is carried out using four methods: direct sun drying, solar drying, greenhouse drying, and mechanical drying equipment [9, 14]. Sun drying remains the most common traditional method due to its low cost and energy efficiency. However, due to its dependence on weather conditions, this process is often uneven and can reduce coffee bean quality [15, 16]. Alternatives include solar drying and greenhouse drying, which utilize solar heat in a more controlled manner, while mechanical drying is superior as it is weather-independent, faster, and more efficient. Sun drying typically takes 1–2 weeks, depending on climatic conditions [13, 17, 18].

Closed drying systems with heat pumps feature efficient heating and cooling units, with controlled temperatures ranging from -20 to 100°C and humidity levels between 15–80%. These systems also enable heat recovery [12]. Heat pump drying (HPD) has proven to be an efficient and energy-saving method for drying temperature-sensitive agricultural products due to its ability to precisely control the temperature and humidity of the drying air [19]. HPD demonstrates higher energy efficiency compared to traditional drying methods such as solar drying and greenhouse drying. The integration of heat pump technology enhances heat recovery and provides precise humidity control, which can save up to 50% energy compared to conventional solar drying methods [20, 21]. Assessments indicate that heat pump-assisted drying achieves significant energy and exergy efficiency, highlighting its advantages over traditional drying systems [20]. Drying characteristics are determined by the drying rate constant and the activation energy of the material. In an efficient and flexible heat pump system, these values are significantly influenced by air mass flux and specific humidity [22].

Mechanical drying methods using heat pumps are still very limited. A good understanding of the drying process using heat pumps is important for optimizing coffee processing. Despite the use of various drying methods in the coffee industry, the effectiveness of HPD compared to traditional techniques like solar and conventional heat drying is still not well studied. Additionally, there is limited research exploring how HPD could potentially deliver the same or even better quality results while improving energy efficiency [19].

This study aims to investigate the drying behavior of wet Arabica coffee beans using HPD with forced convection, at various drying temperatures and inlet air humidity, both with and without pre-cooling process. One of the main parameters analyzed was the drying rate constant (k), which describes how fast the moisture content in coffee beans is reduced during the drying process. The value of k is very important as it reflects the efficiency of the drying process and forms the basis for the design and control of the dryer system. By knowing how k is affected by air temperature and humidity, the HPD system can be optimized to produce a faster, more energy-efficient drying process while maintaining the quality of the coffee beans.

2. Experimental Methods

This research employs the experimental approach conducted in the Heat Transfer Laboratory at the Faculty of Engineering, University of Indonesia. Sample preparation involved the wet processing of Arabica coffee beans derived from coffee cherries (*Coffea arabica*) picked in Semendo, South Sumatra Province, Indonesia. Wet Arabica coffee beans are acquired by sifting coffee cherries using water. The coffee cherries are depulped with a pulper, thereafter fermented in water for 36 hours to eliminate the mucilage layer from the beans, and then washed and drained. [13]. For storage purposes, the wet Arabica coffee beans are vacuum-packed using layered plastic and stored at a temperature of 4°C [12]. Before drying, the samples are removed from storage, taken out of the vacuum packaging, and placed into the drying chamber (Figure 1).



Figure 1. (a) Coffee beans from vacuum packaging and (b) Coffee beans in the drying chamber

The wet Arabica coffee beans (parchment) used in each test amount to 1 batch stack or cover the bottom part of the drying chamber. Data collection was carried out using NI 9213, NI-CDaq 9174, load cell, thermocouple, relative humidity sensor, rotameter, and power meter. This study used several measuring instruments with a certain level of accuracy to ensure accurate and reliable data collection, including a Type K thermocouple ($\pm 1^\circ\text{C}$), HIH-4031-001 humidity sensor ($\pm 3.5\%$), Zemic load cell ($\pm 0.03\%$), UV-C112 rotameter ($\pm 2\%$), and Fujitsu FSR-A analytical balance ($\pm 0.001\text{ g}$). Sensor calibration is performed by comparing measurements from the thermocouple with a mercury thermometer, the humidity sensor with a calibrated climate chamber, and the load cell with a calibrated analytical balance to ensure the accuracy and precision of the instruments. The laboratory conditions were carefully controlled to guarantee precise and reliable measurements throughout the experiment. The temperature ambient was kept between $27\text{-}30^\circ\text{C}$, while the relative humidity was maintained at $55\text{-}60\%$. Atmospheric pressure was also regulated to create the ideal environment for the testing equipment and sensors. These parameters were consistently monitored during the experiment to reduce any potential variations in the results. The test results were stored using NI LabVIEW software in .lvm file format, then processed and analyzed using Microsoft Excel. A similar device was also used by Kosasih et al. [23] to test the water vapor desorption capability on silica gel.

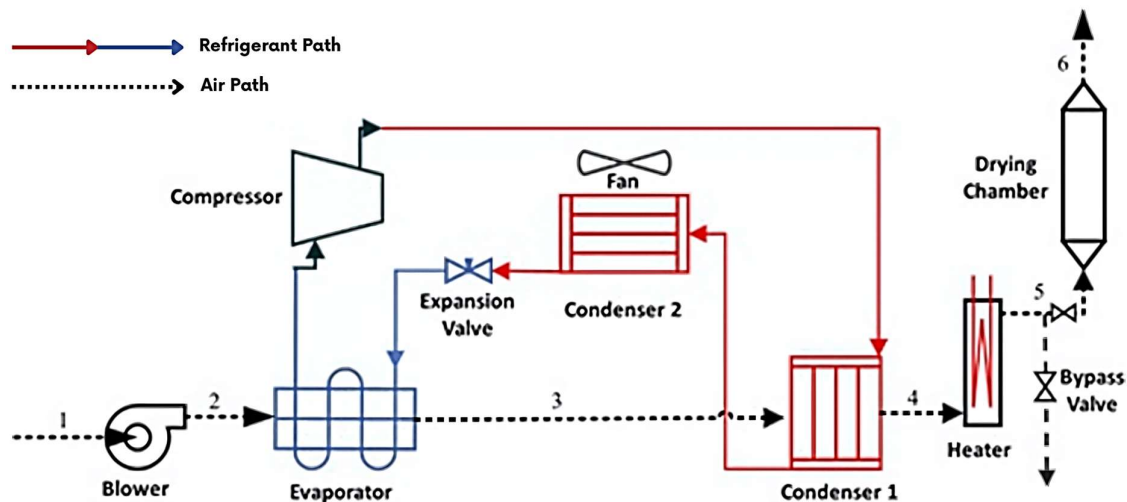


Figure 2. Schematic diagram of HPD

As seen in Figure 2, the blower sucks air from the environment (1) towards and through the evaporator (3), where the dehumidification process occurs. Before reaching the evaporator, the airflow is measured using a rotameter (2). Inside the evaporator, the air temperature drops because the water vapor inside condenses and turns into water droplets on the surface of the tube, making the outgoing air drier. Next, this air flows to condenser 1 (4), where the refrigerant releases heat to warm the air. If the temperature of the air exiting the condenser is not hot enough for the drying process, the air will be directed to the electric heater (5) in sequence. This heater will raise the air temperature until it reaches the level set by the temperature controller connected to the thermocouple sensor. Once the temperature is appropriate, this hot air enters the drying chamber (6) and serves to carry the water vapor from the coffee beans out into the environment.

The refrigerant used in the system is R134a in gas form. The refrigerant is compressed by the compressor, causing its pressure to increase and its temperature to rise after leaving the compressor. The refrigerant flows through condenser 1 and 2. Condenser 2 is equipped with a fan to enhance heat exchange efficiency, causing the refrigerant to condense into a liquid. Next, the refrigerant is passed through the expansion valve to lower its

pressure and temperature, before finally returning to the evaporator. The specific humidity of the drying air is calculated from the dry bulb temperature and RH data obtained from the HPD sensor. The evaporator temperature is controlled through the expansion valve.

Drying was carried out at heating temperatures of 45, 50, 55, 60, and 65°C for 30 minutes. The air mass flux rate was 0.69 kg/m²·s. This rate was based on an air mass flux of 630 lpm at the blower and a drying chamber diameter of 6 inches. The specific humidity varied depending on the settings of the cooling system or the evaporator outlet temperature, which was set to 10, 15, or 20°C. Drying was also performed without a cooling system, resulting in four variations of specific humidity. According to the tolerance limits specified in SNI 7467-2008, Arabica coffee can be dried at temperatures up to 55°C without significantly reducing quality. Temperature variations were selected to observe drying rates above and below 55°C. The measurement of coffee bean weight during the drying process is carried out in real-time and continuously using a load cell installed inside the drying chamber. This load cell is directly connected to the digital data acquisition system, allowing automatic recording of the coffee beans mass without the need to stop the drying process or open the drying chamber. To maintain the drying temperature and specific humidity inside the chamber, each section was insulated with polyurethane (PU) and glass wool. Drying was carried out from an initial moisture content of 55% (w.b.) Specific humidity during the drying process is calculated using the function $Y = f(T, RH)$ where Y is specific humidity as a function of average temperature T and relative humidity RH , or can be determined using a psychrometric chart. Dry basis moisture content (M_{db}) is calculated using Equation (1).

$$M_{db} = \frac{m_t(g) - m_d(g)}{m_d(g)} \quad (1)$$

where m_t is the mass of coffee at time t , and m_d is the dry mass determined using the ASTM method by heating in an oven at 105°C for 24 hours [24]. The M_{db} value is then used to calculate the moisture ratio (MR) using the Equation (2)

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

since the M_e is very small, this formula is simplified to Equation (3).

$$M_{db} = \frac{M_t}{M_o} \quad (3)$$

The exponential model [25] is used to determine the drying rate constant. This model is also known as the Lewis mathematical model [26], as shown in Equation (4), where k denotes the drying rate constant and t is time. As stated in Equation (5), the exponential value (exp) can be simplified using the natural logarithm $\ln MR$.

$$MR = \exp(-k \cdot t) \quad (4)$$

$$\ln MR = -k \cdot t \quad (5)$$

To determine the drying rate constant k , the $\ln MR$ curve against time t s plotted using Microsoft Excel 365 software. The linear equation (Equation 6) can be obtained using the add trendline feature.

$$y = mx \quad (6)$$

In this case, the y values represent $\ln MR$, the x values are time, and the slope of the straight line m is the $-k$, as shown in Equations (5) and (6).

3. Results and Discussion

A HPD with double condensers was used in this study to characterize the drying process of wet Arabica coffee beans with varied drying air conditions. The drying air conditions were controlled by adjusting the expansion valve and heater temperature to obtain variations in evaporator air temperature of 20, 15, and 10°C, which reduced the humidity level in the drying air. Although a cooling system is not used, the drying temperature is controlled using electric heaters. These heaters ensure the air reaches the targeted temperature (45-65°C), so that the effect of temperature on the drying rate can be clearly observed without the influence of air humidity due to cooling.

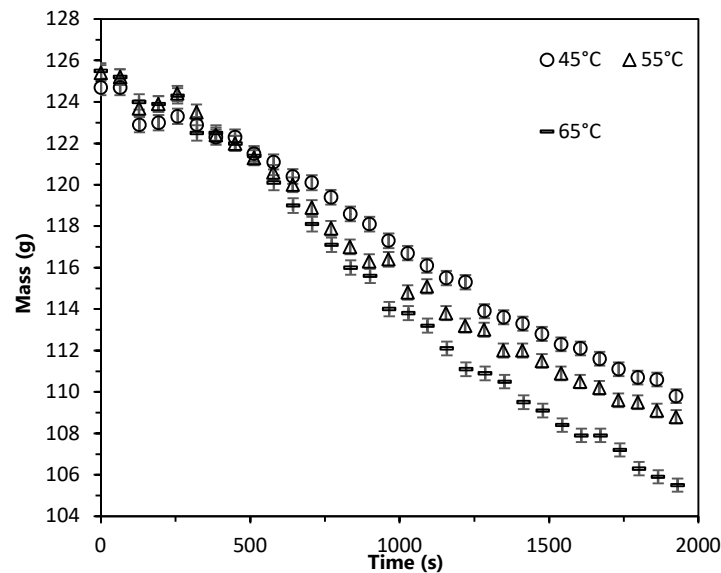


Figure 3. The curve of reducing mass (g) against time during drying with variation temperature at no refrigerant

Figure 3 shows the effect of drying temperature variations on mass (g) that changes during the drying process. The mass of the material shows a downward trend as drying time increases under all tested temperature conditions. This indicates that the drying process is effective in reducing the mass of the material. At lower temperatures (45°C), the rate of mass reduction is slower compared to higher temperatures, such as 55 and 65°C. Increasing the drying temperature significantly contributes to accelerating the rate of water evaporation, as indicated by the steeper curve at higher temperatures. This is due to the increased thermal energy available to evaporate water from the surface and interior of the material.

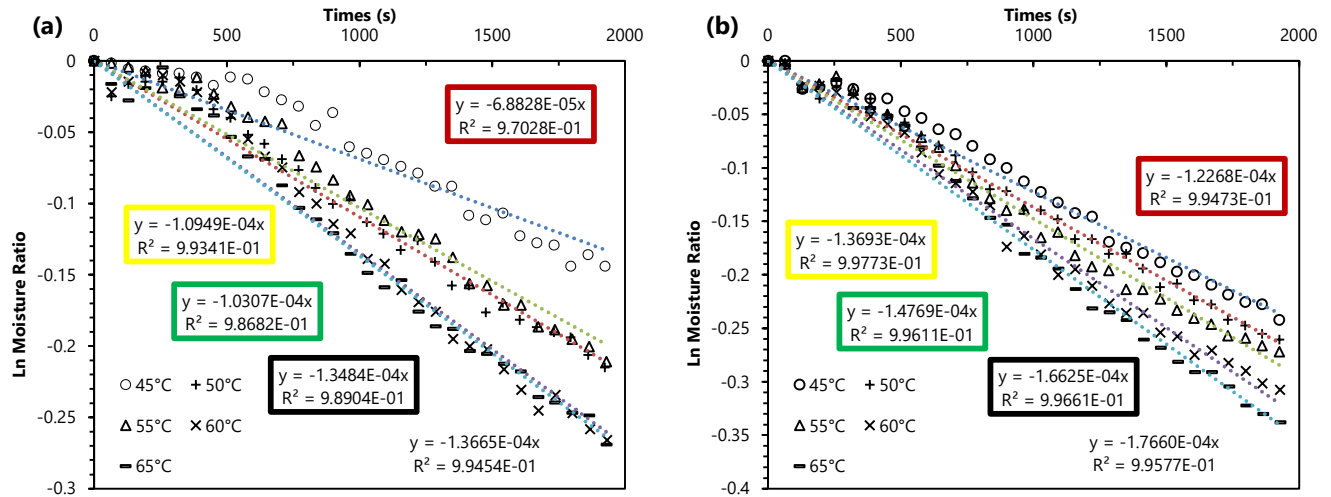


Figure 4. Linear curve of $\ln MR$ versus drying time at various temperatures (a) Drying system without refrigeration and (b) Drying system with refrigeration at 10°C

Figure 4 presents the relationship between the $\ln(MR)$ value (natural logarithm of the Moisture Ratio) and Drying time over the temperature range of 45 to 65°C. Figure 4 (a) illustrates the drying process to pre-air condition with refrigeration system. Meanwhile, Figure 4 (b) shows drying with the assistance of a refrigeration system, where the drying air is passed through a 10°C evaporator before entering the drying chamber. The linear regression results for each curve indicate that all data follow a first-order model, with a coefficient of determination (R^2) above 0.94, indicating excellent model fit. The drying rate constant (k) increases consistently with rising temperature in both systems. Compared to the system without refrigeration (Figure 4 (a)), the system with refrigeration (Figure 4 (b)) produces higher k values for each drying temperature. For example, at 65°C, the k value increases from $1.3655 \times 10^{-4} \text{ s}^{-1}$ without pre-air condition to $1.766 \times 10^{-4} \text{ s}^{-1}$ with pre-air condition. This indicates that cooling the air before heating it in the drying system can enhance evaporation efficiency. It is likely due to the reduction in the initial relative humidity of the incoming air, thereby increasing the driving force for evaporation.

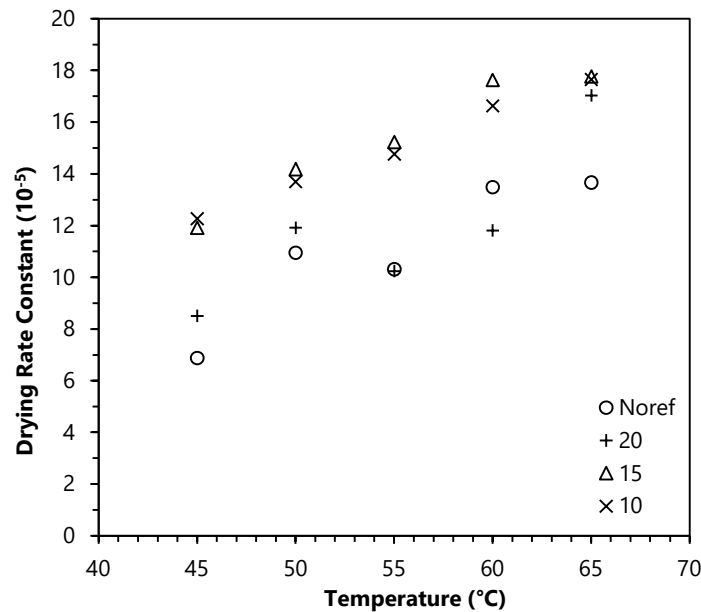


Figure 5. Relationship between drying rate constant and drying temperature under various inlet air conditions

The effect of drying temperature on the drying rate constant (k) under four different drying system conditions is shown in Figure 5. It shows conditions without a refrigeration system (Noref) and with a refrigeration system using inlet air from an evaporator at 20, 15, and 10°C. In general, the curve shows that the drying rate constant increases with the drying temperature from 45 to 65°C. This trend is consistent across all air conditions, indicating that high temperatures accelerate the evaporation rate of water from the material. Additionally, the use of a cooling system to lower the inlet air temperature was found to have a significant effect on increasing the drying rate. At the same drying temperature, inlet air from the cooling system at 10 and 15°C produces higher k constant values compared to air at 20°C or ambient air. As can be seen at 65°C, the highest k value $17,66 \times 10^{-5} \text{ s}^{-1}$ is obtained under 10°C inlet air conditions, while non refrigerated conditions only yield a k value of approximately $13,66 \times 10^{-5} \text{ s}^{-1}$. This indicates that air with lower relative humidity resulting from the cooling process has a greater evaporation driving force, thereby accelerating the drying process. This result is in line with the study of Dzaky et al. [22] who showed that the double-condenser cooling system was able to reduce the drying air humidity and increase the drying rate on robusta coffee bean. They recorded the highest drying rate constant value of $2,44 \times 10^{-4} \text{ s}^{-1}$ at 80°C, much higher than the condition without refrigeration which only reached $5,3 \times 10^{-5} \text{ s}^{-1}$. On the other hand, in our study, the k value for Arabica coffee ranged from $6,88 \times 10^{-5} \text{ s}^{-1}$ to $17,66 \times 10^{-5} \text{ s}^{-1}$ at temperatures varying between 45 and 65°C, indicating that HPD provides faster drying compared to traditional drying methods. This reinforces that the drier air due to cooling can accelerate the evaporation of water from the material.

4. Conclusion

Based on the results of the drying study of wet Arabica coffee beans, it was found that drying temperature and incoming air conditions play a crucial role in determining the drying rate of the material. According to the analysis of the moisture content versus time curve, the $\ln MR$ versus time graph, and the relationship between temperature and the drying rate constant (k), it shows that an increase in drying temperature significantly increases the drying rate. This was proven by faster moisture content reduction and higher k values at 65°C compared to 45°C; the first order drying model provides excellent agreement with experimental data ($R^2 > 0.94$). This makes it reliable for modeling the drying process in this study and the highest recorded value for the drying rate constant (k) was $17,66 \times 10^{-5} \text{ s}^{-1}$ at a drying temperature of 65°C with incoming air from a refrigeration

system at 10°C. It was concluded that a combination of a high temperature and low air humidity creates highly effective drying conditions. Conversely, the lowest k value, $6.8828 \times 10^{-5} \text{ s}^{-1}$ occurred at a drying temperature of 45°C without a refrigeration system. This indicates that low temperatures and high relative humidity slow the evaporation of water from the material.

4.1. Limitations

Although this study provides useful insights into the drying behavior of Arabica coffee beans using the HPD method, there are several limitations that should be noted:

- 1) This study only used wet Arabica coffee bean samples from one specific region. Therefore, the results obtained may not necessarily represent the characteristics of coffee beans from other varieties or regions, given that environmental factors and coffee bean properties can vary significantly.
- 2) This study did not evaluate how drying with HPD affects the quality of coffee beans during long-term storage. The stability of flavor, aroma, and quality of coffee after post-drying storage needs to be further investigated.
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4.2. Suggestions for Future Research

For future studies, it would be beneficial to investigate how different coffee types respond to HPD drying. Additionally, it is important to explore how HPD affects coffee quality and storage over time to ensure consistency in flavor and aroma in the long term. Scalability of the HPD system to assess practical feasibility and cost-effectiveness in large-scale real-world operations will be key to its commercial viability. Finally, improvements to the drying model that account for varying conditions could help optimize the process, making it more efficient and adaptable to different environments.

5. Acknowledgments

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6. References

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