SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2811-3950

Study of Heat Transfer and Product Characterization in Spouted Bed Coffee Roaster

Heryoki Yohanes[1,2,*], Sang Kompiang W.[1], Eko Agus S.[1]

[1] Department of System Engineering, Faculty of Engineering, Universitas Gadjah Mada, 3rd Teknika Utara Street, Yogyakarta, 55281, Indonesia
[2] The National Research and Innovation Agency, Kawasan Puspiptek Serpong, South Tangerang, 15314, Indonesia

ARTICLE INFO

Article history:
Received 26 September 2021
Received in revised form 11 January 2022
Accepted 20 January 2022
Available online 25 February 2022

Keywords:
Spout fluidized bed; heat transfer coefficient; Low-temperature long-time; high-temperature short-time; moisture content; ash content

ABSTRACT

Roasting is one of the essential coffee production processes, which significantly influences the quality of roasted coffee. There are many approaches for roasting, applying rotating cylinder (a standard method of the roasting process), fixed bowl, and fluidized bed method. A study of heat transfer and product characterization was conducted in a spout fluidized bed coffee roaster with a 2000-gram capacity. In this research, Temanggung Robusta Coffee beans were processed with two different operating temperature settings, performing 225°C for a low-temperature long time (LTLT) and 240°C for a high-temperature short time (HTST). At both operating temperatures, the overall heat transfer coefficient for coffee roasting was 26,63 – 92,02 W/m²K for the LTLT process and 44,85 – 139,98 W/m²K for the HTST process. The products, then, were analyzed for moisture and ash content. The results showed that a low-temperature long-time process resulted in lower moisture content. Furthermore, there was no significant difference in ash content compared to the high-temperature short-time process (HTST).

1. Introduction

Coffee is the second most traded commodity after petroleum, playing an essential role in international trade, and globally consume more than 400 billion cups yearly [1]. Many factors affect the quality of a coffee powder, such as soil composition in which it is grown, altitude, climate conditions. Furthermore, the most critical factor in determining the quality of the coffee product is the roasting process. The method used to process the coffee cherries also affects the quality of the final product and the overall quantity and chemical composition of the coffee bean [2]. Thus, the most critical factor in determining coffee quality is the roasting process.

Coffee roasting is a drying process to reduce the water content of coffee beans, usually indicated by weight loss at the end of the process. The roasting process is carried out using a specific temperature until the bean develops, giving the product a distinctive aroma. Generally, two roaster machines are used in the coffee roasting process: rotating cylinder models and fluidization. Roasted

* *Corresponding author.*
E-mail address: heryokiyohanes@mail.ugm.ac.id

https://doi.org/10.37934/arfmts.92.2.182190

coffee with a rotating cylinder model is stirred in a rotating cylinder and heated directly. Meanwhile, the fluidized coffee roaster uses compressed hot air to stir and roast the coffee during the process. Heat transfer in this method is dominantly by convection compared to the rotating cylinder method, which is dominantly by conduction. A study showed that the disadvantage of the rotating cylinder type is difficult to control the temperature of the roasting process, which generally operates in high temperatures and a long time process. In addition, silver skin in the drum mixed with coffee oil was still observed, causing char deposits on the chamber wall, which can cause a smoky smell [2].

The spouted bed is a variation of the fluidization model using a different design from the fluidization model in general. The general fluidization process involves hot air to stir the coffee, flowing hot air to the roasting chamber. However, in the spouted bed model, the air is flowed through the bottom and makes the coffee float up and fall to the side of the roaster chamber. Fluidization using the spouted bed model has advantages in terms of ease of design and process control with less even roast product [3].

This study aimed to analyze the heat transfer process to elucidate the effects of the roasting process on coffee product characteristics.

2. Material and Methods

Temanggung Robusta green coffee beans (*Coffea canephora P.*) were supplied by Giat Kopi. The moisture content of the beans was calculated according to Standar Nasional Indonesia [4] using a weighing vessel which was placed in an oven (105°C, for 3 hours), then cooled in a desiccator, and weighed. Ash content was evaluated from the weight of the sample after a burning process at 550°C for eight hours.

A modified commercial Spouted bed roaster (Giat Kopi Roaster) was used for roasting coffee beans (Figure 1). The hot air and coffee bean temperature were recorded using a data logger (Model midi Logger GL240, Graphtec) and a thermocouple (K-type) that was positioned in the roast chamber.

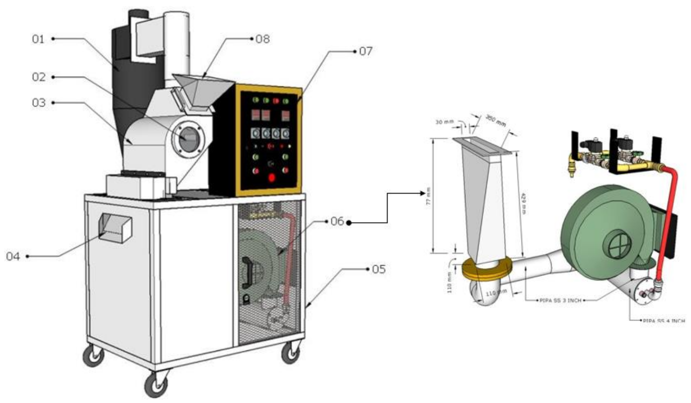

Fig. 1. Spout-Fluidized bed coffee roaster

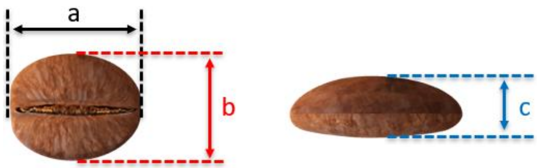

Fig. 2. Coffee bean dimensions

2 Kg green beans were roasted using two different operating temperature settings, performing 220 ± 5°C for 10 minutes (LTLT) and 240 ± 5°C for 5 minutes (HTST) [5]. Twenty g of roasted beans, approximately, was taken during the roasting process to determine moisture and ash content [6].

For unsteady-state heat transfer between hot air and coffee beans was calculated as formula 1. *U* is the overall heat transfer coefficient for heat transfer from air to the material (W/m^2K). *Ta* represents the temperature of air (°C), *Ti* refers to the initial temperature of coffee beans (°C), *Tp* indicates product temperature (°C), ϑ denotes roasting time (minutes), *Mp* is a mass of the coffee bean (kg), *A* represents the total surface area of coffee beans (m^2), and the specific heat of coffee beans (J/kg·K) was represented as *Cp* [7-9].

$$T = \frac{(T_a - T_i)}{(T_a - T_p)} = exp\left(\frac{U\,A\,\theta}{M_p C_p}\right) \tag{1}$$

The surface area of the entire bean is calculated with the number of beans in the batch (i.e., the total weight of the batch divided by the average weight of an individual bean) and the average surface area calculated for a particular coffee bean using Eq. (2) based on the measurements of the equatorial and longitudinal diameter of the bean [10,11]. Another method to determine the average surface area is based on coffee beans dimensions, as in Figure 2 and the geometric diameter of the coffee beans, as in Eq. (3) and Eq. (4) [12,13].

$$A = \frac{\pi}{4}ab + \frac{\pi}{4}\left[b^2 + ab\left(\frac{\arcsin(\varepsilon)}{\varepsilon}\right)\right] \text{ where } \varepsilon = \frac{\sqrt{a^2 - b^2}}{a} \tag{2}$$

$$A = \left[\left(\frac{\pi B^2}{2} + \frac{\pi a B}{2e} sin^{-1} e\right)/2\right] + \left(\frac{\pi a b}{4}\right) \tag{3}$$

Where: $B = (2bc)^{1/2}$; $e = \sqrt{1 - \left(\frac{B}{a}\right)^2}$

$$A = \pi\left(d_p\right)^2 \tag{4}$$

Where: $d_p = \sqrt[3]{abc}$

3. Result and Discussion

3.1 Overall Heat Transfer Coefficient

Coffee bean and air temperatures during a roasting process are displayed in Figure 3 and Figure 4. At the beginning of roasting, as the coffee bean takes up more heat, slow release of water and volatile substance occur. As this happens, the internal temperature of the bean starts to rise, and the chlorophyll inside the bean begins to degrade, initiating a colour change from green to yellow [9].

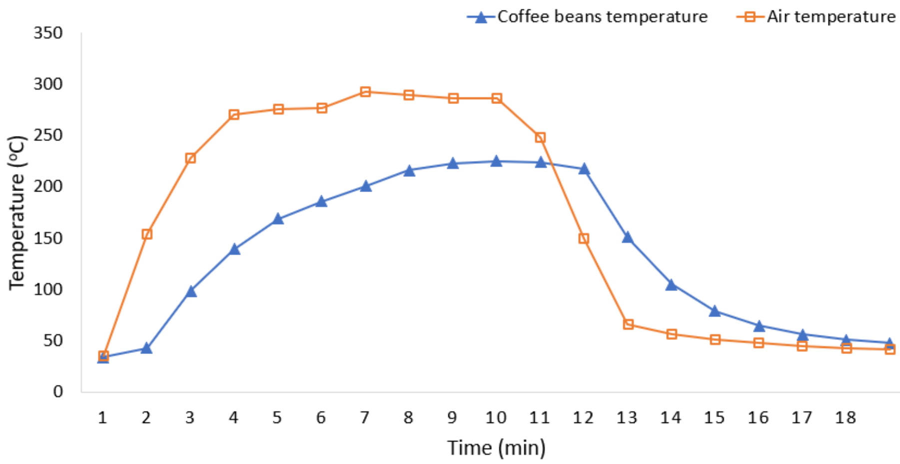

Fig. 3. LTLT Temperature process versus time

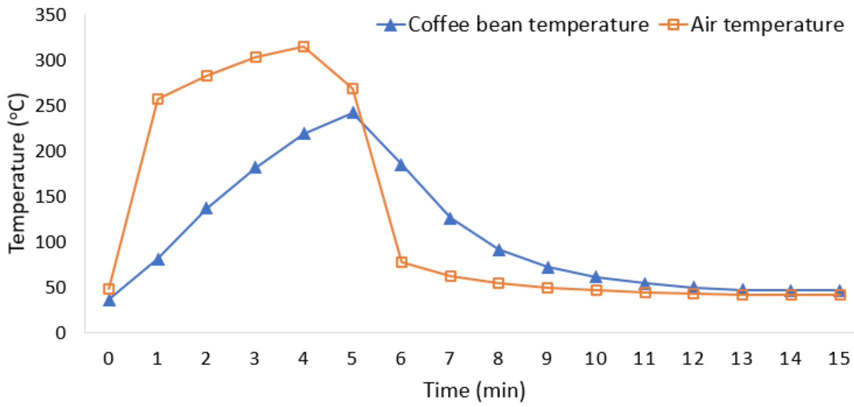

Fig. 4. HTST Temperature process versus time

Table 1 shows the overall heat transfer coefficient for LTLT and HTST processes. The overall heat transfer coefficients include heat transfer from gas to bean and conduction into the bean matrix [14]. It can be seen that the overall heat transfer coefficients for LTLT and HTST Process were 26, 63 to 92,02 W/m^{2}K and 44,85 to 139,98 W/m^{2}K, respectively.

Table 1
Overall heat transfer coefficient

Roasting Process	A (m^2)	U (W/m^2 K)
LTLT	1,84[a]	92,02
LTLT	1,9[b]	74,43
LTLT	5,3[c]	26,63
HTST	1,9[a]	139,98
HTST	2,1[b]	114,92
HTST	5,4[c]	44,85

[a]Total surface area was calculated based on McCabe equation (1986)
[b]Total surface area was calculated based on Hernandez equation (2002)
[c]Total surface area was calculated based on Mohsenin equation (1986)

The heat transfer coefficient is used for most industrial automotive, manufacturing, and heat exchangers [15]. Later, a series of research by experiments raised such as Nasri *et al.,* [16], El-Okda and Nasif [17], and Akbar *et al.,* [18]. According to Vosloo [9], the heat transfer coefficient in the coffee roasting process is highly dependent on the interaction between the fluid and the raw materials used. This condition significantly affects the geometric shape of the coffee beans and the thermodynamic characteristics of the used liquid. According to Clarke and Vitzthum [14], the value of the heat transfer coefficient in the coffee roasting process can be estimated at 14 to 140 W/m^{2}K. Meanwhile, Nagaraju *et al.,* [7] conducted a study using a fluidized bed roaster model to calculate the heat transfer coefficient between hot air and coffee beans. The obtained heat transfer coefficients start from 10.76 W/m^{2}K for a roasting process using the LTLT method and up to 21.69 W/m^{2}K using the HTST method. Basile and Kikic [8] observed a heat transfer coefficient of 14,469 to 80,348 W/m^{2}K performing the fluidization roasting process and 1,246 W/m^{2}K to 3,101 W/m^{2}K applying a drum method. In addition, another study reported by Putra *et al.,* [19] found that heat transfer coefficient values for fluidized bed roasters were 74,51 W/m^{2}K and 77,47 W/m^{2}K.

The overall heat transfer coefficient reported in the present study is higher than the previous researches. It can be explained that the roasting process carried out using a fluidized bed roaster with a spouted flow type can produce a better heat transfer rate than the roasting machine used in previous studies. In addition, several aspects such as the roasting method, airflow, machine design, to the capacity of the raw materials used can affect the value of the heat transfer coefficient in the coffee roasting process. Vosloo [9] reported using a spouted bed roaster, where all the beans were not equal, but the spout of high-velocity air carries the beans to the top of the roasting drum after it drops back to the bean bed. These roasters require less hot air, but the spouting increases the heat transfer that takes place. This method, however, tends to produce an inhomogeneous roasted batch of coffee beans [7,14].

3.2 Moisture Content

The analysis results showed that the interaction between temperature and processing time could affect the moisture content of Robusta coffee. Moisture content is an essential component in determining the quality of a food product, affecting the food product's appearance, structure, freshness, and durability when stored. Figure 5 and Figure 6 demonstrated the moisture content of the final product produced in the roasting process, both LTLT and HTST methods, were 2% and 1,87%, respectively, and met the value of the standard for roasted coffee products, which is maximum at 7% [20].

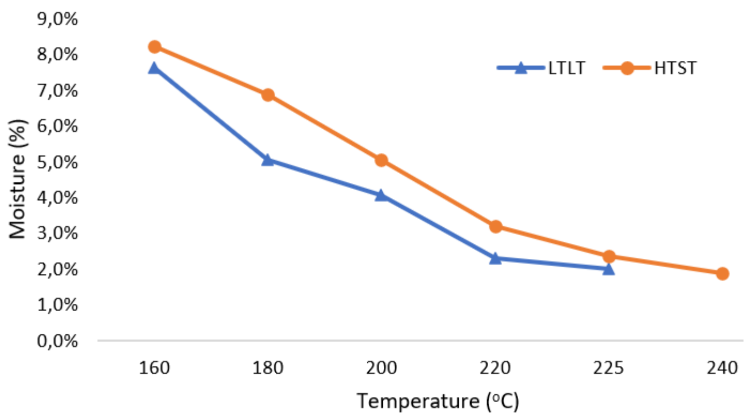

Fig. 5. Moisture content versus temperature

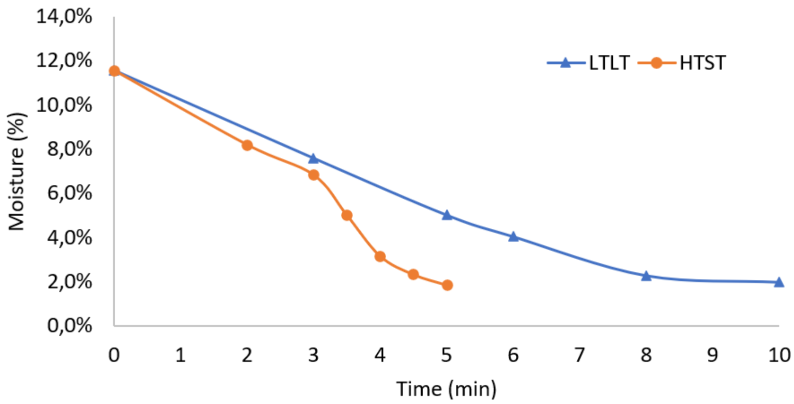

Fig. 6. Moisture content versus time

Figure 5 shows that the roasting process at 225°C for 10 minutes (LTLT) had lower moisture content at various stages of temperatures when compared to HTST at 240°C for 5 minutes. It can be implied that the moisture content in the roasting process decreases as the temperature process increases. Figure 4 demonstrated that water content decrease in the LTLT process was higher than in the HTST process. It means that the higher the temperature and the longer the roasting time, the lower the moisture content.

A decrease in the water content of coffee can be caused by heat transfer in the roasting machine into the bean, causing the liquid phase to turn into gas [21]. Figure 6 explains the decrease of moisture content over time between the LTLT and HTST processes. The bean moisture, initially, was around 12%, then reduce during roasting. In this study, moisture content of the LTLT process decreased from 12 to 5 % in 5 minutes, then diminished slightly to a value of 1,87% after 10 minutes. In contrast, in the HTST process, moisture content was decreased from 12 to 2% after 5 minutes. Clarke and Vitzthum [14] also reported moisture data using a fluidized bed with LTLT roasting. During roasting, the moisture reduced gradually from 11,1% to 2,3% after 6 minutes [14]. Saloko *et al.,* [21], using a rotary drum roaster, observed a moisture content at 4,59% after 10 minutes of roasting time at 225°C.

Water content decrease rate shows a higher tendency at temperatures from 160°C to 220°C and starts to slope ranging from 225°C to 240°C. According to Sivetz [22], decreasing water content occurs because the heat energy in the roasting chamber is used to evaporate the water in the early stages of the process. The moisture content of coffee beans drops rapidly at the beginning of roasting and then proceeds relatively slowly at the end of roasting [23].

3.3 Ash Content

Ash is an inorganic residue after passing through a combustion process of organic matter. The content and composition of ash depend on the type of material and how it is using. Ash content includes non-volatile components (non-volatile), minerals, and organic residues from combustion [24]. The mineral contents in coffee are calcium, potassium, magnesium, and non-metal compounds such as phosphorus and sulfur [14].

Figure 7 and Figure 8 depict an interaction between the time and temperature of the coffee roasting process, which offers a significant difference in the ash content of Robusta coffee roasted by the fluidization method. The higher the temperature in the roasting process, the greater the ash content value would be observed. In addition, it also applies to the duration of the roasting process, where the ash content's value would be higher if the roasting process was carried out for a longer period. Research conducted by Edvan *et al.,* [23] and Saloko *et al.,* [21] shows a similar phenomenon where the temperature and roasting time will significantly affect the ash content due to the roasting process.

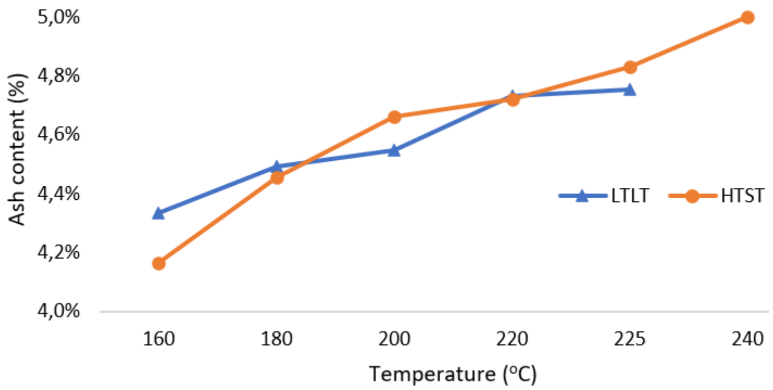

Fig. 7. Ash content versus temperature

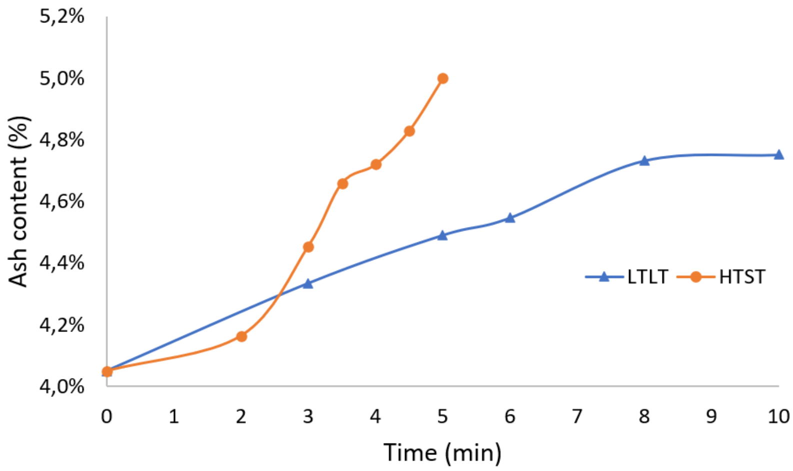

Fig. 8. Ash content versus time

Bicho *et al.,* [25] states that the ash content in coffee beans can vary depending on various factors, including soil conditions, fertilizers, and roasting methods. This study also shows that the obtained ash content from the roasting process using Robusta and Arabica coffee beans did not show significant differences when carried out using the same process method. In addition, differences in the ash content of coffee are caused by differences in coffee quality, where coffee beans with good quality will be cleaner and have higher mineral content, resulting in higher ash content [23].

Figure 7 demonstrates that the increase in ash content in the HTST process was higher than in the LTLT process. It shows that the roasting process at 240°C for 5 minutes produced a higher ash content when compared to 225°C for 10 minutes. Figure 8 shows the increased profile of ash content over time between the LTLT and HTST processes. In this study, the ash content increase from 4,3% (sampling at 160°C) to 4,75 % after 10 minutes in the LTLT process – Meanwhile, the ash content rosed from 4,16% to 5% after 5 minutes in the HTST process. Increased ash content produced in Robusta ground coffee could be caused by temperature treatment and roasting time, affecting a decrease on water content and other compounds such as antioxidants. Thus, the higher the temperature and the length of roasting time, the higher the ash content contained in Robusta coffee would be [21].

Based on the ash content analysis that was carried out on the final product of the coffee roasting process using a Spouted bed roaster machine, both from the LTLT and HTST processes, the ash content values achieved the national standard for coffee beans, which is a maximumly 5% [20].

4. Conclusions

Based on the results and discussion, the conclusions from the study of heat transfer and product characterization in spouted bed coffee roasters are:

i. The overall heat transfer coefficient value was higher in high-temperature conditions (HTST) than in the low-temperature process (LTLT).
ii. The roasting process at 225°C for 10 minutes (LTLT) had lower moisture contents at various stages of temperatures when compared to HTST with a roasting temperature of 240°C for 5 minutes. The moisture content in the roasting process decreases as the process temperature increases.
iii. There was no significant difference in ash content in the LTLT process compared to the HTST process. The ash content increased from 4,3% (sampling at 160°C) to 4,75 % after 10 minutes in the LTLT process. On the other hand, ash content rose from 4,16% to 5% after 5 minutes in the HTST process.

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