Drying air temperature profile of independent hybrid solar dryer for agricultural products in respect to different energy supplies (a research note)

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Abstract. Drying is an important process of food preservation for security and sovereignty. The lack of conventional source of energy and limited supply of electricity urge to develop dryers for agricultural products adaptive to renewable energy sources and electricity independent. The invented dryers should then be able to generate various drying temperatures to accommodate variety of agricultural products to be dried. This study aims to explore the drying air temperature generated by so-called the independent hybrid solar dryer in respect to different energy supplies. The dryer consists of a drying chamber of 4.6 m³ capacities with five stories of ten trays inside, a chimney equipped with turbine ventilator, a heat exchanger embedded to furnace, and double heat collectors. Whole structure of the dryer is covered by transparent glasses and occupies 13m² horizontal area. The dryer operates in three modes i.e. solar energy, energy produced by fuel combustion, and simultaneously solar energy and fuel combusted energy. The dryer can operate any time and in any weather condition. So it is suitable to be installed in remote area to produce hygienic dried products. In this experiment, the dryer was tested without load (product to be dried), when operated with solar energy and energies produced from biomass and coal combustions. The experimental result revealed as follows. When operated with solar energy with average radiation intensity of 956.4 W/m², the dryer generated drying air temperature of 47.1°C which was 12.8°C higher than that of ambient air. Operated with the heat energies from both the coffee by product and coal combustions, the relationship between temperatures and fuel supplies were T = 4.323 s + 22.57 (R² = 0.994) and T = 5.003 s + 22.57 (R² = 0.998) respectively, where T = drying air temperature (°C) and s = fuel supply (kg). This dryer would be able to be operated for wide varieties of agricultural products according to the required temperatures.

Keywords: Hybrid Solar Dryer; Temperature; Fuel Supply; Coffee By-Product; Coal

1. Introduction
Most agricultural products are perishable and then need to be conserved as soon as possible after harvesting. Conservation is important process for food security and sovereignty. Drying is a method of conservation that is widely employed in all over the world. Lack of fossil energy and scarcity of electricity urges to use renewable sources of energy for drying. Sun drying is most practicable drying for almost commodities, especially in developing countries. Despite practicable, sun drying is hindered by some discrepancies such as intensive of space, risk of interrupted drying due to bad weather, produce damage and losses, rat and insect attacks, product contamination, and time and labour consuming especially during rainy season. Facing these problems various types of solar dryer
have been developed, comprising direct types [1], [2], [3], [4], indirect types [2], [5], [6], [7], and mixed types [8], [9].

The direct type solar dryer works similar to sun drying, but the product to be dried was covered with a transparent material such as glass or plastic and the process of drying mainly takes place from the upper surface of the product. The indirect type solar dryer is equipped by a heat collector that accumulates the heat of sun rays to heat the drying air before supplying it into the drying chamber. Here the moisture content of the product to be dried is evaporated by the hot drying air passing through it. The mix type solar dryer receives solar energy from both direct sun rays and collected heat by the heat collector to evaporate the moisture content of the wet product.

All types of solar dryer depend on the presence of the sun so the dryer is able to operate only during the day-time and good weather. This handicap urges researchers to develop hybrid solar dryers. In fact a hybrid solar dryer is a solar dryer with other energy supplies to increase its performance. The important device provided in the solar hybrid dryer is heat exchanger that transfers the energy supply to the drying air of the system. The dryer works with supplemented energy during bad weather or night-time. Many models of hybrid solar dryer have been introduced which operate utilizing electric energy [10], [11], [12], [13], [14], [15], [16], [17] and biomass energy [18], [19], [20], [21], [22]. The utilization of electric energy or gas as energy substitution in the hybrid solar dryer is easier to elaborate in the drying system but the cost of electricity increases drastically in the recent years. On the other hand the cost of gas supply also is also expensive. So it is important to elaborate the use of biomass energy in the development of hybrid solar drying system.

In the hybrid solar drying system, the moisture of the product being dried is evaporated by the drying air passing through it. Therefore most of the models employ a fan to circulate the drying air[23], [24], [25], [26], [27]. The electricity demand to operate the fan becomes a serious problem in the development of hybrid solar dryer to be installed in remote areas. So it will be advantageous to develop a hybrid solar dryer that is able to operate independently.

In this study, the hybrid solar dryer was constructed to operate independently. This dryer was a modified version of the previous hybrid solar dryer developed by [18]. Previously this dryer was designed merely for fish drying and it was modified to seek the possibility for drying the other commodities. The modification was mainly conducted on several components including the heat exchanger, furnace, chimney, and the cover of structure. In order to improve the circulation of drying air, the fine of heat exchanger was stripped into five small fines, except the fine of the lowest story. The oxygen supply of the furnace was facilitated by the ventilation holes at the furnace's wall rather than by the perforations at the bottom of furnace. The air outlet of chimney was replaced with a turbine ventilator to accelerate the air flow in the chimney. The heat exchanger was filled with water to store the heat transferred from the furnace. The whole structure of dryer was covered with transparent glasses instead of the UV plastic to improve its durability. The dryer still comprises of dryer chamber equipped with the chimney together with the turbine ventilator at its upper end, double heat collectors, the heat exchanger containing water, the furnace with exhaust tunnel, ten racks arranged in five stories.

The sources of energy used were coffee by-product composing bean’s shell (husk) and pulp of coffee berries and intact coal resulted from traditional mining. The reason behind for using the coffee by-product, it is because the dryer is prospective to be employed for coffee drying so that this material will be available nearby the area of drying installation. In term of potential, a ton of fresh coffee berries produces 200 kg dry coffee by-product. The intact coal is a unique coal since it is mined traditionally by the people in the river and riverbank in the area of Middle Bengkulu Regency, the regency where coffee becomes important commodity. This typical coal is abundant and very cheap. In term of availability, Bengkulu Province produces 3.16 million ton per year and the calorific value of coal is 4760 to 6322 kcal per kg [28].

Furthermore, the hybrid solar dryer is expected to dry wide variety commodities. Since every commodity needs suitable drying temperature, it is important to explore the effect of fuel supply on the generated drying temperature.
This study aimed to configure the profile of drying air temperature together with relative humidity and velocity air in the chimney generated by the hybrid solar dryer when it was operated with the solar energy and the fuel generated energies.

2. Methods
The hybrid solar dryer occupied about 2.3 m x 3.9 m horizontal area, comprised a drying chamber, a chimney, two front doors, double heat collectors, a heat exchanger, and a furnace. The wall and roof of drying chamber, the plenum of heat collector, and the wall of chimney were made of transparent glass. The frame of principal structures was constructed from hollow light steel painted in black. The drying chamber with 2.3 m x 1.1 m x 1.56 m dimension, contained ten racks arranged in five stories, five right racks and five left racks. Each rack measured of 2 m x 1 m x 2 m, and was made of anti-corrosive mesh. With this dimension, it was expected to be loaded with 200 kg fresh coffee berries so the capacity of this dryer was about 2 tons. The chimney was 1.5 m tall with 0.45 m x 0.45 m cross area. The front doors measured of 1.56 m x 1.1 m each and facilitated the in-out movement of the racks. The heat collectors were made of corrugated zinc plates painted in black, and each measured of 2.3 m x 1.83 m. This plate was isolated with plywood at the lower surface. The heat collector was provided with an air inlet at the lower end having 0.15 m clearance. The heat exchanger made of an aluminium sheet surface and a hollow metal frame. The main body of heat exchanger measured of 0.2 m x 1.45 m x 2 m that supported five stories of hollow fines with 0.05 m thick. All fines were striped with 0.2 m x 0.05 m x 0.85 m dimension except the lowest story fine. The heat exchanger was filled with water as heat storage. The furnace measured of 0.5 m x 0.35 m x 2 m and was provided with a front door for fuel supply and two alleys of oxygen supply, left and right. The wall of furnace was equipped with 16 holes (8 rights, 8 left) of oxygen supply connected to the alleys. An exhaust tunnel having 0.16 m x 0.16 m x 1.m measure was provided at the back for gas escape. The walls of furnace, oxygen alley and gas exhaust were made of brick adhered with cement-sand mix. This dryer is configured schematically in Fig. 1. The installation of the dryer was made in the open area.

The dryer operates in three modes according to the energy supply i.e. solar energy mode, fuel generated energy mode, and mixed mode in which solar energy and fuel generated energy are supplied simultaneously into the dryer.
In the solar energy mode, the energy is created by the heat of penetrating sun rays into the drying chamber through its wall and roof, and the heat of penetrating sun rays into the heat collector through its plenum. Since most of entering sun rays in the plenum are accumulated by the plate of heat collector, the solar energy collected here becomes major sources of energy supplied in the drying chamber. The solar energy accumulated by the structure heats the entering air from the inlet to increase its temperature. This hot air is then circulated by the turbine ventilator throughout the drying chamber to evaporate the water content of the product to be dried. The humid air is then discharged from the drying chamber through the outlet of turbine ventilator.

In the fuel generated energy mode, the heat exchanger receives heat resulted from the burning fuel in the furnace through the copper plate embedded at the bottom of the heat exchanger and then transfers it to the air in the drying chamber. The hot air is circulated in the same manner as in the solar energy mode.

In the mixed mode, the drying air is heated by the heat of solar energy gain and the heat produced by the furnace. Here, the heat supplied by the furnace acts as an energy supplement for the dryer to generate a higher drying air temperature if it is necessary.

In this experiment, the dryer was tested by utilizing the solar energy mode and the fuel generated energy mode. The solar energy mode testing was conducted as follows. Six thermo-hygrometers were prepared in the experiment, five thermo-hygrometers were placed on the rack of each story and a thermo-hygrometer was located in the shading area outside the dryer. The experiment was run from 9.00 AM to 4.00 PM and recording of temperature and relative humidity was made in 30 minutes interval. At the same time, the velocity of air inside the chimney was recorded by using an anemometer and the solar radiation intensity in the plenum of heat collector, the drying chamber, and outside the dryer was also measured by utilizing a solarmeter. The temperature and relative humidity readings of every story were averaged to represent the temperature and relative humidity of the drying chamber. The experiment was conducted in three times from August 14th to 16th 2018. The records of temperature, relative humidity, air velocity, and solar radiation intensity were then averaged to configure the fluctuation in function of observation time.

In the fuel generated energy mode, the temperature and relative humidity of the drying chamber were recorded by placing the thermo-hygrometers at the racks of lower, middle, and upper stories. The other parameters were measured by utilizing the same procedure as the solar energy mode. Coffee by-product biomass (nut's coffee bean and pulp) and traditional mining coal were utilized as sources of fuel. These fuels were sun-dried and their moisture contents were determined by using oven method and calculated on a wet basis. The biomass and coal moisture contents were found to be 9.07 and 9.3 respectively. Doses of biomass supply were 5, 7, 9, 11, and 13 kg whereas doses of coal supply were 4, 6, 8, 10, and 12 kg. A digital balance with 1 g accuracy was employed for weighing the fuels.
The experiments were carried out according to the doses of supply and every dose of supply was replicated in three times. To conduct the experiments the dryer was shaded with a dark tarpaulin and the clearance from the roof of the dryer was properly justified in order to guarantee that there was no heat effect of the sun rays. Each experiment was run as follows. The fuel was fed into the furnace and then flamed. Soon after the fuel was properly burned, the experimental parameters were observed. The observation was completed when the fire was extinct. These parameters comprised the drying chamber temperature and relative humidity, the ambient temperature and relative humidity, and the air velocity in the chimney. The experiments were run for three times from September 13\textsuperscript{th} to October 15\textsuperscript{th} 2018. Experimental data were presented in the form of the relationship between the fuel supply and the above parameters.

3. Results and Discussion
The results of experiments are presented according to the order of drying test and the discussion is mainly focused on the temperature profiles.

The source of solar energy in the form of solar radiation intensity observed during the solar energy testing of the dryer is presented in Figure 2.

![Figure 2 Solar radiation intensity outside and inside the dryer](image)

The figure reveals that the solar radiation intensity in the ambient air was higher and was followed subsequently by that solar radiation intensity in the heat collector plenum and the solar radiation intensity in the drying chamber. This fact suggests that the glass cover reduced the solar radiation intensity. The average values of these solar radiation intensities were 956.4 Wm\textsuperscript{-2} in the ambient air, 764.8 Wm\textsuperscript{-2} in the heat collector plenum and 714.9 Wm\textsuperscript{-2} in the drying chamber.

The profiles of the drying air temperature (temperature in the drying chamber) and the ambient temperature are shown in Fig. 3. The average values of the drying air temperature and the ambient temperature were 47.1°C and 34.3 °C respectively so the temperature gain of the dryer was 12.8°C. This temperature gain was higher than the temperature gain produced by the dryer before modification [18] suggesting that the modified version performed better.
Figure 3 Solar drying temperature

Figure 4 shows the profiles of the drying air relative humidity and the ambient relative humidity. The average values of the drying air relative humidity and the ambient air relative humidity were 22.7% and 55% respectively.

Figure 4 Solar drying relative humidity

Figure 5 indicates the observed drying air velocity in the chimney that fluctuated along the day. The average value of air velocity was 0.5 ms$^{-1}$.
Figure 5 Solar drying air velocity

Figure 6, Figure 7, and Figure 8 show the profiles of drying air temperature, drying relative humidity, and drying air velocity generated by the dryer when operated with the biomass fuel, together with the ambient temperature and relative humidity.

Figure 6 Biomass energy drying temperature

The drying air temperature strongly increased linearly with the biomass fuel supply with a high determination coefficient ($R^2 = 0.994$). Compared to the ambient temperature, the higher
Biomass fuel supply generated the higher temperature gain (the difference between the drying air temperatures from the ambient air temperature). On the other hand, the drying air relative humidity slightly decreased linearly with the biomass fuel supply ($R^2 = 0.959$), and the higher biomass fuel supply also produced the higher relative humidity gain. The drying air velocity also increased linearly with the biomass supply with $R^2$ value of 0.924. Although there was a strong correlation between the drying air velocity and the biomass fuel supply but the value of this parameter was not really significantly different from the drying air velocity generated by the solar energy drying since the performance of turbine ventilator was mainly determined by the wind condition outside the dryer.

The profiles of drying air temperature, drying air relative humidity, and drying air velocity produced by the dryer when operated by the coal fuel are presented in Fig. 9, Fig. 10, and Fig. 11. These drying parameters were strong linearly correlated to the coal fuel supply with coefficient determination values ($R^2$) of 0.998, 0.984, and 0.941 respectively for the drying air temperature, the drying relative humidity, and the drying air velocity. In term of curve characteristic, the coal fuel produced a higher gradient (slope of the curve) than the biomass fuel. It is reasonable since the caloric value of coal [28] is higher than the caloric value of coffee biomass.
Figure 9 Coal energy drying temperature

Figure 10 Coal energy drying relative humidity

Figure 11 Coal energy drying air velocity
Finding the relationship equations between fuel supply and drying temperature for the biomass fuel and the coal fuel makes it possible to generate any range of drying temperatures to dry wide varieties of agricultural products. So this independent hybrid solar dryer would be able to provide the drying process of commodities performed by the various types of hybrid solar dryer developed by other researchers according to the range of explored temperatures, such as slice onions (60°C) [12], chilli (50-70°C) [13], saffron (40-60°C) [16], fish (41-57°C) [18], cashew (55-65°C) [20], herbal and medicinal plants (60°C), fermented cassava (33-34°C) [29], tomato (50-75°C) [30], copra (43-62°C) [31], and groundnut (53°C) [32].

4. Conclusions
The independent hybrid solar dryer was experimented without load using three different source energies, i.e. the solar energy, the biomass fuel energy, and the coal fuel energy. When operated with solar energy with average radiation intensity of 956.4 W/m², the dryer generated drying air temperature of 47.1°C which was 12.8°C higher than that of ambient air. Operated with the heat energies from both the coffee by product and coal combustions, the relationship between temperatures and fuel supplies were $T = 4.323 \times s + 22.57$ ($R^2 = 0.994$) and $T = 5.003 \times s + 22.57$ ($R^2 = 0.998$) respectively, where $T$ = drying air temperature (°C) and $s$ = fuel supply (kg). This finding suggested that the dryer would be able to be operated for wide varieties of agricultural commodities.

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