

Research Article

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Enhancing the performance of conventional coffee beans drying with low-temperature geothermal energy by applying HPHE: An experimental study

<https://doi.org/10.1515/opag-2021-0053>

received November 3, 2020; accepted October 18, 2021

Abstract: The unpredictable weather in Indonesia results in a less effective conventional coffee beans drying process, which usually uses solar energy as a heat source. This experiment aimed to examine the performance of the coffee beans drying using low-temperature geothermal energy (LTGE) with solar energy as the energy source. Heat pipe heat exchanger, which consists of 42 straight heat pipes with staggered configuration, was used to extract the LTGE. The heat pipes have 700 mm length, 10 mm outside diameter with a filling ratio of 50%, and added by 181 pieces of aluminum with a dimension size of 76 mm × 345 mm × 0.105 mm as fins. LTGE was simulated by using water that is heated by three heaters and flowed by a pump. Meanwhile, to simulate the drying process with conventional methods, a system of solar air collectors made of polyurethane sheets with a thickness of 20 mm and dimensions of length × width ×

height = 160 cm × 76 cm × 10 cm, respectively, was used in this study. Zinc galvalume sheet with 0.3 mm thickness was installed and coated by the black doff color throughout the inner of the container wall. The result showed that the drying process with LTGE and solar energy is faster than with solar energy or geothermal energy only. The drying coffee beans using the hybrid system can speed up the drying coffee beans time by about 23% faster than the solar energy only.

Keywords: coffee bean drying, drying, low-temperature geothermal, HPHE, heat pipe

1 Introduction

Coffee is the most popular beverage in the world, and Indonesia is one of the largest coffee producers in the world. Thus, coffee is also one of the main export commodities that can help the economy sector grow in this country. Coffee beans are obtained from coffee cherries that the skin has been peeled off. The production process of coffee starts from harvesting, drying and roasting, and being ready to be served to the consumer.

There are two ways of drying coffee commonly used in Indonesia, namely the wet process and the dry process (natural). In the wet process method, coffee is peeled off first after being harvested to separate the cherry and coffee beans using a pulper machine. This method does not require a large amount of solar energy but requires a lot of water since the coffee will be fermented for 24 h in a water bath before drying. Then, the process immediately focuses on the beans that have been peeled off from the cherry. Meanwhile, in the dry process (natural), the coffee is soaked to remove the defective beans and then dried using a bed under the sun. The shape of the bed to dry coffee in the natural process varies. Coffee can be

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directly dried on the ground using a mat or on a mesh with a 30 cm gap space from the ground to allow airflow. To prevent excessive fermentation process, each cherry is routinely reversed. After the coffee cherries are completely dried, they are peeled off using a pulper machine and sorted before distribution to the roaster.

The taste of coffee is affected by all of the processes stated above especially in the drying process. The coffee beans should be dried to reduce the water content. The initial water content of coffee mostly is around 65% before drying and 11% after drying [1].

Indonesia is located on the equator, which allows Indonesia, potentially, to use solar energy more effectively than other countries. The average solar irradiation value is about 4–5 kW h/m² spread all around Indonesia [2]. Traditionally, the coffee bean drying process uses open sun drying, and most of coffee farmers in Indonesia usually need only 3–4 h under the sunny day for 7–12 days. This less effective drying duration can affect the quality of coffee beans. Besides, the coffee beans that are dried in open space can be contaminated by the air and take longer drying time as it merely depends on the weather condition [3,4]. Open sun solar drying can be improved using indirect solar drying method [5,6]. The heat from the solar energy can be utilized by trapping them using a solar collector [7]. However, the indirect solar drying using a solar collector will also depend on the weather condition.

There are many ways to enhance the solar drying performance. Goud *et al.* [8] used fan to increase the air inlet velocity and found the final moisture content of the product decreased. Dina *et al.* [9] conducted solar drying process with desiccant as thermal storage, and the result shows that the process increased the effectivity of consumed energy and reduced the duration of the drying process. Adding the glass on the solar collector can also improve the performance of the solar collector [10]. Bahammou *et al.* [11] examined the drying characteristic under natural and forced convection solar drying, and the result showed that the forced convection could increase the indirect solar drying performance, temperature, and drying rate. The aforementioned studies show a similar issue, that is, a consistent temperature is needed to make the drying process faster. This means that it is difficult to achieve that condition if the drying process depends only on solar energy.

Furthermore, Indonesia is located on the ring of fire, which means Indonesia has many active volcanoes. This condition makes Indonesia to have a huge geothermal energy potential, which is totally around 28,000 MW spread all around Indonesia [12]. Indonesia's geothermal energy potential can be used either directly for the drying process or combined with solar energy, similar to what Al Faqih *et al.* did for cacao drying [13]. Meanwhile,

Prasetyo *et al.* [14] used the geothermal energy for coffee drying with heat exchanger to extract the energy from geothermal brine. One of the conventional ways to extract the geothermal energy especially the low temperature one is by flowing fluid through the pipe connected with heat exchanger. But unfortunately, this way has many obstacles. The main problem is scaling of silica, which may occur inside the tube especially when the geothermal fluid through the narrow channel inside the heat exchanger. This will cause the pressure drop below the safe working pressure value on the silica saturation index [15,16]. To solve this problem, several experimental studies to extract the geothermal energy without withdrawing or flowing the geothermal fluid to heat exchanger have been done by applying heat pipe heat exchanger (HPHE) and have shown good results [17–19].

HPHE is a heat transfer device that has a high conductivity value that is already well tested for several applications. It has some advantages over conventional heat exchangers [20–22]. These advantages are as follows: HPHE does not require additional energy (passive devices), is more compact and has a simpler operation, and may reduce the production and the maintenance costs. Therefore, this study is conducted to investigate how much the effectivity will increase if conventional coffee drying process with solar energy is combined with low-temperature geothermal energy extracted by HPHE. It is expected that the result of this research will give a chance to improve the productivity and quality of coffee, especially in Indonesia.

2 Research method

2.1 Experimental design

The experimental study used the laboratory scale model. Solar energy was simulated by using solar air collectors (SACs) of indirect solar dryer-forced convection type. The material used to build SAC is the polyurethane sheet with 20 mm thickness and dimensions of length × width × height = 160 cm × 76 cm × 10 cm, respectively. To absorb the solar energy effectively, an additional material was needed. In this study, zinc galvalume sheet with 0.3 mm thickness and coated by the black doff color was used. The zinc galvalume sheet was installed throughout the inner of the container wall. To reduce the convection losses, the transparent lid is installed above the SAC.

Meanwhile, as a representative of low temperature of geothermal fluid, simulation used water that is heated by heater and flowed by pump. In this study, the capacity

of heater is 9 kW, whereas the capacity of pump is a flow of 18 L/m. Then, to control water temperature, Autronics TC4Y temperature controller was installed, and PT 100 thermocouple was used to set the point temperature control of water in bath. The flow of hot water was measured by Dwyer Flowmeter installed before the hot water enters the bath.

The heat from geothermal energy is transferred using HPHE. The HPHE is arranged into staggered arrangement, which consists of 42 heat pipes and added with 181 fins on the heat pipe. The type of heat pipe used in this experiment is wicked heat pipe made from sintered copper with 10 mm diameter and 700 mm length. The heat pipe used water as working fluid with 50% filling ratio. It consists of three sections, namely a condenser with 350 mm length, an evaporator with 250 mm length, and an adiabatic with 100 mm length. The adiabatic section is isolated by glass wool and polyurethane sheet. Additional fins are placed on the condenser area that is made from aluminum with 0.105 mm thickness and 76 mm \times 345 mm dimensions as shown in Figure 1. The detail of this set up is shown in Figure 2.

The air used for the drying process is flowed by fan in which the velocity is adjusted to 0.6 m/s using inverter from air inlet through the drying chamber. The inlet air will be heated when the air passes the solar collector and condenser area of HPHE. The coffee bean is placed on the tray inside the drying chamber heated by air from the solar collector and HPHE. The load cell is placed on the tray inside the drying chamber as well to measure the weight loss during the experiment. All the equipment was then assembled in the experimental setup as shown in Figure 3.

Figure 4 shows the sensor position. Type K thermocouples were used to measure the temperature in some places, namely the area of hot water entering the evaporator HPHE ($T_{w,i}$), the exit area of hot water from the

evaporator HPHE ($T_{w,o}$), air inlet area ($T_{a,i}$), air outlet of the solar collector area ($T_{a,SC}$), air exit of the HPHE condenser area ($T_{a,HPHE}$), and hot air outlet of the drying tray area ($T_{a,o}$).

All of the thermocouples are connected to the NI-cDAQ 9124 module. The relative humidity sensor used is Autronics THD-D. It is connected to NI-cDAQ 9201 module placed on air inlet of the solar collector area ($RH_{a,i}$), air outlet of the solar collector area ($RH_{a,SC}$), air outlet of the HPHE condenser area ($RH_{a,HPHE}$), and hot air outlet of the drying tray area ($RH_{a,o}$). Load cell with 1,000 g capacity was installed in the drying tray with tray area is 360 mm \times 360 mm and connected to NI-cDAQ 9237 module. Lutron AM-4204 hot wire anemometer was installed to measure the air flow through the drying chamber. The sun radiation during the experiment was measured by LP02-LI19 pyranometer. Figure 3 shows the final assembly of experimental equipment located on the rooftop of the Manufacturing Research Center building, Faculty of Engineering, Universitas Indonesia. The accuracy value of the whole sensors used in this experiment is shown in Table 1.

2.2 Experimental procedure

The fresh coffee used in this study was picked from plantations in Sumedang, West Java, Indonesia. Before being placed into the drying tray, the coffee's skin was peeled off for getting the seeds and then measured to find the initial moisture content of it. The water content measurements were performed by applying 1980 AOAC standards and ISO 712. To measure coffee beans moisture content, ± 3 g of fresh coffee beans was used as weight of wet coffee beans. Then, coffee beans were put into a petri dish. After

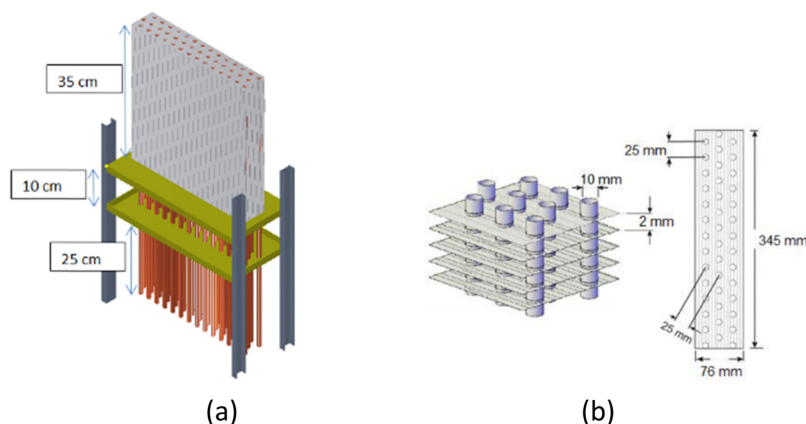


Figure 1: Sizes of the (a) HPHE and (b) fins.

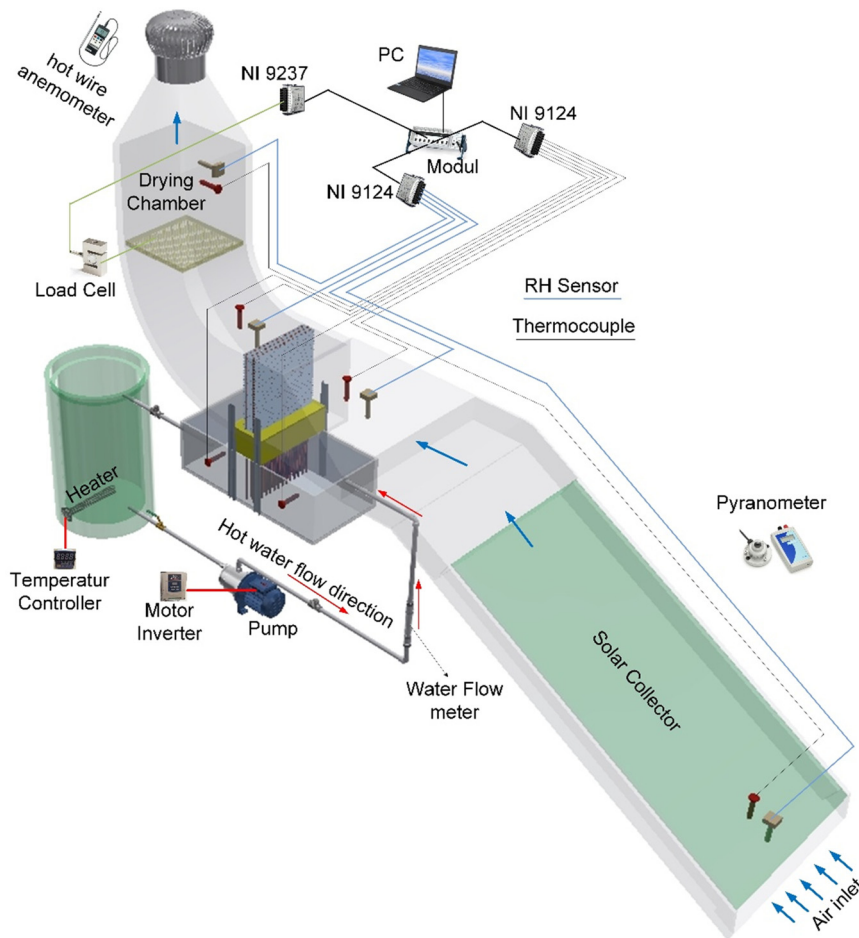


Figure 2: Schematic of the experimental setup.

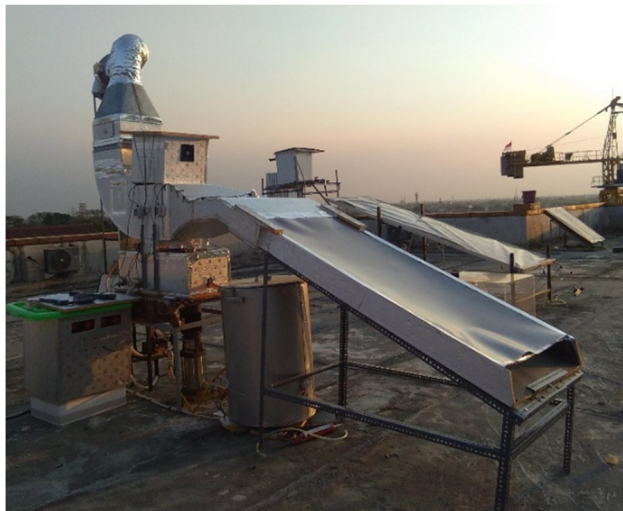


Figure 3: Final assembly of the testing equipment.

that, the petri dish containing coffee beans was put into vacuum oven in which the temperature was set at 105°C for ± 3 h. The petri dish containing dried coffee beans was

put into the desiccator for 15 min to remove the remaining water content, and then the mass was measured. This process was repeated until the constant dry weight of dry coffee beans was obtained ($c \leq 0.05$). Thus, the weight of dry coffee beans can be obtained. Meanwhile, to calculate the moisture content of coffee beans, the formula is as follows:

$$\text{Moisture/water content (dry basis)} = \frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{dry}}} \times 100\%, \quad (1)$$

where W is weight of coffee (g).

The initial condition of the experimental procedure included the amount of dried coffee beans was 100 g, the temperature of hot water was simulated to 60°C, the hot water flow was simulated to 18 lpm by using a pump, and the air velocity was adjusted to 0.6 m/s. The initial value of hot water temperature, hot water flow, and air velocity was obtained from previous study by Hakim *et al.* [17]. The experiment started in the afternoon around 4 pm and

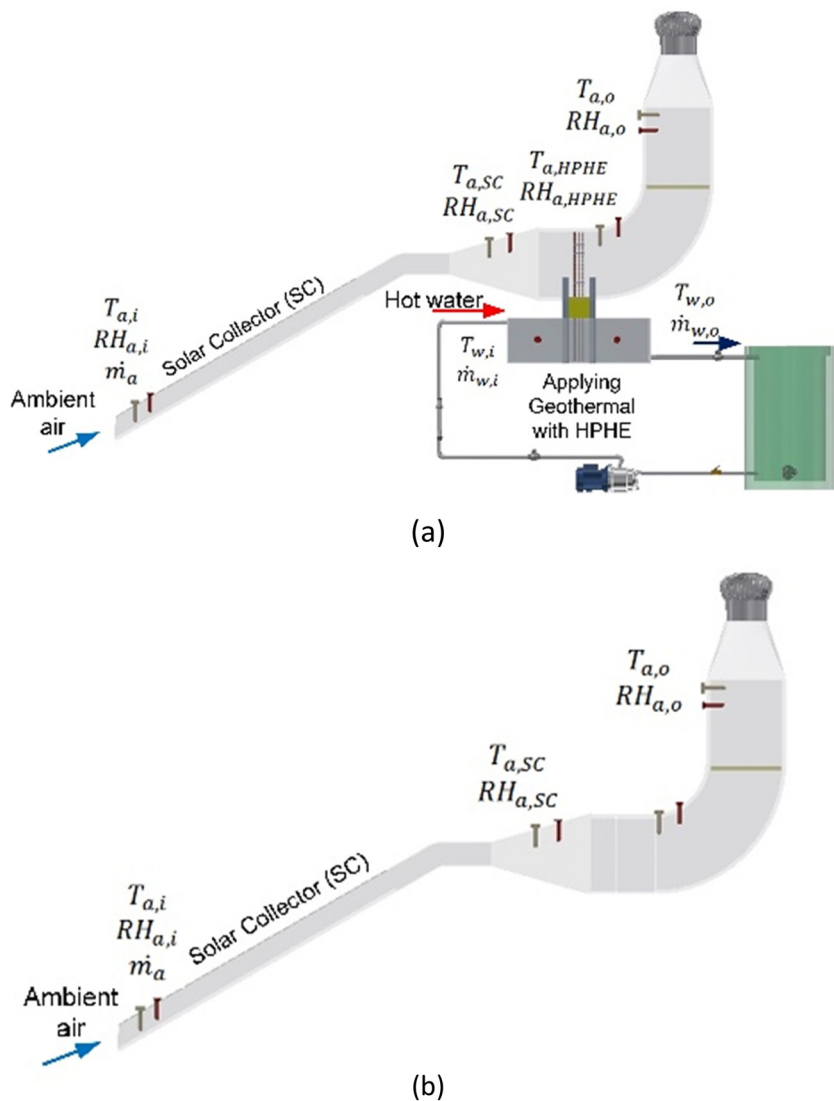


Figure 4: Positions of the measuring instruments and condition of experimental variation: (a) hybrid system and (b) solar system.

conducted for 24 h after the hot water temperature reached the steady-state condition. The steady-state condition was reached after the equipment commissioning for 1 h and after that the drying process began.

Figure 4 shows the experimental procedure for two different conditions. Figure 4a shows the experimental

procedure in which the drying source was combined by using a solar collector that used solar energy and the heat from geothermal energy, which was transferred using HPHE. The second procedure is an experimental procedure in which the drying energy source was obtained by using the solar collector as shown in Figure 4b.

Table 1: Accuracy of all sensors used

| No. | Sensors | Accuracy |
|-----|-------------------------|--|
| 1 | Thermocouple | ±5%°C |
| 2 | Relative humidity meter | ±2% relative humidity |
| 3 | Load cell | 0.05% full scale |
| 4 | Hotwire anemometer | ±(5% + 1 day) reading or ±(1% + 1 day) full scale depending on which is larger |
| 5 | Water flow meter | ±2% full scale |

2.3 Analysis of experimental data

The performance of the HPHE can be indicated by the values of its effectiveness and heat recovery. For the value of its effectiveness, according to El-Baky and Mohamed [23], assumptions were applied that there is no condensation on the freshwater flow and the specific heat that passes through the evaporator and condenser is constant, the equation is as follows:

$$\varepsilon = \frac{T_{\text{air},i} - T_{\text{air},m}}{T_{\text{hot water},i} - T_{\text{air},i}}, \quad (2)$$

where $T_{\text{air},i}$ is the temperature of air inlet HPHE in the condenser area (°C), $T_{\text{air},m}$ is the temperature of air outlet HPHE in the condenser area (°C), $T_{\text{hot water},i}$ is the temperature of hot water inlet HPHE in the evaporator area (°C).

To find out the comparison of the performance of each test condition, the moisture ratio (MR) value was used. MR value was used as a comparison because the coffee beans used in each test had different water content values.

$$\text{MR} = \frac{M - M_e}{M_o - M_e}, \quad (3)$$

where M is the moisture content of coffee beans % (d.b.), M_e is the equilibrium moisture content % (d.b.), and M_o is the initial moisture content % (d.b.).

The moisture content (M) on the dry basis was calculated using equation 3. From the research that is similar to the research that we have done, including research by Dairo *et al.* [24], Sanni and Odugode [25], Tun *et al.* [26], Suherman *et al.* [27], and Deeto *et al.* [28], because during our experiment, the RH value fluctuates and the M_e value is relatively small compared to the M or M_o value, in this analysis, the value of the equilibrium moisture content (M_e) is considered to have a value of 0.

Table 2 shows the mathematical models for the process of drying coffee beans used in this study. The drying curve of coffee beans was matched to the experimental data using two different equations. χ (χ_{square}), root mean square error (E_{RMS}), mean bias error (E_{MB}), and R^2 (R -square) were used as the main criteria for selecting the best equation to account for variations in the drying curve of coffee beans and to determine the most suitable model.

3 Results and discussion

3.1 Data collection from experiment

The experiment for each condition (according to Figure 4) began in the afternoon and under the sunny day. For the

Table 2: Mathematical model of drying in this experiment [29,30]

| Model name | Model |
|------------------------------|--|
| Newton | $\text{MR} = \exp(-kt)$ (4) |
| Page | $\text{MR} = \exp(-kt^n)$ (5) |
| Modified Page | $\text{MR} = \exp(-(kt)^n)$ (6) |
| Henderson and Pabis | $\text{MR} = a \exp(-(kt)^n)$ (7) |
| Wang and Singh | $\text{MR} = 1 + at + bt^2$ (8) |
| Logarithmic | $\text{MR} = a \exp(-kt) + c$ (9) |
| Two term | $\text{MR} = a \exp(-bt) - c \exp(-kt)$ (10) |
| Two term exponential | $\text{MR} = a \exp(-kt) + (1 - a) \exp(-kat)$ (11) |
| Modified Henderson and Pabis | $\text{MR} = a \exp(-kt) + b \exp(-ct) + d \exp(-et)$ (12) |
| Midilli | $\text{MR} = a \exp(-kt^n) - bt$ (13) |
| Approximation of diffusion | $\text{MR} = a \exp(-kt) + (1 - a) \exp(-kbt)$ (14) |
| Verma <i>et al.</i> | $\text{MR} = a \exp(-kt) - (1 - a) \exp(-bt)$ (15) |

experiment using simulation of low-temperature geothermal energy conditions, it needs to warm up the hot water circulation and time to reach setpoint temperature (60°C) of hot water until it is steady. For each condition for this purpose, the time needed is approximately 1 h. All data recorded during the experiment is shown in Figure 5. The data that can be seen is for the experiment variations when using the solar only and hybrid variations, so we can compare the two phenomena that occurred in this experiment.

The fresh 100 g coffee beans were put in the tray drying after the system was steady and reached the set point temperature consistently. From Figure 5a, we can see that because fresh coffee beans still had a high-water content, the temperature after tray drying decreased and relative humidity increased. This phenomenon indicates that some of the water content from coffee beans released dominantly because of the air velocity by the suction fan without any heat. The dominant parameters that influence the performance of the drying of the agriculture product are temperature and velocity of the drying air [17]. The temperature of the inlet tray depends on the irradiant value. Thus, since there is no irradiant at night, the performance of the drying is only influenced by air velocity and the air used to drying, which has a high relative humidity. The night phenomena in the drying process must be considered because it is possible for coffee beans to reabsorb the water from air that has a high relative humidity at night [31].

Different phenomena occurred in the drying process using geothermal and solar (hybrid) as source energy for the drying process of coffee beans as shown in Figure 5b. The weight of the coffee beans in the tray reduced quickly

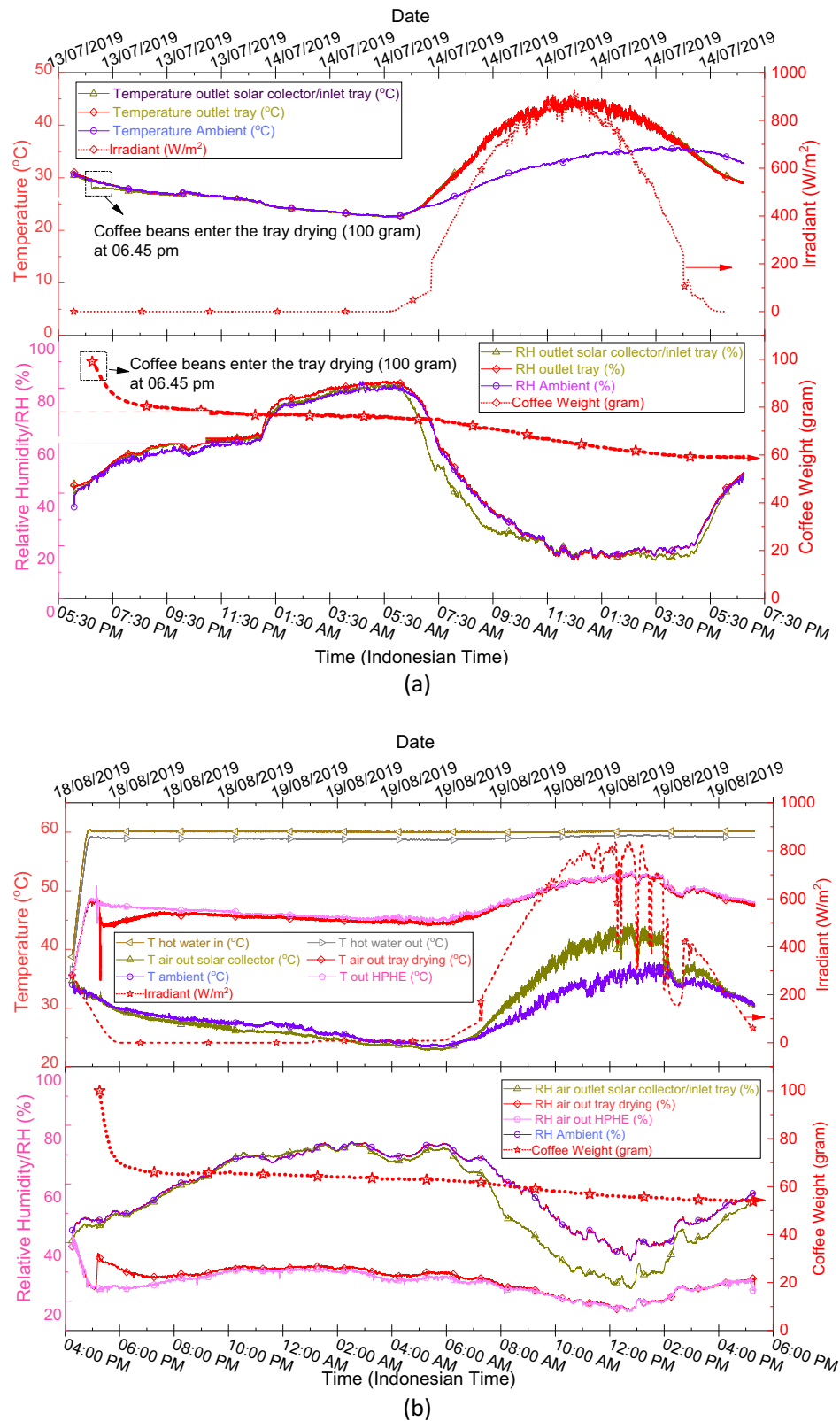


Figure 5: Temperature, relative humidity, irradiant, and the reduce weight of coffee beans profile during the experiment. (a) Solar only and (b) solar and geothermal (hybrid).

because of a suction fan; any heat from the air is able to release or evaporate the water in coffee beans. Figure 5b shows a temperature difference between the water entering and exiting the HPHE evaporator, that is, around 0.8°C . The different temperature indicates that some of the heat is absorbed into the evaporation area and transferred through the adiabatic area and then to the HPHE condenser area. In the condenser area, heat is released to heat the air passing through it and can be maintained at a value of around 46°C so that the drying process can continue at night. It can be seen, in this experiment, that the heat transfer in this HPHE does not need the help of the other energy.

During the day, although it had almost the same irradiance for the two test conditions, that is, between 800 and 850 W/m^2 , the maximum temperature of the drying air was also different. The maximum drying air temperature reached in the testing using solar energy only was around 45°C , but it fluctuated according to the irradiation and the weather conditions [32]. Meanwhile, the drying process of the hybrid solar with geothermal energy shows that the maximum drying air temperature reached was around 53°C and without weather constraints.

3.2 HPHE effectiveness

The performance of the HPHE system can be seen from the value of its effectiveness as seen in the equation 2. The value of HPHE was reached after the steady condition in the experiment set up, and it was about an hour after the experiment started. The effectiveness value on the HPHE was identical to the value of thermal efficiency in

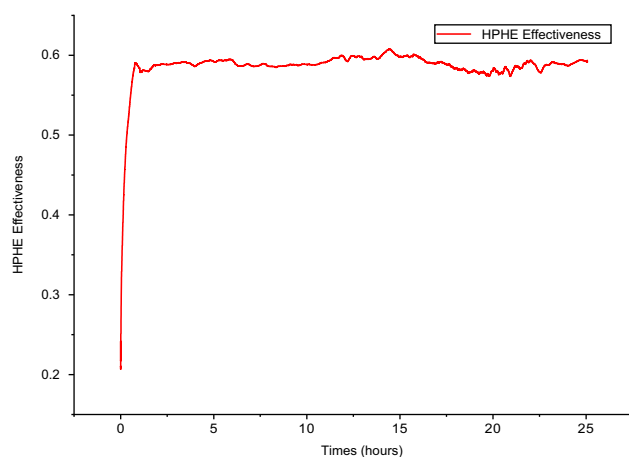


Figure 6: Effectiveness of HPHE along the experiment in the hybrid system.

the drying system using SAC. Due to the intermittent and high dependence on the weather, the SAC system's efficiency value was very fluctuating. Meanwhile, the value of the effectiveness of the HPHE by utilizing geothermal energy continued throughout the day (no fluctuation). From Figure 6, it can be noted that the highest effectiveness of the HPHE was 0.62 , and the lowest was 0.51 , with the average value of 0.59 .

3.3 MR model

Because of the test time for both models was not carried out at the same day and time, to obtain a comparable drying yield ratio for the two models, the most likely thing to do is to compare the MR value. The results of calculating the MR of the two experiments, based on equation 3 above, are shown in Figure 7.

The results of calculating the moisture content of the coffee beans before being put into the drying tray for the two experimental models were 80% of the wet base. In the first 1 h , the decrease in MR was quick. The quick decline of MR in the first hour was because almost all of the water content in the skin of the coffee beans evaporated quickly due to the influence of air velocity (in the solar system) and the impact of air velocity and temperature (in the hybrid system). This condition is called a falling rate period until the rate of water discharge decreases with decreasing moisture content [33]. After that, the MR charts for both types of drying tended to be constant until early

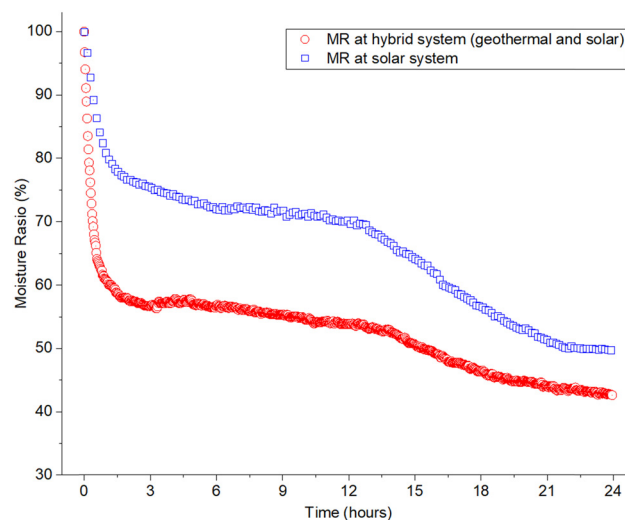


Figure 7: Comparison of the MR curve for coffee beans commodities for all variations in this test.

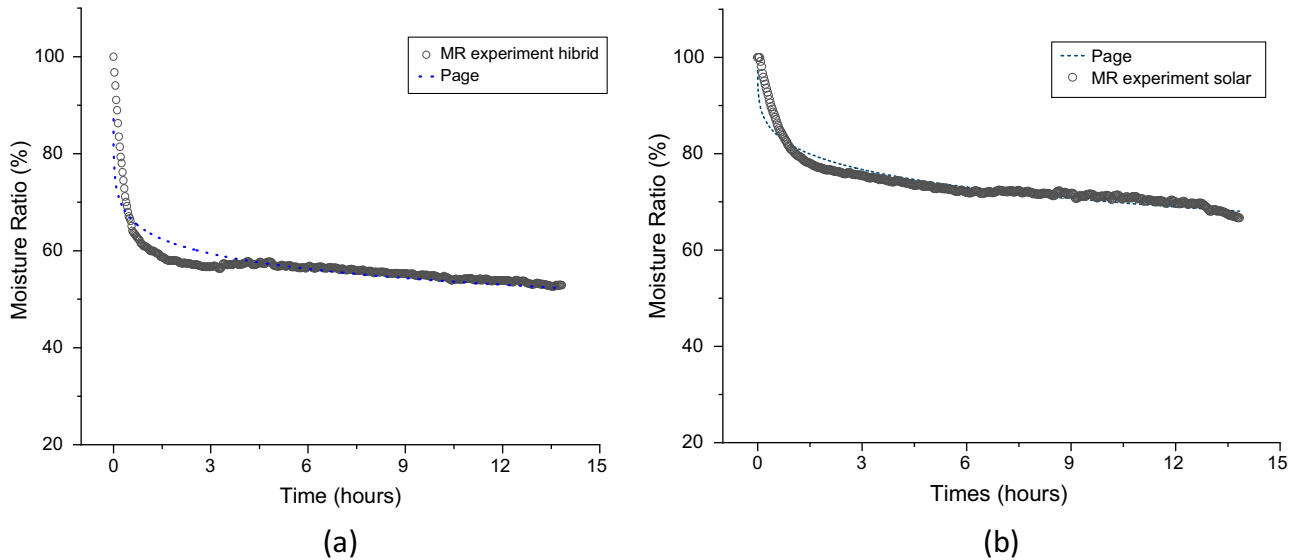


Figure 8: The MR fitting curve between the experiment model and Page model for coffee beans commodities: (a) hybrid system and (b) solar system.

morning. The decrease in MR value increased again during the day until late in the afternoon.

To predict how long the drying process reaches the water content of the coffee beans (11%), the mathematical model can be used as the result of proper fitting from the MR experiment graph to the numerical model. Because the graph in Figure 7 is similar to the MR intermittent category graph [34], it is not possible to fit for the entire drying period to the mathematical model. To get the proper fitting from the MR experiment graph to the numerical model, according to Mwithiga and Kigo [33], it is enough to use the first 8 hours of data from the drying test results. However, because the data that is not affected by the intermittent in the results of this test have an interval of up to 13 hours, then to predict how long the drying process reaches the water content of the coffee beans (11%) in this study uses data intervals of up to 13 hours to both drying systems, as shown in Figure 8.

Nonlinear regression was performed using Microsoft Excel software. The results of this test obtained a constant value and R^2 value in each model being tested. A summary of the results of this analysis is presented in Table 3. Based on Table 3, it appears that the Page model consistently provides a higher R^2 when compared to the other three models. From research conducted by Panchariya et al., it was stated that the accepted values for R^2 , χ^2 , and E_{MB} for the mathematical model of drying were above 0.93 for R^2 and below 9×10^{-4} and 0.018 for χ^2 and E_{MB} , respectively [35]. The Page model also consistently provides lower E_{RMS} and E_{MB} values than other models.

The fitting curve between the experiment model and Page model is shown in Figure 8.

For the first 8 h of the drying process using two drying systems, as in Figure 8, it can be seen that the MR value of the hybrid system reached 52%, whereas in the conventional method, it only got the MR value of 68%. From these results, it can be concluded with certainty that hybrid systems can dry out faster, about 23%, than conventional methods.

4 Conclusions and recommendations

The HPHE used for the direct utilization of low-temperature geothermal energy has successfully absorbed heat effectively and transferred it to the drying chamber without fluid withdrawal. It can be combined (hybrid) with the conventional system or solar energy system, as it can increase the capability of drying coffee, especially at night, which cannot be done in conventional systems.

In this study, the performance of HPHE system in drying using geothermal energy drawn from HPHE can be indicated by its effectiveness value, which is on average from 59%. The Page model is the best model to represent the behavior of coffee bean drying process using the solar system and hybrid system as well. Drying coffee beans using the hybrid system can speed up the drying coffee beans time by about 23% faster than the solar system only.

Table 3: Parameters values of drying kinetics models

| System drying | Model name | Model parameter | | | | | | R ² | E _{RMS} | E _{MB} | Chi-square | |
|-------------------------------|----------------------------|-----------------|-------------------------|-------------------------|----------|------------------------|----------------------------|-----------------------|------------------------|-------------------------|--------------------------|--------------------------|
| | | a | b | c | d | e | k | | | | | N |
| Solar | Newton | | | | | | 1.08748 × 10 ⁻⁵ | 100,000 | -2.05573 | 0.16944 | -0.12506 | -0.00483 |
| | Page | | | | | | 0.027529015 | 0.243801 | 0.999 | 0.031782 | 0.001603 | 0 |
| | Modified Page | | | | | | Error | Error | Error | Error | Error | Error |
| | Henderson and Pabis | 0.523542 | | | | | 0 | 1.000002 | 0.901425 | 0.406731 | 0.734728 | 0.165441 |
| | Wang and Singh | 0.001 | 0 | | | | | 1.000002 | -13365.3 | 53.96445 | -87.0936 | 2912.364 |
| | Logarithmic | 0.392772 | | 0.735913 | | | 1750.472357 | | 0.994003 | 0.09693 | -7.5 × 10 ⁻¹⁵ | 0.009396 |
| | Two term | 0.52222 | 0 | 0.07019 | | | 0.685946482 | | 0.396352 | 0.409126 | -7.5 × 10 ⁻¹⁵ | 0.009396 |
| | Two term exponential | 0.52222 | | | | | 7.98463 × 10 ⁻⁶ | 1 | 1.5 × 10 ⁻⁷ | -1.3 × 10 ⁻⁹ | 2.25 × 10 ⁻¹⁴ | |
| | Modified Henderson | 0.180251 | 0.180268 | 1.74 × 10 ⁻⁵ | 0.164487 | 7.8 × 10 ⁻⁷ | 0 | 0.188094 | 0.512692 | 0.947415 | 0.262866 | |
| | and Pabis | | | | | | | | | | | |
| Solar and Geothermal (hybrid) | Midilli | 0.575182 | 0 | | | | 0.42218874 | 0.109562 | 0.8688655 | 0.432655 | 0.788807 | 0.187199 |
| | Approximation of diffusion | 0.189642 | 1.79 × 10 ⁻⁵ | | | | 0.22026356 | | 0.990668 | 0.058096 | 0.000343 | 0.003375 |
| | Verma et al. | | | | | | | | | | | |
| | Newton | 1.524968 | 0 | | | | 4.642063024 | | 0.881563 | 0.404155 | 0.729795 | 0.163349 |
| | Page | 0.863358 | | | | | 2.06505 × 10 ⁻⁵ | 1000000 | -8.97264 | 0.305149 | -0.19249 | -0.01566 |
| | Modified Page | | | | | | 0.137795105 | 0.143176 | 0.998 | 0.049595 | 0.000957 | 0.00246 |
| | Henderson and Pabis | 0.523542 | | | | | 2.1378 × 10 ⁻⁵ | 1 | 0.563 | 0.305653 | -0.16029 | 0.09343 |
| | Wang and Singh | 0.001 | -0.84058 | | | | 0 | | 0.981503 | 0.128318 | 0.15704 | 0.016467 |
| | Logarithmic | 0.392772 | 1750.472 | 0.568934 | | | | -9 × 10 ¹⁸ | 1.74 × 10 ⁹ | 2.41 × 10 ⁹ | 3.01 × 10 ¹⁸ | |
| | Two term | 0.52222 | 0 | 0.07019 | | | 0.685946482 | | 0.987875 | 0.096629 | 3.33 × 10 ⁻⁹ | 0.009337 |
| Solar and Geothermal (hybrid) | Two term exponential | 0.52222 | | | | | 7.98463 × 10 ⁻⁶ | | 0.95931 | 0.129968 | 0.16162 | 0.016892 |
| | Modified Henderson | 0.180251 | 0.180268 | 1.74 × 10 ⁻⁵ | 0.164487 | 7.8 × 10 ⁻⁷ | 0 | 0.903961 | 1 | 1.5 × 10 ⁻⁷ | -1.3 × 10 ⁻⁹ | 2.25 × 10 ⁻¹⁴ |
| | and Pabis | | | | | | | | 0.903961 | 0.142902 | 0.21112 | 0.020422 |
| | Midilli | 0.575182 | 0 | | | | 0.042218874 | 0.109562 | 0.968658 | 0.142902 | 0.21112 | 0.020422 |
| | Approximation of diffusion | 0.475291 | 2.15 × 10 ⁻⁵ | | | | 0.393110946 | | 0.849662 | 0.274492 | 0.487305 | 0.07535 |
| | Verma et al. | 1.524968 | 8.7 × 10 ⁻⁶ | | | | 4.642063024 | | 0.875405 | 0.278425 | 0.494352 | 0.077524 |

Further study for evaluating the quality of coffee beans obtained using the hybrid system process of drying should be conducted to optimize the hybrid system. In addition, the scale-up of this system to the real conditions/applications should be done to get the real problem solved.

Acknowledgments: The author would like to thank Renewable Energy and Energy Conservation Technology (P3tek KEBTKE), Ministry of Energy and Mineral Resources (KESDM) for supporting the process of publishing this manuscript.

Funding information: The research was funded by Directorate of Research and Community Engagements Universitas Indonesia (DRPM UI) under the Q1Q2 Program 2019, no. NKB-0315/UN2.R3.1/HKP05.00/2019.

Author contributions: Conceptualization: Y.G. and N.P.; data curation: Y.G. and S.N.; formal analysis: Y.G.; funding acquisition: S.K.; investigation: Y.G. and K.T.M.; methodology: Y.G.; project administration: K.T.M.; software: G.T.S.; supervision: N.P. and I.I.H.; validation: Y.G., G.T.S., D.S., and S.K.; visualization: Y.G., K.T.M., and R.A.F.; writing – original draft: Y.G., K.T.M., and R.R.; writing – review and editing: Y.G.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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