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Heat transfer simulation for re-design of tray dryer to reduce the energy consumption in the cocoa bean drying process

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Abstract. The tray dryer for the cocoa bean drying process is a solution to overcome conventional drying methods that rely on solar heat. The tray dryer is expected to facilitate the cocoa farmers to dry cocoa beans because it is faster and does not depend on weather conditions. However, even though the current condition of the tray dryer can reduce the energy consumption of drying cocoa beans (from Gunung Kidul, Yogyakarta, Indonesia) compared to the solar heat method, it remains unknown whether the cocoa beans drying quality is good enough. Therefore, this research analyzed the heat transfer phenomena of the cocoa drying process using the computational simulation method to re-design the current tray dryer design so that the new design can fit the drying characteristic of the cocoa bean and reduce energy consumption. As a result, for the air velocity of 25.91 m/s and the ½ opening of the gas valve in 10 minutes, which is already at steady-state conditions, the temperature distribution in the existing tray dryer is not suitable with the characteristics of the cocoa beans drying process. The temperature can be increased by reducing the airflow velocity or increasing the heating value by opening the valve. However, with a new design, the temperature can be increased by up to 37.00% at a velocity of 25.91 m/s with a ½ gas valve opening. Furthermore, the new design can achieve the same conditions as the existing design by only using an opening for a 1/8 gas valve. Thus, using the new design, the tray dryer can achieve the drying characteristics of cocoa beans and reduce energy consumption.

Keywords: Cocoa bean tray dryer, Heat transfer, Computational simulation, Re-design, Energy consumption.

1. Introduction

Cocoa beans, also known as chocolate beans, are seeds from the cocoa tree (*Theobroma cocoa*), the primary ingredient for chocolate-making. Cocoa greatly contributes to the Indonesian economy, ranking third-highest in the cocoa processing industry after the Netherlands and Ivory Coast [1]. Other data shows that cocoa is Indonesia's most important export commodity apart from oil and gas for earning foreign exchange, making Indonesia the sixth largest cocoa-producing country in the world [2].

Cocoa bean processing is necessary to improve the quality of the cocoa beans. Cocoa bean processing comprises two main stages: fermentation and drying [3]. Fermentation is carried out naturally within a few days to make high-quality cocoa beans suitable for consumption [4]. Through this fermentation stage, the taste, aroma, and color precursors will be formed in the cocoa beans [5]. Then, the drying process of cocoa beans aims to reduce the water content, which is still high after harvest, from around 51.00% - 60.00% to 6.00% - 7.00% [6]. If there is no drying process, it will cause difficulty in removing the nibs from the skin and cause rot due to the growth of microorganisms [7].

The drying of cocoa beans that has been done so far is by natural drying (by using the sun as a heat source). However, drying cocoa beans using this method is not optimal due to the unstable heat from the sun and the occurrence of rain, so the drying process takes longer (a day or more than one day). Therefore, a cocoa bean dryer is needed to reduce drying time. A cocoa bean dryer is an artificial drying tool used to dry cocoa beans after fermentation to reduce the water content. The drying process of the cocoa beans in the dryer must be carried out at the appropriate temperature and heat transfer distribution to maintain the quality of the dry cocoa beans. The drying temperature is one of the critical variables to obtain the best taste and flavor of cocoa [8]. Moreover, the temperature should be uniformly distributed through the tray dryer to ensure the same drying process characteristics in the whole tray dryer.

The current drying temperature of cocoa beans in Gunung Kidul, Yogyakarta, Indonesia, which is the target of this research, using the existing tray dryer, is lower than the common drying temperature used to dry the cocoa beans. Even though a different variety of cocoa beans has a specific drying temperature to obtain the unique taste, generally, the temperature required for the drying process to reduce the water content of cocoa beans is between 50 ℃ - 60 ℃ [9,10].

This study uses the computational simulation method to simulate the heat transfer phenomena during the drying process in a tray dryer type of cocoa bean. Heat transfer simulations and analysis are needed for the re-design of the existing tray dryer that is currently used in Gunung Kidul, Yogyakarta, Indonesia, to obtain the best heating process during cocoa bean drying and determine the best-designated temperature, temperature distribution, and how long it takes to reach the desired temperature.

2. Methodology

2.1. Experimental methods

We conducted two different experiments in this study. The first was the temperature measurement inside the drying chamber with an empty tray from initial to steady-state conditions. This experiment was used as a validation of the computational simulation. The temperature in the center of each tray (a total of eight trays that were utilized, four on the left side and four on the right side) was measured by the thermocouple sensor installed in each tray's center. The second experiment was the actual drying process of the cocoa bean. The 8 kg fermented cocoa bean (around seven days) was dried using the tray dryer. Eight trays were utilized during the drying process, filling each tray with one kg cocoa bean. Initially, the drying chamber was heated to reach the steady-state temperature by using the air velocity u_i = 25.91 m/s and the gas valve opening θ = ½. Then, the cocoa beans were put into the tray dryer for an 8-hour drying process. The temperature inside the drying chamber and the moisture content of the cocoa beans were measured using a thermocouple sensor and moisture meter every 30 minutes during the drying process.

2.2. Computational methods

2.2.1. 3-D computer-aided design (CAD) model for simulation. Two 3-D CAD models of the tray dryer, the existing and new models, were used for the simulation. The existing model was designed following the tray dryers currently used by the home cocoa industry in Gunung Kidul, Yogyakarta, Indonesia. Figure 1 shows the 3-D CAD model of the existing tray dryer. The tray dryer has two blowers, two heat exchangers, two drying chambers, and a partition wall. The domain of the simulation is taken as half of the tray dryer because the tray dryer is symmetrical in design. The new model was created by redesigning the existing design to re-adjust the heat transfer phenomena to increase the quality of the dried cocoa and reduce the energy consumption during the drying process of the cocoa bean. Figure 2 shows the 3-D CAD model of the new design of the tray dryer for (a) heat exchanger and (b) partition wall parts.

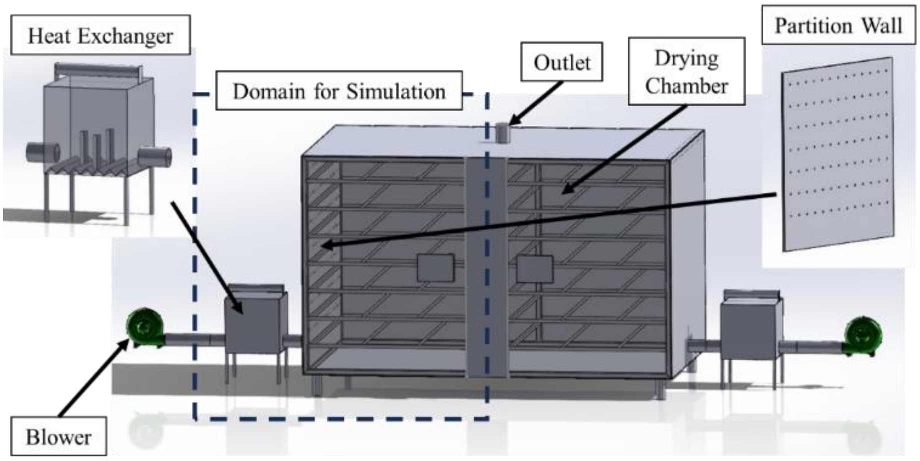
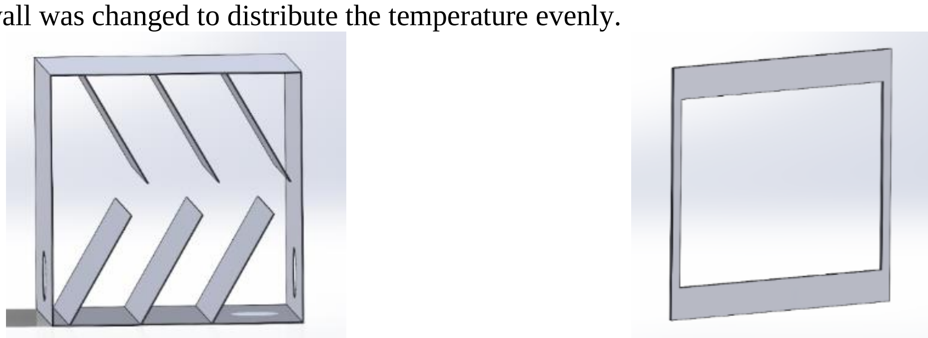


Figure 1. The 3-D CAD model of the existing tray dryer.

The re-design was conducted by improving the heat exchanger and partition wall because these parts are the easiest to modify (considering the economic factor). Another consideration was that the primary heat transfer phenomena in the heat exchanger and the partition wall are related to the flow separation and temperature distribution. The design was made by adding the fins with a specific angle to increase the heating contact area without hindering air movement. In the drying chamber, the shape of the partition wall was changed to distribute the temperature evenly.



(a) (b)

Figure 2. The 3-D CAD Model of the new design of the tray dryer for (a) heat exchanger; (b) partition wall.

2.2.2. Computational setups and conditions. The computational heat transfer simulation was carried out using Ansys 2020 software. The computational setups and conditions were divided into several steps: (1) model definition, (2) pre-processing, (3) processing, and (4) post-processing.

The first step, model definition, was a determination of physical phenomena that occur during the drying process of the cocoa bean inside the tray dryer. The model definition involves the schematic of drying phenomena, the governing equations, boundary and initial conditions, the flow conditions, and materials properties. Figure 3 shows the schematic of the drying phenomena. The airflow from the blower was defined as an airflow in the inlet. Then, the airflow was heated through the heat exchanger. The bottom plate of the heat exchanger was subjected to the heat flux from the gas burning. The heat transfer modes inside the heat exchanger were assumed to be convection and conduction (neglecting the radiation). The heat was spread through the heat wall by conduction and then transferred to the air by convection. The heated air then flows through the drying chamber to dry the cocoa bean and through the outlet.

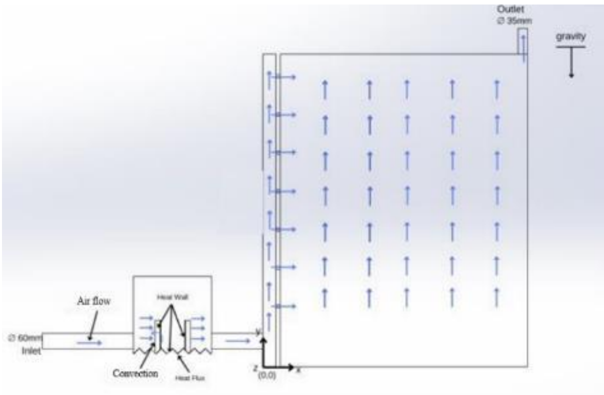


Figure 3. Schematic of the drying phenomena inside the tray dryer.

The material in the heat wall part is low-carbon steel, and the fluid is air (ideal gas and Newtonian fluid) with the properties taken at a temperature of 27.00 ℃, as shown in Table 1.

Table 1. The materials properties.

Materials	Density $\boldsymbol{\rho}$ (kg/m^3)	Specific heat $\boldsymbol{C_p}$ (J/kg °C)	Thermal conductivity k (W/m °C)	Dynamic viscosity $\boldsymbol{\mu}$ (Pa s)	Prandtl number Pr (-)
Low carbon steel	2850	450	25.3	-	-
Air	1.1769	1006.3	0.02624	1.8464×10^{-5}	0.708

Table 2 shows the flow conditions in the tray dryer were defined based on the value of Reynolds Number *Re* (flow pattern), Mach Number *Ma* (air compressibility), hydrodynamics entry length *Lh* (velocity profile), calculated from the inlet boundary velocity following the blower operation by using the equations from [11]. Three different inlet velocities were induced by the blower, i.e., 25.91, 15.00, and 5.00 m/s. The airflow pattern is turbulent because *Re* > 10,000. The air can be treated as an incompressible fluid since *Ma* < 0.30. The air velocity profile is uniform as the actual length *Li* is below the value of *Lh*.

Table 2. The flow conditions in the tray dryer.

Inlet velocity (m/s)	*Re* (-)	Flow pattern	*Ma* (-)	Compressibility	*Li* (m)	*Lh* (m)	Velocity profile
25.91	99,090.59		0.07			1.45	
15.00	57,366.23	Turbulent	0.04	Incompressible	0.35	1.26	Uniform
5.00	19,122.08		0.01			0.96	

The governing equations, a series of mathematical equations that describe the formulation of physical phenomena following the flow conditions that occur in tray dryers, were stated as follows:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \boldsymbol{g} \tag{2}$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot \left(k_{eff} \nabla T + \boldsymbol{\tau} \cdot \mathbf{u}\right) \tag{3}$$

where $\mathbf{u}$ is air velocity (m/s), ρ is the air density (kg/m^3), p is air pressure (Pa), μ is air dynamic viscosity (Pa s), $\rho\boldsymbol{g}$ is gravitational body force (N/m^3), C_p is the specific heat of the air (J/kg °C), $\boldsymbol{\tau}$ is viscous stress tensor (Pa), T is air temperature, and k_{eff} is the effective thermal conductivity (W/m °C) that was defined according to the turbulence model. In this study, the standard $k - \varepsilon$ turbulence model was implemented.

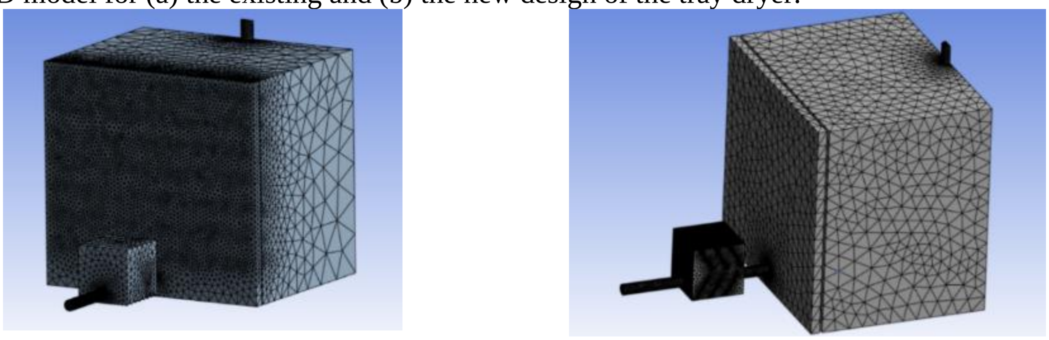
The equations (1) to (3) are the continuity equation, the momentum equation, and the energy equation. The phenomenon of airflow through the tray dryer was described by momentum and continuity equations, and the energy equation expresses the heat transfer (conduction and convection) phenomenon. In this simulation, forced convection occurs when the air flows in contact with the heat wall as a heat source.

Several boundary conditions were required to solve the governing equations above. Table 3 shows the boundary and the initial conditions. The inlet boundary was defined as the velocity inlet u_i based on the blower operation. The inlet temperature T_{in} was considered the same as the ambient temperature. The outlet boundary was subjected to ambient pressure. The bottom plate of the heat wall boundary was subjected to the heat flux q_f that related to the valve opening of the gas burner θ that is $\frac{1}{2}, \frac{1}{4}, \frac{1}{8}$, with the diameter of the burner d = 9 cm. The upper section of the heat wall was the interface boundary in which the conduction in the bottom plate was transferred to the forced convection in the airflow. Thus, the calculation of convection heat transfer coefficient h_c is necessary. h_c was calculated based on the Nusselt Number obtained by using the Dittus-Boelter equation [12]. The tray dryer was initially filled with air with the ambient pressure p_∞ and temperature T_∞.

Table 3. The boundary and initial conditions (a) inlet; (b) heat wall; (c) outlet; (d) initial.

(a) Inlet		(b) Heat wall		(c) Outlet	(d) Initial	
$\boldsymbol{u_i}$ (m/s)	T_{in} (ºC)	$\boldsymbol{q_f}$ (W/m^2)	h_c (W m^2 ºC)	$\boldsymbol{p_{out}}$ (Pa)	$\boldsymbol{p_\infty}$ (Pa)	T_∞(ºC)
25.91	27.00	4367.79 ($\boldsymbol{\theta} = \frac{1}{2}$)	4306.00	101,325	101,325	27.00
15.00		4434.92 ($\boldsymbol{\theta} = \frac{1}{4}$)	2780.82			
5.00		3225.38 ($\boldsymbol{\theta} = \frac{1}{8}$)	1154.72			

The second step is pre-processing, which comprises importing 3-D CAD models (geometry), defining boundaries, and meshing according to the model definition. Figure 4 shows the meshing results of the 3-D CAD model for (a) the existing and (b) the new design of the tray dryer.



(a) (b)

Figure 4. The meshing results of 3-D CAD model for (a) existing and (b) new design of tray dryer.

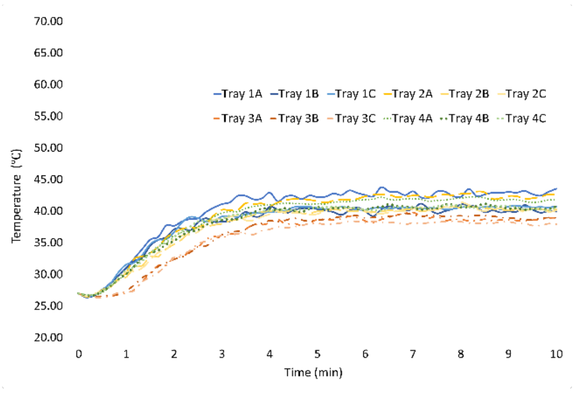
The third step is processing, including the model input setup and determining the solution before running the simulation. The type of solver used is pressure-based because the flow is incompressible. The transient phenomena were implemented because one simulation purpose was to obtain the temperature as a function of time. The solution method used was PISO, which can solve continuity, momentum, and energy equations with a separate or segregated steps approach such as SIMPLE. Still, this method is more suitable for turbulent and more complex flows. The simulation was run for 600 seconds or 10

minutes, where the number of time steps was 60 with a time step size of 10 seconds. The iteration was conducted until convergence with a relative tolerance of 10^{-3}.
The last step is post-processing, which presents computational results as a figure or graph. The post-processing was necessary to obtain a better analysis and understanding of the heat transfer phenomena inside the tray dryer.

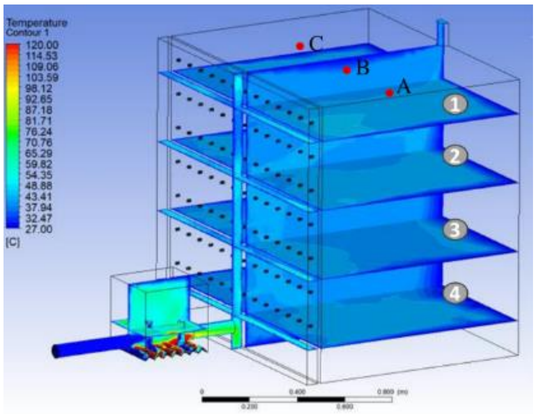
3. Results and discussion

3.1. Computational simulation results

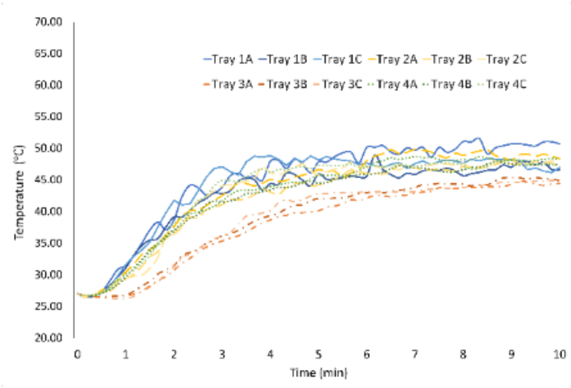
3.1.1. The existing design. Figure 5 shows the temperature distribution in the center point of each tray for $\theta = \frac{1}{2}$ as a function of time with inlet velocity (a) u_i = 25.91 m/s; (b) u_i = 15.00 m/s; (c) u_i = 5.00 m/s. Figure 6 indicates the isometric view of the temperature distribution image inside the tray dryer for $\theta = \frac{1}{2}$ at time t = 10 minutes with inlet velocity (a) u_i = 25.91 m/s; (b) u_i = 15.00 m/s; (c) u_i = 5.00 m/s. Figure 7 exhibits the temperature distribution in the center point of each tray for (a) $\theta = \frac{1}{4}$; (b) $\theta = \frac{1}{8}$ as a function of time with inlet velocity u_i = 25.91 m/s. Figure 8 reveals The isometric view of the temperature distribution image inside the tray dryer for (a) $\theta = \frac{1}{4}$; (b) $\theta = \frac{1}{8}$ at time t = 10 minutes with inlet velocity u_i = 25.91 m/s. All the figures above are the simulation results for the existing design.
Based on the Figure 5(a), it can be seen that by using the existing parameter of u_i = 25.91 m/s and $\theta = \frac{1}{2}$ opening, within 10 minutes after steady-state, the tray dryer is not able to reach the best temperature that corresponds to the drying characteristics of cocoa beans, which is around 50.00 ℃-60.00 ℃, even though the temperature is uniformly distributed in all of the trays as shown in and Figure 6(b).
At the value of $\theta = \frac{1}{2}$, the temperature distribution inside the drying chamber is varied 37.94 ℃ - 43.55 ℃, 44.45 ℃ - 50.73 ℃, 56.56 ℃ - 64.85 ℃ for u_i = 25.91 m/s, u_i = 15.00 m/s, and u_i = 5.00 m/s, respectively. Reducing the blower or inlet velocity will increase the maximum steady-state temperature or the designated temperature for the drying process of cocoa beans. However, the temperature distribution is unequally distributed. In Figure 5(b) and (c), the temperature in tray number 3 is lower than others. The decrease of gas opening valve θ will reduce the energy consumption but increase the time to reach the steady state temperature, as shown in Figure 7 and Figure 8. This phenomenon happens because the airflow moves more slowly, giving the heat exchanger more time to heat the air, but the result is that it takes longer to reach steady-state conditions.



(a)



(a)



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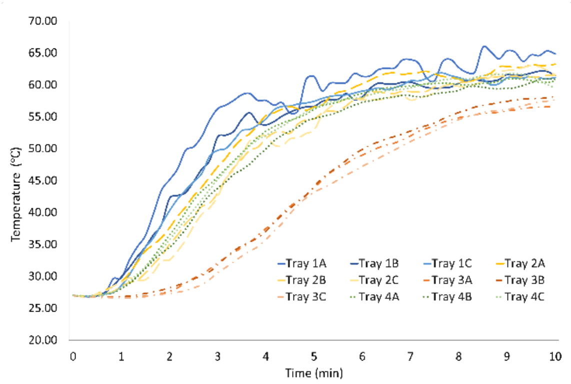
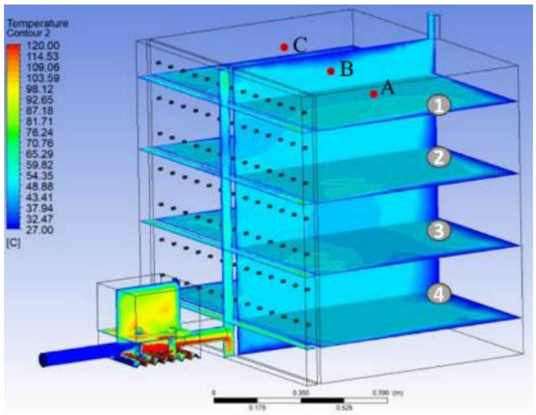


(c)

Figure 5. The temperature distribution in the center point of each tray for $\theta = \frac{1}{2}$ as a function of time with inlet velocity (a) u_i = 25.91 m/s; (b) u_i = 15.00 m/s; (c) u_i = 5.00 m/s.



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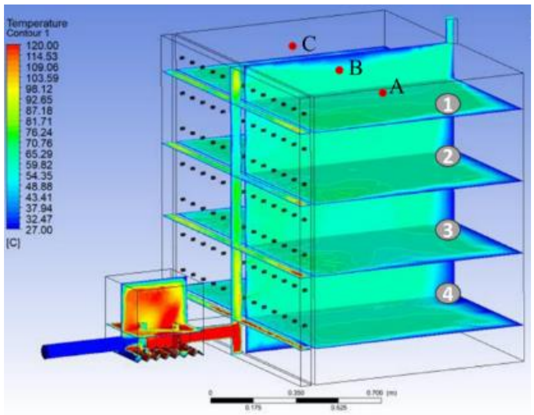
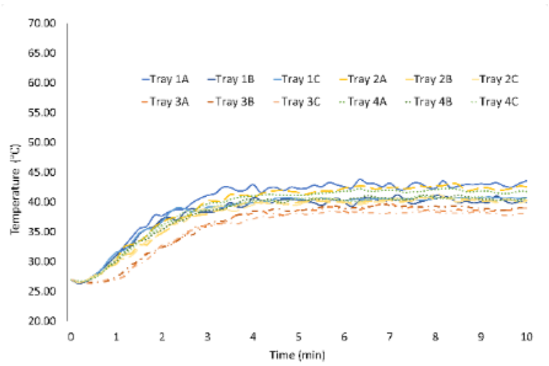
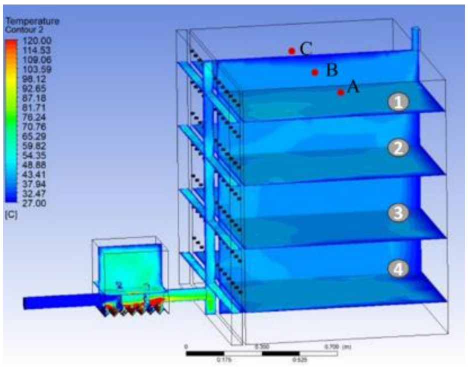


(c)

Figure 6. The isometric view of the temperature distribution image inside the tray dryer $\theta = \frac{1}{2}$ at time t = 10 minutes with inlet velocity (a) u_i = 25.91 m/s; (b) u_i = 15.00 m/s; (c) u_i = 5.00 m/s.



(a)



(a)

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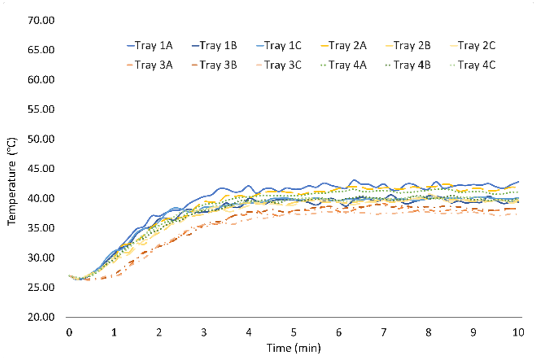
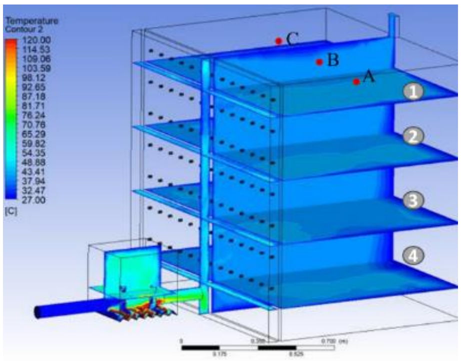


(b)

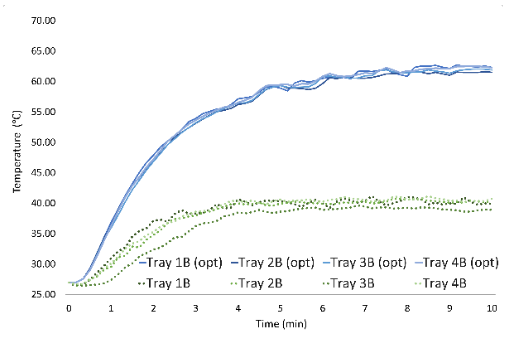
Figure 7. The temperature distribution in the center point of each tray for (a) $\theta = \frac{1}{4}$; (b) $\theta = \frac{1}{8}$ as a function of time with inlet velocity u_i = 25.91 m/s.



(b)

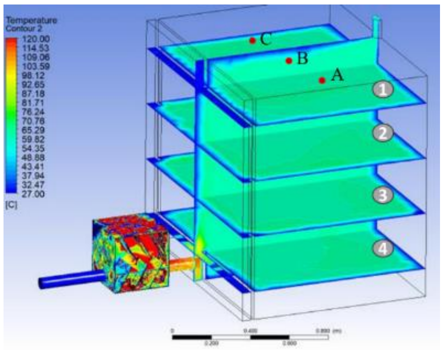
Figure 8. The isometric view of the temperature distribution image inside the tray dryer for (a) $\theta = \frac{1}{4}$; (b) $\theta = \frac{1}{8}$ at time t = 10 minutes with inlet velocity u_i = 25.91 m/s.

3.1.2. New design. Figure 9 and Figure 10 show the comparison of temperature distribution in the center point of each tray between existing and new designs for $\theta = \frac{1}{2}$ and u_i = 25.91 m/s and the isometric view of the temperature distribution image inside the tray dryer; for $\theta = \frac{1}{2}$ at time t = 10 minutes with u_i = 25.91 m/s, respectively. It is found that the designated temperature increased from around 40.00 °C for the existing design to around 60.00 °C (an increase up to 37.00%). Moreover, the temperature distribution also becomes more uniform.



(a)

Figure 9. The temperature distribution in the center point of each tray for $\theta = \frac{1}{2}$ as a function of time with inlet velocity u_i = 25.91 m/s.



(b)

Figure 10. The isometric view of the temperature distribution image inside the tray dryer for $\theta = \frac{1}{2}$ as a function of time with inlet velocity u_i = 25.91 m/s.

3.2. The comparison between experimental and computational simulation results

Figure 11 shows the comparison of temperature distribution between the existing and new designs in the center point of each tray for $\theta = \frac{1}{2}$ as a function of time with inlet velocity u_i = 25.91 m/s. The triangle, rhombus, circle, and rectangle dots represent experimental data. The simulation and experimental values are compared to each other, with a percentage error value of 0% - 19%. The difference occurs because the simulation results are ideal conditions where all the fluid flow and energy principles are fulfilled. Meanwhile, the experimental results do not always experience ideal conditions; air leaks in the tray dryer cause one. However, the trendline of temperature as a function of time between simulation and experimental data shows similar characteristics.

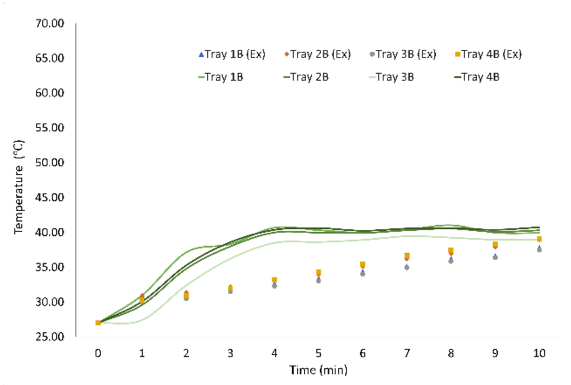


Figure 11. The comparison of temperature distribution between existing and new designs in the center point of each tray for $\theta = \frac{1}{2}$ as a function of time with inlet velocity u_i = 25.91 m/s.

3.3. *Energy consumption analysis*

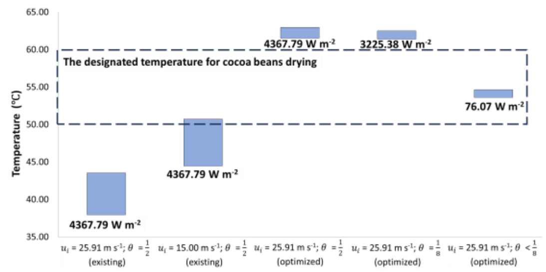


Figure 12. The comparison of energy consumption between existing and new designs of tray dryers.

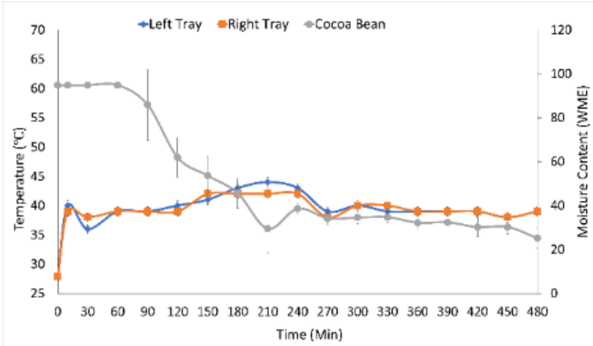


Figure 13. The drying chamber temperature and the moisture content of the cocoa bean during the drying process in the existing tray dryer.

Figure 12 reveals the energy consumption comparison between the existing and new designs of the tray dryer. The black dashed line indicates the designated drying temperature area. Figure 13 shows the drying chamber temperature and the moisture content of the cocoa bean during the drying process in the existing tray dryer. The blue and orange lines indicate the average temperature as a function of time inside the left tray and right tray, respectively. The gray line indicates the moisture content (WME) of cocoa beans as a function of time during drying. The moisture content decreases with the increase of time since the water content inside the cocoa beans evaporates during the drying process. However, during the 8 hours of drying, the final product of dried cocoa beans is still not good, with sour smells, which indicates the water content inside the dried cocoa beans is still higher than standard. The drying process in Figure 13 was conducted at u_i = 25.91 m/s and $\theta = \frac{1}{2}$. It is shown that with these two parameters, the energy consumption reaches 4367.79 W/m^2. Energy consumption corresponds to the heat flux boundary value since heat flux is calculated based on the gas usage following the gas valve opening value. To achieve the designated temperature according to the drying characteristics of cocoa beans, the parameters should be changed to u_i = 15.00 m/s and $\theta = \frac{1}{2}$ with the existing design. However, the energy consumption is still high. By using the new design, at u_i = 25.91 m/s and $\theta = \frac{1}{8}$, the energy consumption decreases to 3225.38 W/m^2. The value of u_i is maintain to 25.91 m/s because in this air velocity, the temperature distribution inside the drying chamber is uniform. By carrying out more simulations to get an energy consumption of less than 3225.38 W/m^2, the heat flux value was obtained, 76.07 W/m^2 or equivalent to 300 kJ/kg, with a time to reach steady-state within 5 minutes.

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4. Conclusion

In this study, we conducted a re-design of the existing tray dryer that has been used for the cocoa beans drying process in Gunung Kidul, Yogyakarta, Indonesia. A new design for the tray dryer was created by modifying the existing tray's heat wall and partition wall. The computational simulation was successfully carried out in the new design to analyze the heat transfer phenomena during the drying process. The simulation proved that the new design could reduce the energy consumption of gas with the steady-state or designated drying temperature in the range of drying temperature of cocoa beans. Moreover, the effects of the tray dryer's operating parameters such as blower velocity and gas valve opening to the temperature characteristic inside the tray dryer were observed.

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