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Analysis Of Temperature Distribution On The Coffee Roaster Drum For A Capacity Of 2 Kg Using Computational Fluid Dynamics (CFD)

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Abstract

Coffee, one of Indonesia's largest commodities, is often processed using traditional methods and tools that rely heavily on manual labor and can be labor-intensive. To make the coffee roasting process more efficient and reduce the need for human effort, a coffee roasting machine can be used. This study aimed to analyze coffee roasting drums using Computational Fluid Dynamics (CFD) to determine the optimal drum thickness and rotation speed in a coffee roasting machine. The study considered three different thicknesses (1mm, 2mm, and 3mm) and three different rotation speeds (60rpm, 65rpm, and 70rpm). The coffee roasting drum was modeled using CFD. The study's results showed that a drum thickness of 2mm and a rotation speed of 70rpm achieved the best heat distribution during roasting, reaching the desired temperature in 900 seconds. This information could be used to design a more efficient coffee roasting machine or improve the performance of existing machines.

Keywords:
Coffee roaster, CFD, drum, rotational speed, temperature distribution.

1 Introduction

Coffee is a popular beverage worldwide, with approximately 3 billion cups consumed daily [1]. It is the second most valuable commodity after oil. Bengkulu is known for its high-quality coffee, which has been recognized in various scientific publications. In Bengkulu, coffee is a major commodity [2, 3].

Coffee is valued for its complex mixture of flavors and aromas, as well as its numerous bioactive substances that have been linked to various health benefits [4, 5]. To fully capitalize on these benefits, it is important to standardize the entire coffee production process, including drying, roasting, and resting [6].

Roasting coffee plays a crucial role in developing its aroma and influencing the composition of biologically active compounds. The roasting level is determined by the duration [7] and temperature [8] of the roasting process. It is essential to carefully control these factors in order to achieve the desired chemical reactions without burning the beans [9]. Coffee roasts are typically categorized as light, medium, or dark based on their color. However, achieving the perfect roast can be challenging due to the varying properties of different types of coffee beans and the different roasting techniques employed [8].

Currently, there are two main methods for roasting coffee beans. The traditional batch process involves roasting beans in a continuous system using different methods of heat transfer, such as conduction, convection, or radiation [10]. The most common approach is to use a rotating horizontal cylinder, also known as a roaster drum, which continuously heats and agitates the beans to ensure an even roast [11]. Various attempts have been made to optimize the heat flow in roaster drums in order to enhance the roasting process.

Numerous studies have been conducted on the topic of coffee roasting, including the design of coffee roasters [12], the optimum design of roaster drum thickness [13], simulations of heat transfer in roaster drums, and experimental analyses of coffee bean dynamics in rotary drums [14]. These studies often employ methods such as the Finite Element Method (FEM) and numerical displacement modeling to evaluate temperature, flow velocity, and other factors that affect the roasting process [15]. The aim of these studies is to gain a better understanding of the dynamics of coffee beans in roaster drums and to determine the optimal roasting conditions for different types of beans [16].

Despite the progress made through these studies, there are still factors that can influence the temperature distribution in roaster drums, such as time, rotation speed, and thickness of the drum walls. Therefore, it is important to consider these factors when studying the roasting process.

This study utilizes Computational Fluid Dynamics (CFD) to analyze the temperature distributions along the roaster drum. The coffee roaster drum has a capacity of 2 kg and dimensions of 20 cm in diameter and 35 cm in length. The rotation speed and thickness of the drum walls will be varied to investigate their effects on the temperature distribution within the drum. To achieve an even temperature distribution in the roaster, it is necessary to take into account the various factors that can impact temperature distribution.

2 Research Methods

In this study, ANSYS Fluent is used to simulate the flow characteristics of a coffee roaster drum. A 3D numerical model based on the finite-volume method was used to solve the governing equations and to apply the necessary boundary conditions. The geometry of the numerical model is the same as the physical drum used in the experiments. The drum was heated using LPG as the fuel source, and the temperature inside the drum was kept between 180°C-210°C. Temperature was recorded at various points on the drum wall and inside the drum. The drum is heated directly by the LPG combustion coming into the drum.

2.1 Dimensions and Material

In this study, there were three main areas in the coffee roaster that should be considered: drum, housing, and burner. Fig. 1 shows the dimensions of the model. The drum had a diameter of 200 mm and a length of 350 mm. The housing was 300 mm wide. The drum had thicknesses of 1, 2, and 3 mm [13]. The material used for the drum was stainless steel, and its properties are presented in Table 1.

Table 1. Material properties of stainless steel [17][18]

Material properties	Stainless steel
Density (kg/m^3)	7930
Young modulus (GPa)	200
Thermal conductivity (W/m.K)	14.5
Thermal expansion coefficient (1/˚K)	1.68×10^{-5}
Specific heat (J/Kg.K)	480
Poisson ratio	0.3

The details of the generated meshes are shown in Fig. 2. The model was cut along the centerline to show the internal mesh. Most of the elements are evenly shaped rectangles. The simulation was analyzed using four cases with 1.2 million elements.

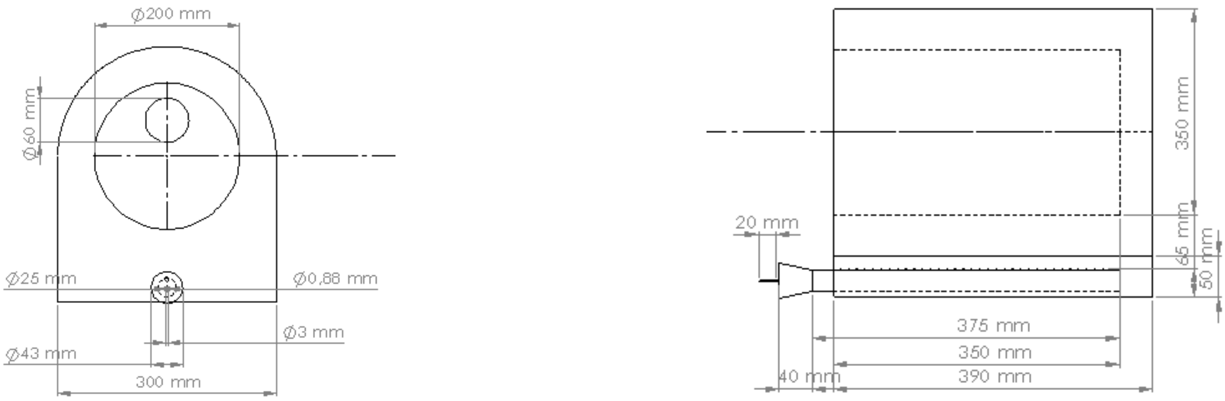


Fig. 1. Dimension of the coffee roaster drum.

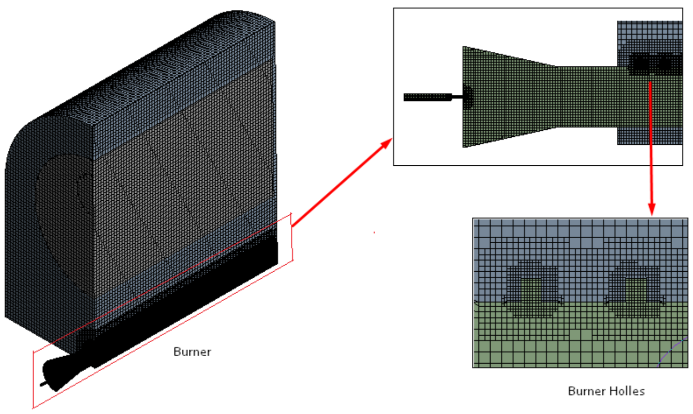


Fig. 2. Generated mesh of the considered model.

2.2 Boundary Conditions

In this simulation, the boundary conditions included two inlets at the pipe burner and an outlet located on the front side of the drum, as shown in Fig. 3. There was a gap of 3 mm between the back side of the drum and the housing for airflow to the drum. The drum was mounted on a support structure on both sides of the front and back. The drum was rotated at speeds of 60, 65, and 70 rpm. Details of the boundary conditions of the roaster are listed in Table 2.

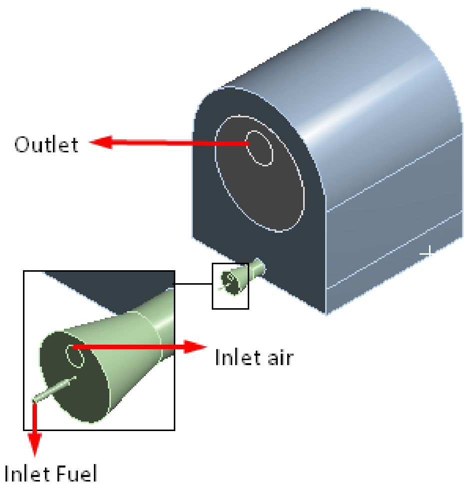


Fig. 3. The boundary conditions.

Table 2. Parameters of the boundary conditions of the coffee roaster

Input	Type	Unit
Inlet fuel C_3H_8	Mass flow inlet	0.00025 kg/s
Inlet air O_2	Inlet vent	1 Atm
Outlet	Pressure outlet	1 Atm
Drum	Rotational speed	60 rpm
		65 rpm
		70 rpm
Drum thickness	-	1 mm
		2 mm
		3 mm

The solution method used in this simulation is based on the simple algorithm with second-order upwind spatial discretization. The solution was treated as transient, and the simulation was run until the drum wall reached the target temperature of 200°C. The time-step size was set to 1 second, the simulation was repeated 20 times, and the total simulation time was 1200 seconds.

3 Results and Discussion

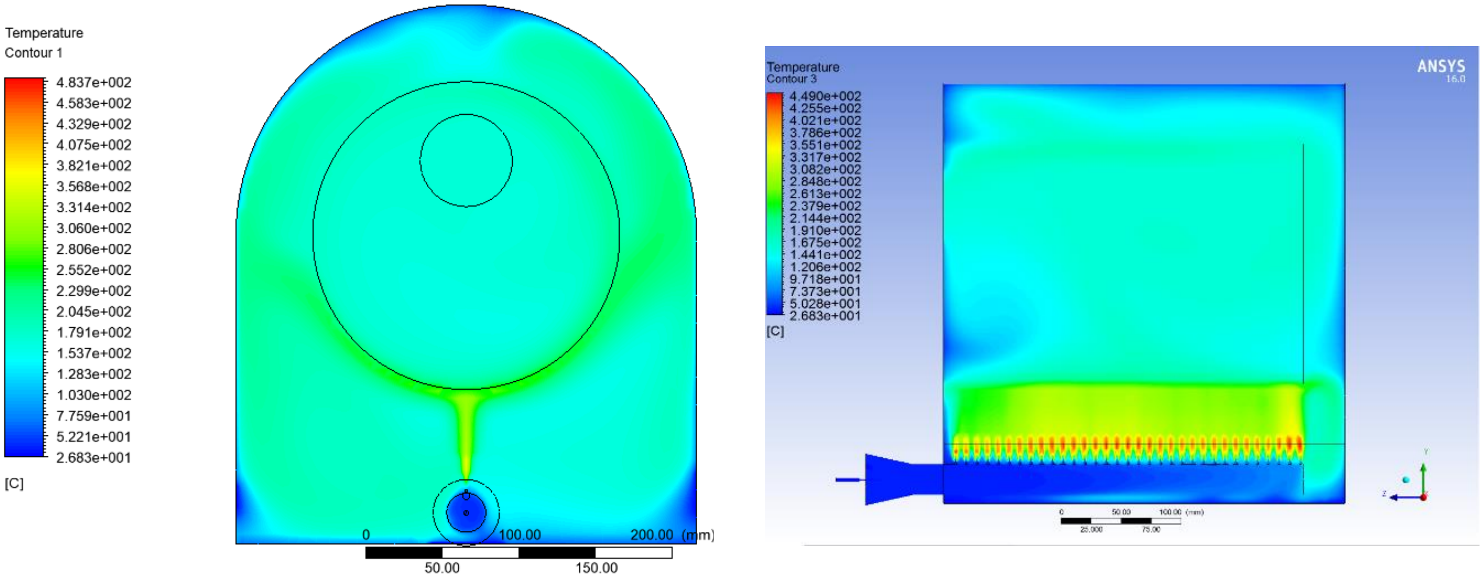
Fig. 4 shows the temperature distribution on the coffee roaster area during burning for a thickness of 2 mm at a rotational speed of 60 rpm. The temperature distribution was analyzed in the XY and ZY planes, with six vertical and eight horizontal points along the drum in each plane. When fuel was injected from the inlet, a temperature of 400°C was required around the outside of the burner to ignite the fire and heat the drum. It took 600-1000 seconds for the drum to reach this condition, as shown in Fig. 4(a).As shown in the temperature contour in Fig. 6, the drum temperature reached 200°C; however, the temperature inside the drum was between 155°C-200°C. Additionally, the temperature near the inlet was much lower than that at the other points, as shown in Fig. 4(b).

Fig. 5 shows the temperature distribution on the roaster drum in the XY (1,2,3,4,5,6) andZY (A,B,C,D,E,F, G, H) planes along the drum. The XY plane has 6 points with a distance between points is 3.3 mm. Moreover, the YZ plane has 8 points with a distance between points is 4.3 mm. According to Fig. 5(a), the temperature distribution along the drum with a thickness of 1 mm is uniform at all points, with the highest temperature value at point 6H (206°C) and the second highest value at point 1H (206°C). The lowest value was at the center of the drum at points 3A and 4B (157°C). The wall temperature in contact with the fire from points A to C significantly increased because of the heat distribution from points A to B, which was not ideal.

For a drum with a thickness of 2 mm and rotation speed of 60 rpm, it took 950 seconds to reach the target temperature on the drum wall. The highest temperature values in this variation were 205°C at points 6H and 1H, whereas the lowest value on the drum wall was at points 1A and 2A (182°C). The lowest temperature at the center of the drum was at point 3A (158°C), as shown in Fig. 5(b).

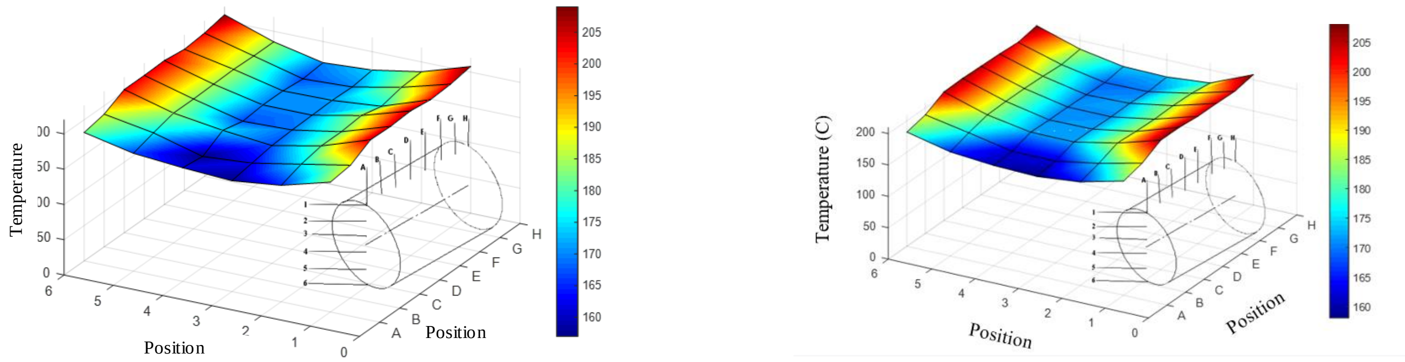
A drum with a thickness of 3 mm and a rotation speed of 60 rpm required 1100 seconds to reach the target temperature. The highest temperature was observed at points 1H and 6H (205°C), and the lowest was observed at points 3A and 4A (160°C). The lowest wall temperature was observed at points 1A and 6A (184°C). The temperature increase across the drum wall was not significant, indicating that the temperature distribution was quite good. The temperature distribution of the 3 mm drum at a rotation speed of 60 rpm is shown in Fig. 5(c).

As shown in the graph in Fig. 5, the drum with a thickness of 3 mm and rotation speed of 60 rpm had a lower temperature than the drum with a thickness of 2 mm and the same rotation speed, with a difference of 2°C.

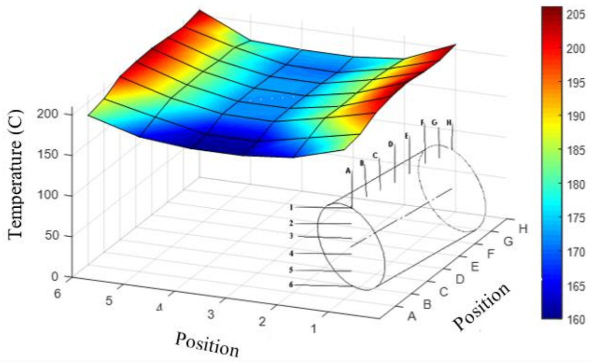


(a) XY plane (b) ZY Plane

Fig. 4. The contour of the temperature distribution in the roaster drum.



(a) Drum thickness of 1 mm (b) Drum thickness of 2 mm



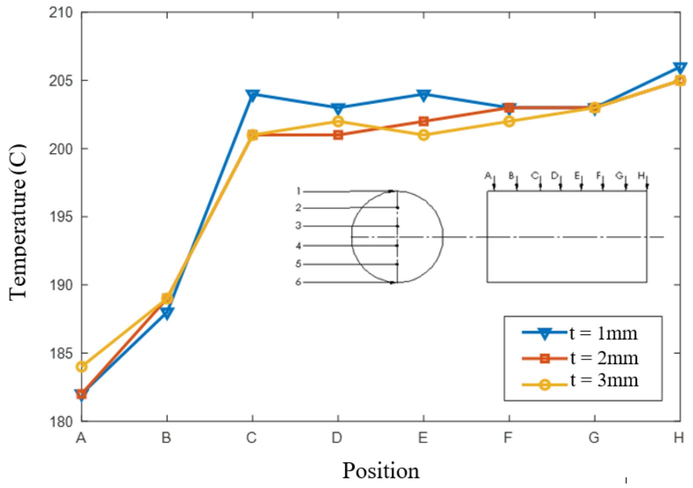
(c) Drum thickness of 3 mm

Fig. 5. Temperature distribution on the roaster drum in the XY (1, 2, 3, 4, 5, 6) and ZY (A, B, C, D, E, F, G, H) planes along the drum.

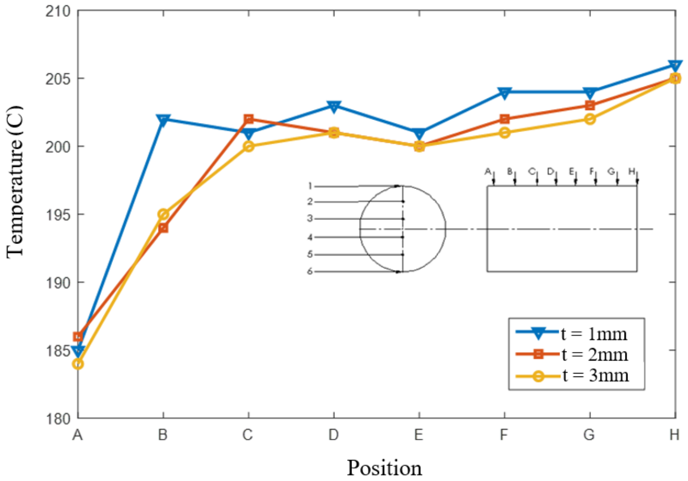
A graph comparing the variations in thickness (t) on the drum wall is shown in Fig. 6. The graph in Fig. 6(a) shows that for a drum thickness of 1 mm, the highest temperature is at point H, with a temperature of 209℃, and the lowest temperature is at point A. However, for thicknesses of 2 mm and 3 mm, the difference in temperature distribution is not too high, with a difference of only 1℃ to 2℃ between points C, D, E, and F. It can be observed that there was always a temperature difference on the wall. However, the temperature distribution value is not too high at variations of 60rpm for plate thicknesses of 1, 2, and 3 mm.

The temperature on the drum wall at 65rpm rotation was the highest at point H with a thickness variation of 1 mm, reaching a temperature of 206℃. There was a temperature difference of 1℃ for a thickness of 1 mm and a difference of 2℃ for a thickness of 3 mm. However, at points B, C, D, and E on the drum with a thickness of 1 mm, the temperature is higher than the other two variations of thickness owing to faster heat transfer in this variation because the drum is thinner. This can be seen in Fig. 6(b), which shows a comparison of the thickness variations of 1, 2, and 3 mm at 65rpm rotation. At a rotation of 65rpm, it can be seen that the drum with a thickness of 1 mm has a relatively high-temperature distribution, but there is a decrease in the temperature at point E before it rises again.

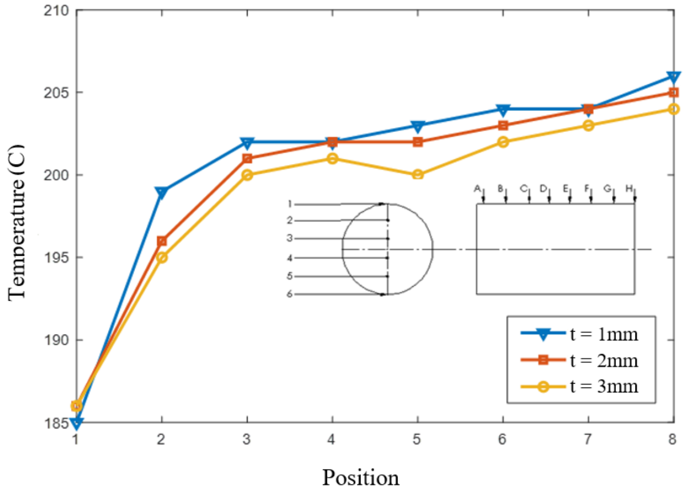
At 70 rpm rotation (Fig. 6(c)), it was found that the drum with a thickness of 1 mm had a relatively high temperature distribution compared to the other variations. However, the temperature distribution trend on the drum with a thickness of 2 mm is of concern because it shows a stable increase in temperature, reaching a maximum of 1-2 degrees Celsius higher at point H than the expected temperature for this thickness at this rotation. The drum with a thickness of 2 mm at a rotation of 70rpm requires 900 seconds longer to reach this temperature compared to the 60rpm rotation but has a better temperature distribution [13].



(a) Drum rotational speed of 60 rpm



(b) Drum rotational speed of 65 rpm



(c) Drum rotational speed of 70 rpm

Fig. 6. Temperature distribution on the coffee roaster drum.

4 Conclusion

The analysis of the effect of drum thickness and rotation on the temperature distribution rate using the CFD method indicates that a drum with a thickness of 2 mm at a rotation of 70 rpm has the most evenly distributed temperature on the wall and reaches the expected temperature in 900 seconds. This is compared to a rotation of 65rpm, which takes 850 seconds but has an uneven temperature distribution.

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