Design, development and testing of Universiti Malaysia Sabah (UMS) eco-solar dryer

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Abstract. Utilization of solar drying for food preservation would be a step towards sustainable food processing. Even today, most of the agricultural and marine products are dried under open sun-drying. However, this method is associated with several drawbacks, which then leads to the use of solar dryer. Universiti Malaysia Sabah (UMS) has developed a solar drying system with loading capacity of 50kg to enhance the drying process of various food products. Design parameters particularly focused in this project includes the air movement pattern in drying chamber, heating system employed, air circulation ventilation and the airflow configuration in solar heat collector. Results revealed that solar dried products attained desired moisture content in shorter drying time. Temperature profile in updraft and downdraft drying mode indicated that no temperature fluctuation occurred when switching in between. Maximum temperature achieved under complete solar mode were 65°C and 83°C for single-pass and multi-pass solar heat collector, respectively. Under solar-hybrid mode, higher temperature was attained under intermittent ventilation mode. It can be concluded that UMS Eco-Solar Dryer is an environmentally and economically efficient drying system for the food processing industry.

Keywords: Downdraft, updraft, hybrid solar dryer, solar heat collector, efficiency

1. Introduction
Utilization of solar drying for food preservation would be a step towards sustainable food processing. Even today, most of the agricultural and marine products are dried under open sun drying. Due to its free and renewable energy source from the sun, it is still an extensively used method to preserve perishable products in most tropical and subtropical countries [1]. However, this method is associated with several drawbacks in term of hygienic, drying efficiency and quality characteristics of end products. Hence, the revolution of today’s technology has come up with solar dryer as a solution to overcome
such problem encountered during open sun drying. To ensure maximum performance is achieved during the drying process, continuous efforts in optimizing the performance of solar dryer are essential.

There are several drawbacks encountered when employing solar drying in food drying, and such include uncontrollable drying condition in the dryer due to the periodic characteristics of solar radiation. Although this could be easily overcome by installing electrical or photovoltaic powered auxiliary devices, higher electrical energy consumption and expenses are required for the operation. This could be a limitation, particularly for the application of small-scale farmers in the rural area. Hence, different approaches must be taken to enhance the performance of a solar dryer.

In a natural convection (passive) solar dryer, air movement in the dryer is voluntarily circulated by natural buoyancy force action [2]. Since no additional auxiliary system required to operate, passive solar dryers are extensively utilized in smallholders and rural communities. In an updraft drying system, low density heated air flowing into the drying chamber will flow in an upright motion across each drying tray for drying purposes. Without adequate ventilation, drying air will eventually lose its momentum to progressively rise up while carrying moisture removed from the commodities and consequently reduced the drying efficiency. On the other hand, using downdraft solar dryer will result in less efficient drying when heated air begins gaining less moisture from the commodities or when the moisture level is low. These drawbacks encountered in natural convection can be overcome using a forced convection solar dryer. In this project, Universiti Malaysia Sabah has developed a solar dryer classified as an indirect tray-type cabinet solar dryer, namely UMS Eco-Solar Dryer to overcome these limitations in drying food products.

2. Methodology

2.1. Design consideration

Many types of solar dryer have been introduced for domestic and industrial application in food dryings such as cabinet dryers, greenhouse dryers and chamber-type dryers. Among these dryers, solar dryer with multiple tray arrangement is most extensively used due to its capability to dry the high volume of products without complex design. The drying process in a tray-type dryer takes place by forcing heated drying air stream to flow across each level of drying tray either from the uppermost or lowermost level depending on the location of drying air inlet. In a tray-type dryer, an important parameter that defines the drying performance is the uniformity of airflow distribution across the food products [3].

Hence, in this project, a solar dryer system that offers a flexible feature in switching between updraft and downdraft drying mode is proposed. With this, extra manpower to manually turn over the food products can be avoided, and the basic problem of updraft and downdraft drying system can be resolved. In an attempt to ensure adequate air circulation in the dryer, wind ventilated system is employed. Auxiliary heating source is installed to ensure continuous heating throughout unfavorable weather and during the off-sunshine period.

2.1.1. Solar heat collector

The solar heat collector was designed to achieve drying temperature $T_p$, of 50 °C to dry 50 kg of palm fruitlet with the initial moisture content of 35% to 15% within 16 hours drying time. To enhance heat absorptivity of the collector, black painted aluminum cans were used for the construction of absorber. The frame was made up of plywood due to its high insulation performance ($k = 0.02675$ W/mK). Furthermore, heat intensity was enhanced by installing acrylic cover with 5 cm air gap from the absorber to produce the greenhouse effect in the collector.

Two solar heat collectors that provide different airflow configuration were proposed – single-pass and multi-pass. Flow configuration in the single pass solar heat collector is shown in Figure 1. This design will be used for the commissioning of solar dryer under non-loaded and loaded condition. The latter design offers longer drying air residence time in the air channel to attain higher drying air temperature than that of single-pass solar heat collector. This approach was taken to ensure the highest possible drying temperature attained in the drying system with electrical assisted devices. Drying
condition of the system can then be regulated through the air ventilation system. The area of solar heat collector was determined from equation (1) [4].

\[ Q = A_c \left( I_t \delta_a - U_L (T_p - T_a) F_R \right) \]  

(1)

Where \( A_c \) is the area of solar heat collector, \( I_t \) is the solar radiation, \( \delta_a \) is the transmissivity, \( U_L \) is the heat coefficient, \( F_R \) and \( T_a \) are the heat removed factor and ambient temperature, respectively.

2.1.2. Drying chamber

The drying chamber was constructed to have a closed system with an airtight environment which helps to build up pressure inside the chamber. The enclosed chamber was covered with glass wool fiber for insulation purpose. The updraft and downdraft system windows are hinged on the drying chamber inner wall to enable easy opening and closing. Figure 2 demonstrates the airflow configuration for different drying mode. Drying area in the chamber was fixed at 0.64 m\(^2\) with five drying trays arranged in 0.1m interval space. Minimum height drying tray was determined from equation (2) as follow:

\[ H_t = \frac{H}{n} \]  

(2)

where \( H_t \) is the minimum height of drying tray, \( H \) is the height of 50 kg palm fruit and \( n \) is the number of trays.

Six infrared heating bulbs were installed at the top of the drying chamber as an auxiliary heating source. The heating system was connected to a control panel that automatically regulates drying condition in the chamber according to the value set in the differential temperature controller.

The calculation of energy required to heat drying air in the chamber up to 80 °C is expressed in equation (3) [5].

\[ Q = m \times C \times \Delta T \]  

(3)

where \( Q \) is the heat energy required, \( m \) is the mass of air in the drying chamber, \( C \) is the heat capacity of air at 328 K, and \( \Delta T \) is the temperature change from initial temperature.

![Figure 1. Airflow configuration in single-pass solar heat collector](image1)

![Figure 2. Air flow configuration in updraft and downdraft drying mode.](image2)

2.1.3. Chimney

A wind ventilator was installed at the top of the chimney to allow forced convection throughout the process. In this design, the controlling factor is the height of the chimney and the draft produced was determined based on equation (4) [6].
\[ D_i = Hg(\rho_a - \rho_e) \]  

where \( D_i \) is the pressure difference, \( H \) is the height of the chimney, \( \rho_a \) and \( \rho_e \) is the density of ambient air and exit air, respectively, and \( g \) is the gravitational force.

### 2.2. Experimental set-up

A series of experimental tests were performed to study the dryer performance under no-load and loaded condition. Another test with a solar dryer integrated with a multiple-pass solar heat collector was performed to determine its performance in terms of drying temperature attained at the inlet of the drying chamber.

Variables such as solar radiation, ambient temperature, drying chamber temperature, relative humidity and drying chamber airflow were measured using Zonon CMP3 pyranometer, GLOBE Hygro-Thermometer, thermocouple and anemometer, respectively. The initial moisture content of drying products – Senduduk and Jasmine flower were determined by Sartorius MA35 Moisture Analyzer Test. The weight change of products was recorded every 2 hours interval.

### 3. Results and Discussions

#### 3.1. Commissioning without load

The first experiment was conducted without load to verify the performance of the solar drying system proposed. Tests were conducted under complete solar mode and hybrid mode for comparison. Under complete solar mode, the variation of average drying air temperature in the chamber for both updraft (UT) and downdraft (DT) drying modes with average airflow of 0.2 m/s and 0.13 m/s, respectively are presented in Figure 3. Based on the temperature profile exhibited, updraft drying mode offers a higher drying temperature. This is due to higher solar radiation was determined when performing updraft drying. However, minimal drying air temperature difference of 1±0.9 °C to 4±2.4 °C was observed between updraft and downdraft drying modes. Therefore, it could be deduced that both drying modes exhibit similar temperature profile, and that no temperature fluctuation would occur while switching between the two different drying modes.

Temperature variation across the drying trays under updraft and downdraft drying mode is presented in Figure 4. In both drying modes, the uppermost level drying tray received higher drying temperature than that at the lowest level drying tray. In updraft mode, hot air with low density rises up, hence resulting in a higher temperature at the top. Whereas in the downdraft mode, additional energy and longer air residence time are required for low-density hot air to reach the bottom level, resulting higher temperature observed at the uppermost tray located near the drying chamber inlet.

From this observation, it can be inferred that the solar drying system proposed could improve the air circulation in the drying chamber. When employing updraft mode during a drying process, the solar dryer will eventually encounter inadequate ventilation as hot air gains moisture from the products and loses its momentum to progressively rise up. At this point, switching to downdraft mode allows hot air from the inlet to compensate low temperature at the top. The minimum and maximum drying temperature observed from both drying modes were 31 °C and 65 °C, respectively.

In hybrid mode, the dryer was operated under two ventilation mode – continuous ventilation and intermittent ventilation. The temperature profile in the chamber was observed with the temperature set at 55 °C. Figure 5 shows temperature variation across the drying trays with continuous ventilation. Based on the graph plotted, the desired temperature was observed only at the uppermost drying tray between 10:00 AM to 12:00 PM under this condition. This was due to the heating source was installed right above the drying tray, and the temperature sensor was placed on the middle tray, hence, resulting in...
insufficient heating in the remaining trays. In contrast, the desired temperature was achieved at top and middle tray before 10:00 AM under intermittent ventilation mode, as shown in Figure 6. Based on the data recorded, it can be deduced that the intermittent ventilation system offers shorter heating to achieve the desired temperature. As a comparison, Noh et al. suggested using intermittent ventilation to reduce the energy consumption of the drying process [7]. Based on their findings, the intermittent ventilation system offers a higher temperature in the drying chamber compared to passive ventilation and continuous active ventilation mode. However, this results in poor temperature distribution uniformity in the drying chamber than that of continuous ventilation.

![Figure 3. Temperature profile in drying chamber under updraft and downdraft drying modes.](image1)

![Figure 4. Temperature profile across drying trays under updraft and downdraft drying modes.](image2)

![Figure 5. Temperature profile across drying trays at the temperature set at 55 °C under continuous ventilation mode.](image3)

![Figure 6. Temperature profile across drying trays at the temperature set at 55 °C under intermittent ventilation mode.](image4)

### 3.2. Commissioning with load

Drying products used to verify the performance of hybrid dryer developed were Senduduk and Jasmine flowers with the initial moisture content of 64.27 % and 74.13 %, respectively. Weight loss of about 75 % to 77% was taken as the reference line for the drying process under drying temperature of 40 °C. Figure 7 shows the weight loss of products against drying time in a solar dryer. Based on the plotted results, drying time required to achieve desired moisture loss in solar dryer are 26 hours and 32 hours for Senduduk and Jasmine, respectively. A longer drying time of more than 56 hours was required under open sun drying.
3.3. Test with a multiple-pass solar heat collector

Experiment tests to study the performance of multiple-pass solar heat collector were conducted under wind ventilated condition with airflow ranged from 0.2 to 2 m/s. Variables measured were ambient temperature, collector outlet temperature, drying chamber temperature, airflow rate and solar radiation. Performance of the collector was evaluated based on the collector efficiency calculated from these parameters. The test was performed from 9:30 AM to 4:30 PM. Figure 8 shows the temperature variation taken on 20 July 2020 that exhibits the highest outlet temperature during the one-month experimental period.

Throughout the day, maximum outlet temperature attained was 83 °C at 1:00 PM with the solar intensity of 209.8 W/m². Whereas the minimum temperature of 36 °C was recorded at 9:00 AM with low solar intensity. Comparing to the maximum temperature recorded from previous experiments that used single-pass solar heat collector, this result indicated that thermal enhancement was achieved by increasing the length of air channel in solar heat collector. This result is in accordance with Yeh et al. findings [8].

Data that shows the collector efficiency of multi-pass solar heat collector against air velocity are shown in Figure 9. Based on the graph plotted, lower efficiency was observed at low air velocity. In contrast, the efficiency increased at high air velocity, which enhanced the heat transfer rate in the solar heat collector.

![Figure 7](image7.png)

**Figure 7.** Weight loss of Senduduk and Jasmine flowers throughout the drying period.

![Figure 8](image8.png)

**Figure 8.** Temperature attained at the outlet of multiple-pass solar heat collector throughout the experimental period.

![Figure 9](image9.png)

**Figure 9.** Collector efficiency against air velocity.
4. Conclusion
An indirect type of solar dryer with 50 kg drying capacity was developed in UMS. Uniformity of temperature distribution across the multiple tray arrangement in the chamber was enhanced by employing flexibility features to switch the drying system in between updraft and downdraft drying modes. A maximum collector outlet temperature of 65 °C was observed by using a single-pass solar heat collector. The total drying time of 26 hours and 32 hours were required to achieve 78 % weight loss in Senduduk and Jasmine flowers, respectively under this condition. By integrating the multiple-pass solar dryer, the maximum temperature at the collector outlet was increased to 83 °C, indicating thermal enhancement.

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