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THERMAL EFFICIENCY ANALYSIS OF COFFEE BEAN ROASTER BASED *ON PARABOLIC DISH COLLECTOR* (PDC) WITH THE ADDITION OF FRESNEL GLASS AS A SOLAR RADIATION AMPLIFIER

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Abstract
This study discusses the use of solar energy as a heat source in the roasting process of coffee beans using *a Parabolic Dish Collector* (PDC), and analyzes the effect of Fresnel glass integration on improving the thermal performance of the system. Field test data collection is carried out repeatedly on two system configurations, namely PDC without and with Fresnel glass. The results showed that in the configuration without Fresnel glass, the temperature of the coffee beans only reached about 200 – 210 °C in the 15th minute, because the heating took place indirectly through the walls of the heating tube. Conversely, with the addition of Fresnel glass, the temperature of the coffee beans reaches the roasting threshold (~200 °C) faster, namely in the 9th to 10th minute, and increases to 241 – 249 °C in the 12th minute. This shows an acceleration of heating time of about 5 – 6 minutes at the same relatively same intensity of the sun. In addition, the average thermal efficiency of the system increased from 8.36% to 10.60%, or an increase of about 26.9%. This finding proves that the integration of Fresnel glass in PDC is able to accelerate the heating process, increase the working temperature, and improve heat absorption efficiency, so that this technology has the potential to be applied to small-scale coffee roasting processes based on solar energy.
Keywords: solar energy, Parabolic Dish Collector, Fresnel glass, coffee roasting, thermal efficiency

Abstrak
Penelitian ini membahas penggunaan energi surya sebagai sumber panas dalam proses penggorengan biji kopi menggunakan Parabolic Dish Collector (PDC), serta menganalisis pengaruh integrasi kaca Fresnel terhadap peningkatan kinerja termal sistem. Pengumpulan data uji lapangan dilakukan berulang kali pada dua konfigurasi sistem, yaitu PDC tanpa dan dengan kaca Fresnel. Hasil menunjukkan bahwa pada konfigurasi tanpa kaca Fresnel, suhu biji kopi hanya mencapai sekitar 200–210 °C pada menit ke-15, karena pemanasan terjadi secara tidak langsung melalui dinding tabung pemanas. Sebaliknya, dengan penambahan kaca Fresnel, suhu biji kopi mencapai ambang batas pemanggangan (~200 °C) lebih cepat, yaitu pada menit ke-9 hingga ke-10, dan meningkat menjadi 241–249 °C pada menit ke-12. Hal ini menunjukkan percepatan waktu pemanasan sekitar 5–6 menit pada intensitas matahari yang relatif sama. Selain itu, efisiensi termal rata-rata sistem meningkat dari 8,36% menjadi 10,60%,

atau peningkatan sekitar 26,9%. Temuan ini membuktikan bahwa integrasi kaca Fresnel dalam PDC mampu mempercepat proses pemanasan, meningkatkan suhu kerja, dan meningkatkan efisiensi penyerapan panas, sehingga teknologi ini berpotensi diterapkan pada proses pemanggangan kopi skala kecil berbasis energi surya.
Kata kunci: *energi surya, Parabolic Dish Collector, kaca Fresnel, penggorengan kopi, efisiensi termal*

INTRODUCTION

The coffee roasting process is one of the most crucial stages in determining the final aroma, flavor profile, and quality of coffee beans. During roasting, green coffee beans undergo complex physical and chemical transformations that influence the formation of volatile aromatic compounds, caramelization reactions, and Maillard reactions that contribute to the distinctive flavor of roasted coffee. The roasting temperature, heating rate, and roasting duration significantly affect the development of flavor compounds and overall coffee quality. Therefore, precise control of the heat source is essential to ensure consistent roasting results and maintain product quality (Serrano-Arellano et al., 2026). In conventional roasting systems, heat is typically generated using fossil fuels such as gas or electricity, which not only increases operational costs but also contributes to greenhouse gas emissions. As the global coffee industry continues to expand, there is increasing interest in alternative roasting technologies that are more sustainable, energy-efficient, and environmentally friendly.

Indonesia is one of the world's largest coffee-producing countries, with abundant solar radiation potential throughout the year due to its geographic location in the tropical region. Solar energy represents a renewable and sustainable energy source that can be utilized for various thermal processes, including food processing, drying, and roasting. The use of solar thermal energy in agricultural processing offers several advantages, including reduced operational costs, reduced dependence on fossil fuels, and minimized environmental impacts. Solar energy utilization also aligns with global efforts to transition toward clean energy systems and reduce carbon emissions associated with industrial processes (Islam et al., 1992). In many developing regions where access to stable energy infrastructure may be limited, solar-based thermal systems provide an attractive alternative for small-scale food processing industries, including coffee roasting.

In solar thermal applications, one of the primary challenges is achieving sufficiently high temperatures to support heat-intensive processes such as roasting. Direct sunlight alone often does not provide the level of thermal energy required for rapid heating. Therefore, solar concentrator systems are commonly used to increase the intensity of solar radiation by focusing sunlight into a smaller target area. Solar concentrators operate based on the principle of concentrating solar radiation using reflective or refractive optical elements so that the energy density at the focal point becomes significantly higher than the ambient solar radiation intensity. Among various solar concentrator technologies, the Parabolic Dish Collector (PDC) is widely recognized as one of the most efficient solar thermal concentrator systems for achieving high temperatures.

A Parabolic Dish Collector works by reflecting incoming solar radiation toward a focal point using a curved reflective surface shaped like a paraboloid. The reflective surface directs parallel sunlight rays toward a single focal region, where a receiver or absorber tube is positioned to capture the concentrated heat. Due to its point-focus design, a PDC is capable of achieving high concentration ratios and producing temperatures significantly higher than those achieved by flat plate collectors or linear concentrators. The concentrated heat can then be used for various applications such as power generation, cooking, water heating, and thermal processing (Buscemi et al., 2020). In the context of coffee roasting, the absorber or heating tube placed at the focal point can transfer thermal energy directly to the roasting chamber, enabling the roasting process without relying on fossil fuels.

The performance of a Parabolic Dish Collector depends on several important factors, including the quality of the reflective surface, optical alignment, solar tracking accuracy, and thermal losses within the system. High reflectivity materials are required to maximize the amount of solar radiation directed toward the focal point. Additionally, precise alignment between the reflector surface and the receiver is essential to ensure that the concentrated radiation is properly focused on the heating element. Optical errors, surface imperfections, and misalignment can reduce the concentration efficiency and significantly decrease the thermal output of the collector. Optical characteristics of concentrator systems also influence the distribution of radiation at the focal point and determine how effectively the thermal energy can be transferred to the absorber (Huang, 2011).

Another important factor influencing solar concentrator performance is heat loss from the system. Heat losses can occur through convection, conduction, and radiation from the receiver surface and surrounding structures. Efficient thermal insulation and proper design of the absorber tube are required to minimize energy loss and maintain stable operating temperatures. When properly designed, PDC systems can provide stable and high-temperature heat suitable for food processing applications. Several studies have demonstrated that solar concentrator systems can successfully generate sufficient heat for roasting agricultural products such as cocoa and coffee, indicating strong potential for solar-powered roasting technologies (Serrano-Arellano et al., 2026).

Although Parabolic Dish Collectors are capable of generating high temperatures, improvements in optical concentration can further enhance system efficiency. One promising approach to increasing solar concentration is the use of Fresnel lenses or Fresnel glass as an additional optical element. Fresnel lenses are designed to concentrate sunlight using refraction rather than reflection. Unlike conventional convex lenses, Fresnel lenses consist of a series of concentric grooves that allow them to focus light efficiently while using less material. Because of their lightweight design and high optical efficiency, Fresnel lenses are widely used in solar concentrator systems to enhance radiation intensity at the focal point (Hornung et al., 2012).

The addition of Fresnel glass to a solar concentrator system can significantly increase the concentration of solar radiation directed toward the receiver. Fresnel lenses are capable of achieving high concentration ratios by refracting incoming solar rays into a narrow focal region. In some solar thermal systems, Fresnel-based concentrators have demonstrated high optical efficiency and the ability to produce temperatures exceeding 100°C or more, depending on system design and solar intensity (Schwarzer et al., 2022). When integrated with a reflective concentrator such as a parabolic dish, Fresnel lenses can enhance the optical performance of the system by increasing the amount of radiation reaching the absorber.

The use of Fresnel lenses in solar thermal systems has been explored in various applications, including solar cookers, water heating systems, and solar desalination systems. Experimental studies have shown that Fresnel-based concentrators can significantly increase the heating rate and reduce the time required to reach target temperatures. For example, experimental research on solar cookers using Fresnel lenses demonstrated improved heating performance and higher thermal efficiency compared to conventional solar heating systems (Asrori et al., 2020). These results indicate that Fresnel lenses have strong potential to enhance the thermal performance of solar concentrators used for food processing applications.

In the context of coffee roasting systems, the integration of Fresnel glass with a Parabolic Dish Collector may provide several important advantages. First, the additional optical concentration from the Fresnel lens can increase the solar heat flux received by the heating tube or roasting chamber. Higher heat flux allows the system to reach roasting temperatures more quickly, which is essential for maintaining proper roasting profiles. Second, increased heating rates may reduce roasting time, leading to improved operational efficiency. Third, the use of solar energy as the primary heat source reduces fuel consumption and operating costs for coffee producers.

Energy efficiency is an increasingly important factor in the coffee processing industry, particularly for small and medium-scale producers who often face rising energy costs. Solar-powered roasting systems offer a sustainable alternative that reduces reliance on fossil fuels while maintaining the quality of roasted coffee. In addition, environmentally friendly roasting technologies can support sustainable coffee production practices and improve the environmental footprint of the coffee supply chain. The development of renewable-energy-based roasting systems also aligns with global sustainability initiatives aimed at reducing greenhouse gas emissions and promoting renewable energy utilization in industrial processes.

Despite the promising potential of solar concentrator systems, several technical challenges must be addressed to ensure reliable operation. Solar radiation intensity varies depending on weather conditions, time of day, and seasonal variations. These fluctuations can affect the stability of the roasting temperature and may influence roasting consistency. Therefore, system design must consider thermal storage, insulation, or auxiliary heating mechanisms to maintain stable roasting conditions when solar radiation decreases. In addition, accurate measurement and monitoring of key thermal parameters such as solar irradiance, receiver temperature, and bean temperature are necessary to evaluate system performance and optimize roasting conditions.

This study focuses on the development and experimental evaluation of a solar coffee roasting system based on a Parabolic Dish Collector with the addition of Fresnel glass as an optical concentrator. Two system configurations are compared: a conventional PDC system without Fresnel glass and a modified PDC system integrated with Fresnel glass. The objective of this comparison is to determine whether the addition of Fresnel glass can enhance solar concentration, accelerate temperature rise, and improve thermal efficiency during the roasting process.

Experimental testing was conducted under field conditions by collecting thermal performance data from both system configurations. The parameters measured during testing include solar irradiance, ambient temperature, heating tube wall temperature at several points (bottom, middle, and top), and coffee bean temperature inside the roasting chamber. Temperature measurements were recorded periodically during the roasting process to observe heating patterns and evaluate the system's ability to reach and maintain roasting temperatures. By comparing the heating characteristics of both configurations, it is possible to determine the influence of Fresnel glass on the thermal performance of the solar roasting system.

The main objective of this research is to analyze the thermal performance improvement achieved through the integration of Fresnel glass into a Parabolic Dish Collector system. Specifically, the study aims to evaluate whether the Fresnel-enhanced system can achieve faster temperature increases, higher peak temperatures, and improved heat transfer efficiency compared to the conventional PDC configuration. The results of this study are expected to contribute to the development of more efficient solar roasting technologies that support sustainable coffee processing.

Ultimately, the implementation of solar-powered roasting technology has the potential to transform coffee processing practices, particularly in regions with high solar radiation such as Indonesia. By utilizing renewable solar energy as the primary heat source, coffee producers can reduce operational costs, minimize environmental impacts, and promote sustainable production systems. The integration of optical concentrators such as Parabolic Dish Collectors and Fresnel lenses represents an innovative approach to improving the efficiency of solar thermal systems used in agricultural processing. If successfully implemented, this technology could provide a practical and environmentally friendly solution for coffee roasting, supporting both energy sustainability and high-quality coffee production.

METHOD

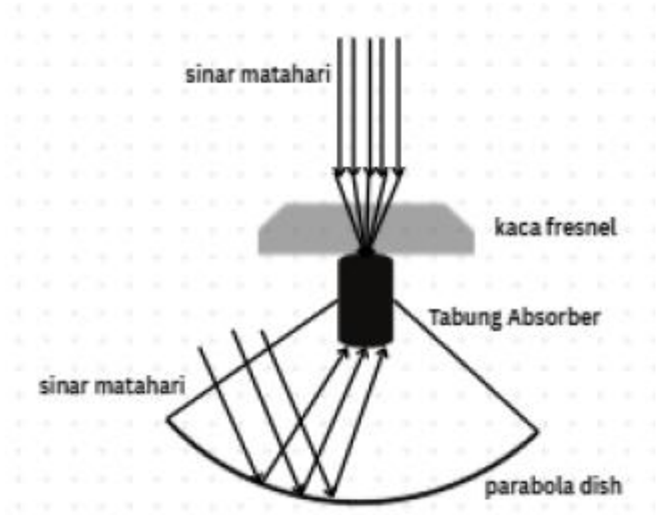
roasting process of Arabica coffee beans using a Parabolic Dish Concentrator (PDC) and the addition of fresnel glass. Furthermore, the design and manufacture of the roasting system is carried out, followed by the preparation stage of tools and materials, including tool calibration and coffee bean preparation and test operating conditions. The test was carried out in two scenarios, namely PDC without and with fresnel glass. The data obtained was used to (1) compare the roasting duration before and after the addition of fresnel glass, and (2) calculate the efficiency of the roasting process under both conditions. The test results are then analyzed and presented in the results and discussion section to evaluate the effect of adding fresnel glass on the performance of the roasting system.

This study is a comparative experiment on a coffee roaster system based on *Parabolic Dish Collector* (PDC) with two configurations working in an open system, namely: (i) PDC without Fresnel glass, which focuses solar radiation directly into a copper absorber tube with a thickness of ± 1 mm; and (ii) PDC with Fresnel glass, which adds direct heating to the bean mass from the top so that both radiation sources work simultaneously.

Each configuration had its test data taken twice in the daytime irradiation time range. Each test uses 100 g of Arabica coffee beans with an initial moisture content of about 12%. This approach aims to analyze heating performance based on three main parameters: the rate of temperature rise, the time of reaching the target temperature, and the thermal efficiency of the system. The specific heat capacity value of Arabica coffee beans used is 1.50 $kJ \cdot kg^{-1} \cdot K^{-1}$ [10], while the copper absorber tube material has a heat capacity of 385 $J \cdot kg^{-1} \cdot K^{-1}$ [11]. Temperature measurements are taken periodically every 3 minutes until the seed temperature reaches the roasting range of ± 200°C.

Field testing was carried out in East Ciputat, South Tangerang, in sunny weather conditions, with the intensity of solar irradiation at 600 – 900 $W \cdot m^{-2}$.

Figure 2. Experimental Tool Scheme



The configuration of the tool used consists of PDC with a reflector area of 1.2 m^2 and Fresnel glass with an effective area of 0.09 m^2. The reflector surface is made of aluminum foil which has a theoretical reflectivity value of about 90% [5]. However, due to the installation process that causes wrinkles and spots on the surface, the actual reflectivity value decreases to about 65%. The Fresnel glass used is made of acrylic with a theoretical transmissibility value of 92% [12]. However, due to the condition of the lens surface that has been dusty and scratched, the effective transmissibility value decreases to about 62%.

Meanwhile, the absorber tube is made of copper with dimensions of 10 cm high, 8 cm in diameter, 1 mm thickness, and a mass of 0.22 kg. The complete scheme of the appliance configuration is shown in Figure 2.

Data Capture

The temperature measurement of the absorber tube is carried out on the outside of the wall using a thermogun (infrared gun). This method was chosen because the thickness of the absorber tube is only about ± 1 mm, while the inner side of the tube is not directly accessible. This non-contact measurement is also beneficial for minimizing interference with heat flow on the tube surface. The temperature of the coffee beans was measured using the same IR-gun device, with the shot directed at the surface of the bean's top layer. Since both system configurations work in the open condition, the path of sight to the test object is not obstructed, so the measurement results remain representative. The emissivity value on the measuring instrument was kept constant for all readings, and each measurement point was carried out in a double (twice) manner and then the results were averaged.

Luminance measurements and conversion to irradiation were performed using a lux meter on a shadow-free horizontal plane, about ± 1 meter away from the test device. The global luminance value obtained was then converted to irradiation (G) using a fixed factor used in this study, which is 122 lux ≈ 1 $W \cdot m^{-2}$.

The measuring points and the distances between the "blankets" are set at five measurement points, with the following details:

1. Absorber tube base (bottom),
2. Blanket under the wall of the tube (0 cm from the base mold),
3. The middle blanket of the tube wall (+ 5 cm),
4. Blanket top of the tube wall (+ 10 cm),
5. The mass of coffee beans in the tube (top layer surface).

For measuring points 1–4, the IR-gun is aimed perpendicular to the surface with a constant distance and angle of view. Meanwhile, for measurement point 5, measurements were taken by aiming at the surface of the coffee beans at the same position at each recording interval. The efficiency of a system without Fresnel glass is defined as the ratio of the energy that raises the temperature of the coffee bean and the absorber tube to the solar energy received from the parabolic concentrator (PDC), as shown in Equation (1).

$$\eta_{nf} = \frac{Q_{biji} + Q_{tab}}{E_{in,PDC}} \quad (1)$$

The efficiency of the system with Fresnel glass is defined as the ratio of the energy absorbed to raise the temperature of the coffee bean and the absorber tube to the total input energy received from the PDC and Fresnel glass, as shown in Equation (2).

$$\eta_{f} = \frac{Q_{biji} + Q_{tab}}{E_{in,PDC} + E_{in,Fr}} \quad (2)$$

The energy stored in coffee beans and absorber tubes is modeled as sensible heat, as expressed in Equation (3).

$$Q_{biji} = m_b \cdot c_b \cdot \left(T_{b,akhir} - T_{b,awal}\right) ;\ Q_{tab} = m_t \cdot c_t \cdot \left(T_{t,akhir} - T_{t,awal}\right)$$

The input energy from solar radiation concentrated by the PDC as well as by Fresnel glass is calculated based on the average value of solar irradiation, effective aperture area, optical efficiency or transmissibility, and heating duration, as shown in Equations (4) and (5).

$$E_{in,PDC} = \bar{I} \cdot \Delta t \cdot A_{ap} \cdot \rho \qquad (4)$$

$$E_{in,Fr} = \bar{I} \cdot \Delta t \cdot A_{Fr} \cdot \tau_{Fr} \qquad (5)$$

RESULTS AND DISCUSSION

This study aims to analyze the effect of the addition of Fresnel glass on the improvement of thermal performance in the *Parabolic Dish Collector* (PDC)-based coffee bean roaster system. The test was carried out on two system configurations, namely PDC without Fresnel glass (open system) and PDC with Fresnel glass (open system with additional heating from above), each with two repeated data collections. The main parameters observed include the intensity of solar radiation (irradiance), the temperature of the absorber tube wall at three measurement points (bottom, middle, and top), and the temperature of the coffee beans against the time during the heating process.

Test Results Without Fresnel Glass

Table1. Fresnel Glassless Test Data

MINUTES	T_BAWAH		T_SELIMUT_BAWAH		T_SELIMUT_TENGAH		T_SELIMUT_ATAS		T_BIJI_KOPI		IRADIASI_(W_PER_M2)	
	1	2	1	2	1	2	1	2	1	2	1	2
0	30	30	30	30	30	30	30	30	30	30	0	0
3	384	385	244	245	240	241	231	232	103	107	803.61	809.4
6	373	376	283	285	242	244	221	223	121	129	755.51	803.87
9	370	374	266	270	240	243	221	223	137	149	804.66	817.07
12	360	366	273	278	248	252	229	232	183	188	810.27	810.48
15		351		257		249		222		207		825.14

Based on Table 1, the heating dynamics of coffee beans show a similar pattern of temperature increase in both system configurations. In Table 3.1, the entire measurement point starts heating at an initial temperature of about 30 °C. When the focus of the PDC reflector begins to hit the absorber tube, the temperature T_BAWAH increases sharply until it reaches ≈ 384 – 385 °C at the 3rd minute, then gradually decreases as the heat redistributes along the tube until it reaches ≈ 348 – 351 °C at the 15th minute. The temperature rise in the "blanket" layer shows a vertical sequence from bottom to center to top, as shown in the 3rd minute, which is 244 – 240 – 231 °C in (test 1) and 245 – 244 – 232 °C in (test 2). This pattern indicates the formation of a heat gradient from the bottom side to the top of the absorber tube.

Meanwhile, the temperature of coffee beans (T_Biji_Kopi) rises more slowly than the temperature of the walls. The temperature of the beans was recorded at around 105 – 107 °C in the 3rd minute, increased to 129 – 137 °C in the 6th – 9th minute, and reached 183 – 188 °C in the 12th minute, before finally reaching ≈ 200 – 210 °C in the 15th minute. Throughout the test, the solar irradiation rate was relatively constant in the range of ≈ 803 – 825 W/m², so the delay in achieving the target temperature was mainly due to the indirect heat transfer mechanism, where the heat was first absorbed by the tube wall through conduction and convection, then transferred to the coffee bean mass gradually.

Test Results With Fresnel Glass

Table 2. Test Data with Fresnel Glass

MINUTES	T_BAWAH		T_SELIMUT_BAWAH		T_SELIMUT_TENGAH		T_SELIMUT_ATAS		T_BIJI_KOPI		IRADIASI_(W_PER_M2)	
	1	2	1	2	1	2	1	2	1	2	1	2
0	30	30	30	30	30	30	30	30	30	30	0	0
3	310	381	242	249	203	243	195	235	110	119	810.12	812.4
6	325	375	253	280	211	245	200	225	156	168	815.78	819.88
9	346	368	260	262	222	238	205	219	183	199	817.67	811.1
12	360	352	305	250	253	249	225	224	241	249	829.88	835.21

In configurations with Fresnel glass (Table 3.2), the heating pattern shows a significant shift compared to a system without Fresnel. Although the temperature of the lower wall (*T_{BOTTOM}*) remained high at the beginning of heating (3rd minute: 310–381 °C, depending on the repeat), the temperature rise of the coffee beans was much faster, at 110 – 119 °C at the 3rd minute, 156 – 168 °C at the 6th minute, and 183 – 199 °C at the 9th minute. At the 12th minute, *T_{Coffee Beans}* reached 241 °C (1) and 249 °C (test 2). Thus, the roasting temperature threshold of about 200 °C is reached in the 9th to 10th minute, or ± 5 –6 minutes faster than the Fresnel glassless configuration. This acceleration occurs under relatively comparable irradiation conditions (≈ 81 0– 835 W/m²), so the improvement in thermal performance can be attributed mainly to the optical effect of Fresnel glass that concentrates solar radiation directly onto the surface of the bean. The direct heating reduces the thermal lag between the walls of the absorber tube and the core of the coffee beans, so that heat energy is distributed to the bean mass more quickly.

Figure 3. Graph of Coffee Bean Temperature Against Time

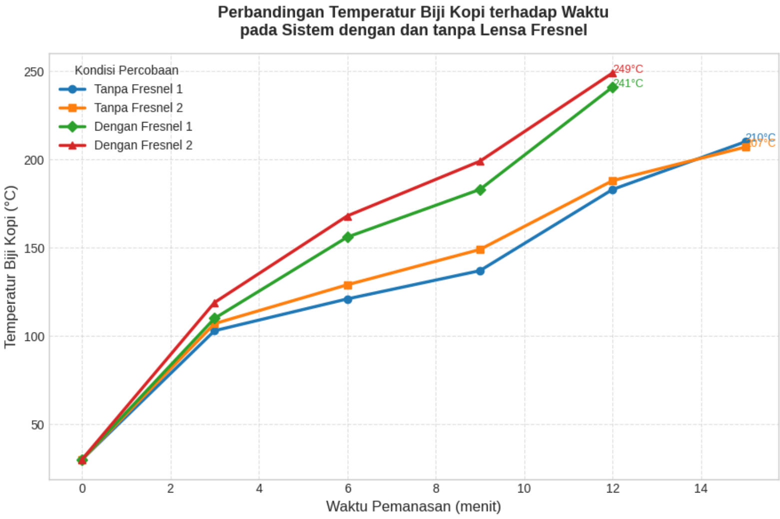


Figure 3. shows four consistent temperature-to-time relationship curves: two curves without Fresnel glass have a more sloping slope, while two curves with Fresnel glass appear steeper from the beginning of warming. In the configuration with a Fresnel lens, the temperature of the coffee beans (*T_biji*) increases consecutively to ±110 – 120 °C in the 3rd minute, 156 – 168 °C in the 6th minute, 183 – 199 °C in the 9th minute, and reaches 241 – 249 °C in the 12th minute. In contrast, in a configuration without a Fresnel lens, the temperature of the coffee beans lags behind and only breaks ±200 °C around the 15th minute. Thus, the time it takes to reach a temperature of 200 °C is reduced by about 5 – 6 minutes or equivalent to an acceleration of 33 – 40%.

At a fixed heating time of 12 minutes, the system with a Fresnel lens showed a temperature advantage of 50 – 60 °C (± 241 – 249 °C compared to ± 183–188 °C without Fresnel), indicating a significant increase in the heating rate in the critical phase of the 3rd to 9th minutes. Mechanistically, this phenomenon is in line with the concept of dual heating, where the PDC acts as an indirect heater through the walls of the absorber tube, while the Fresnel lens adds radiation directly to the surface of the coffee beans, so that the difference in thermal lag between the walls and the beans becomes smaller.

3System Thermal Efficiency

Based on the data from the measurement results in Table 3.1 and Table 3.2 and calculations using Equations (1) to (5), the thermal efficiency value of the system was obtained as follows.

Table.3 System Thermal Efficiency

	EFFICIENCY (%)	
EXPERIMENTS	Without Fresnel Glass	With Fresnel Glass
1	8,51	10,34
2	8,2	10,86

In Table 3.3, the configuration without Fresnel glass shows thermal efficiency of 8.51% and 8.20%, with an average of 8.36%. After the system was equipped with Fresnel glass, the efficiency increased to 10.34% and 10.86%, with an average of 10.60%, or an increase of about 26.9%. This increase is due to the ability of Fresnel glass to concentrate solar radiation onto the absorber surface, so that the received heat flux is increased and convective and reflective heat losses are reduced.

DISCUSSION

The results of this study indicate that the addition of Fresnel glass significantly affects the thermal performance of the Parabolic Dish Collector (PDC)-based coffee bean roasting system. Based on experimental observations, the heating characteristics of the system without Fresnel glass and the system equipped with Fresnel glass show distinct differences in temperature distribution, heating rate, and roasting efficiency. These findings confirm that the integration of optical concentrators in solar thermal systems can enhance energy concentration and improve the heat transfer process within the roasting chamber.

In the configuration without Fresnel glass, the heating process relies primarily on the reflective performance of the Parabolic Dish Collector. The PDC reflects incoming solar radiation toward the focal point where the absorber tube is located. As shown in the experimental data, the temperature at the bottom of the absorber tube (T_bawah) increases rapidly at the beginning of the heating process, reaching approximately 384–385 °C at the third minute. This rapid temperature increase occurs because the focal point of the parabolic reflector directly concentrates solar radiation onto the lower section of the absorber tube. According to solar concentrator theory, parabolic dish collectors are capable of producing high temperature gradients due to their point-focus optical geometry, which concentrates sunlight into a relatively small focal region (Duffie & Beckman, 2013).

However, despite the rapid increase in wall temperature, the temperature of the coffee beans rises more slowly. The experimental data show that the coffee bean temperature reaches approximately 103–107 °C at the third minute and gradually increases to around 200–210 °C at the fifteenth minute. This delay in temperature increase is mainly caused by the indirect heat transfer mechanism occurring in the roasting chamber. In this system, heat is first absorbed by the absorber tube wall and then transferred to the coffee beans through conduction, convection, and radiation. The presence of multiple heat transfer stages creates a thermal lag between the absorber tube wall and the coffee bean mass (Incropera et al., 2017). As a result, although the absorber tube reaches high temperatures early in the heating process, the coffee beans require a longer time to reach the roasting temperature.

The vertical temperature gradient observed along the absorber tube wall further supports this mechanism. The measurement results indicate that the temperature distribution follows a sequence from bottom to middle to top. For example, in the third minute of the test, the temperatures of the lower, middle, and upper wall layers were recorded at approximately 244 °C, 240 °C, and 231 °C respectively in the first trial. This gradient suggests that the heat source is concentrated primarily at the bottom region of the absorber tube where the focal point is located. Heat then propagates upward through conduction along the tube wall and through convective heat transfer within the roasting chamber. Similar temperature distribution patterns have been observed in other solar thermal systems where heat is concentrated at a focal region before being distributed across the absorber surface (Kalbande & Jilte, 2018).

Another important observation from the system without Fresnel glass is the relatively stable solar irradiance during the experiment. The recorded solar irradiation values ranged between approximately 803 and 825 W/m². Since the irradiation level remained relatively constant, the gradual heating of the coffee beans cannot be attributed to variations in solar intensity. Instead, the delay in achieving roasting temperature is primarily caused by the limitations of indirect heat transfer within the roasting chamber. In thermal systems, the efficiency of heat transfer from the heat source to the processed material depends on several factors including thermal conductivity, surface contact, and convective airflow (Çengel & Ghajar, 2015). When heat must travel through multiple layers before reaching the coffee beans, the heating process naturally becomes slower.

In contrast, the configuration equipped with Fresnel glass demonstrates significantly different heating behavior. Although the temperature of the lower absorber wall remains high during the early stages of heating, the temperature rise of the coffee beans occurs much more rapidly compared to the system without Fresnel glass. The experimental data show that the temperature of the coffee beans reaches approximately 110–119 °C in the third minute, increases to 156–168 °C in the sixth minute, and reaches 183–199 °C by the ninth minute. By the twelfth minute, the coffee bean temperature has already exceeded the typical roasting threshold, reaching approximately 241–249 °C.

This accelerated heating process indicates that the Fresnel glass plays an important role in enhancing the concentration of solar radiation within the roasting chamber. Fresnel lenses are designed to refract and focus incoming solar radiation into a smaller focal region, thereby increasing the local heat flux received by the target surface (Li et al., 2017). When integrated into the PDC system, the Fresnel glass provides additional radiation from the upper direction of the roasting chamber, effectively creating a dual heating mechanism. In this configuration, the parabolic dish continues to provide indirect heating through the absorber tube wall, while the Fresnel glass contributes direct radiative heating to the surface of the coffee beans.

The presence of this dual heating mechanism significantly reduces the thermal lag observed in the system without Fresnel glass. Since a portion of the solar radiation is delivered directly to the coffee beans, the beans absorb heat more quickly without relying solely on conduction and convection from the tube wall. Radiative heat transfer can be particularly effective in high-temperature systems because the rate of radiative heat transfer increases with the fourth power of temperature according to the Stefan–Boltzmann law (Incropera et al., 2017). As a result, direct radiation from the Fresnel lens accelerates the heating process and improves the overall thermal response of the roasting chamber.

The experimental results clearly demonstrate the practical implications of this mechanism. In the system with Fresnel glass, the roasting temperature of approximately 200 °C is achieved within the ninth to tenth minute, whereas the system without Fresnel glass reaches the same temperature only around the fifteenth minute. This indicates that the addition of Fresnel glass reduces the heating time by approximately five to six minutes, equivalent to a roasting time acceleration of about 33–40 percent. Faster heating rates are particularly beneficial in coffee roasting processes because they allow better control of roasting profiles and reduce energy consumption during processing.

The temperature–time curves further illustrate the difference between the two system configurations. In the graphical analysis, the temperature curves representing the Fresnel-assisted system show a steeper slope compared to the curves from the system without Fresnel glass. A steeper slope indicates a higher heating rate, meaning that the system is capable of transferring thermal energy to the coffee beans more efficiently. In solar thermal engineering, the heating rate of a system is often used as an indicator of the effectiveness of energy concentration and heat transfer within the system (Duffie & Beckman, 2013).

Another significant finding of this study is the improvement in thermal efficiency observed in the system equipped with Fresnel glass. Based on the experimental calculations, the average thermal efficiency of the system without Fresnel glass is approximately 8.36%. After the addition of Fresnel glass, the efficiency increases to an average of 10.60%. This represents an improvement of approximately 26.9 percent in system efficiency. Thermal efficiency in solar concentrator systems is generally defined as the ratio between useful thermal energy absorbed by the processed material and the total solar energy received by the collector surface. Efficiency improvements indicate that a greater portion of incoming solar radiation is successfully converted into useful heat for the roasting process (Kalbande & Jilte, 2018). The increase in efficiency observed in this study can be attributed to several factors related to the optical and thermal properties of the Fresnel glass.

First, the Fresnel glass enhances the optical concentration of solar radiation. By focusing sunlight into a smaller area, the Fresnel lens increases the local heat flux received by the absorber surface. Higher heat flux results in faster temperature increases and improved heat transfer to the coffee beans. Second, the Fresnel glass reduces optical losses that may occur due to imperfect reflection or misalignment of the parabolic dish. Additional radiation from the Fresnel lens compensates for these losses and ensures that more solar energy reaches the roasting chamber.

Third, the direct heating mechanism reduces convective and reflective heat losses that typically occur when heat must first accumulate in the absorber tube wall before being transferred to the coffee beans. When heat is delivered directly to the beans through radiation, the overall energy transfer path becomes shorter and more efficient. Similar improvements in thermal efficiency have been reported in previous studies of solar concentrator systems that integrate Fresnel lenses with reflective collectors (Li et al., 2017).

Overall, the results of this study demonstrate that the integration of Fresnel glass into a Parabolic Dish Collector system can significantly enhance the thermal performance of solar-powered coffee roasting systems. The addition of Fresnel glass not only accelerates the heating process but also improves system efficiency by increasing solar radiation concentration and reducing heat transfer losses. These findings support the potential application of hybrid solar concentrator systems for sustainable coffee processing, particularly in regions with high solar radiation such as Indonesia. From an industrial perspective, the implementation of solar roasting systems with enhanced optical concentration could provide significant benefits for small-scale coffee producers. Faster roasting times can increase production capacity, while improved thermal efficiency can reduce operational costs associated with energy consumption. Furthermore, the use of solar energy as the primary heat source contributes to environmentally friendly processing methods and supports global efforts toward sustainable agricultural production.

CONCLUSION

The experimental results demonstrate that the addition of Fresnel glass significantly improves the thermal performance of the coffee bean roasting system based on a Parabolic Dish Collector (PDC). One of the most evident impacts is the acceleration of the heating rate of the coffee beans. In the configuration equipped with Fresnel glass, the temperature of the coffee beans reaches approximately 200 °C within the ninth to tenth minute of the heating process. In contrast, in the system without Fresnel glass, the same roasting temperature is only achieved at around the fifteenth minute. This difference indicates that the addition of Fresnel glass is capable of reducing the time required to reach the roasting temperature by approximately five to six minutes, which is equivalent to an acceleration of about 33–40 percent. The faster heating process indicates that the concentration of solar radiation within the roasting chamber becomes more effective when Fresnel glass is integrated into the system, allowing thermal energy to be transferred more rapidly to the coffee beans.

In addition to accelerating the heating process, the use of Fresnel glass also increases the final temperature achieved at the same heating duration. The experimental results show that at the twelfth minute of heating, the temperature of the coffee beans in the system with Fresnel glass reaches approximately 241–249 °C. Meanwhile, in the system without Fresnel glass, the temperature of the coffee beans at the same time only reaches around 183–188 °C. This temperature difference indicates that the intensity of heating in the Fresnel-assisted system is significantly higher, particularly during the critical heating phase between the third and ninth minutes of the roasting process. During this stage, the roasting system experiences the most rapid temperature increase, which strongly influences the efficiency of the roasting process as well as the formation of aroma and flavor compounds in the coffee beans.

The improvement in heating performance can be explained by the working mechanism of the combined solar concentration system. In this system, the Parabolic Dish Collector (PDC) functions as the primary heat source that concentrates solar radiation onto the focal point and transfers heat to the absorber tube wall. The absorber tube then distributes the heat through conduction and convection processes inside the roasting chamber. Meanwhile, the addition of Fresnel glass introduces a second mechanism of solar concentration by focusing additional solar radiation directly onto the surface of the coffee beans. The presence of these two heat sources creates a dual heating mechanism in which indirect heating from the absorber tube wall is complemented by direct radiative heating from the Fresnel glass. This combination reduces the thermal delay that usually occurs between the absorber tube wall and the core of the coffee beans, allowing heat energy to be absorbed more efficiently by the roasted material.

Furthermore, the integration of Fresnel glass also contributes to a significant improvement in the energy efficiency of the roasting system. Based on the experimental calculations, the system without Fresnel glass produces an average thermal efficiency of approximately 8.36 percent. After the addition of Fresnel glass, the thermal efficiency increases to about 10.60 percent. This improvement corresponds to an efficiency increase of approximately 26.9 percent. The increase in efficiency indicates that a greater proportion of the incoming solar energy is successfully converted into useful thermal energy for the roasting process. The higher efficiency is mainly caused by the increase in effective heat flux received by the coffee beans due to the additional optical concentration provided by the Fresnel glass. At the same time, the more direct heat transfer mechanism reduces heat losses that typically occur through convection and radiation within the roasting chamber. As a result, the solar roasting system becomes more effective in utilizing available solar energy while maintaining stable heating conditions during the roasting process.

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