Design, development and performance evaluation of a large-scale hybrid solar dryer

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Abstract. A large-scale hybrid solar dryer was developed to account the limitations encountered in traditional open sun drying. With loading capacity of 500 kg and incorporated with a hybrid heating control system, this dryer is suitable for industrial drying that requires large drying capacity and products with high moisture content. In addition, this drying system offers flexibility in switching between different combinations of air vents based on the drying purpose required. Chaotic air flow produced in the drying chamber ensure uniform temperature distribution across the drying trays in an updraft air movement. Potential application of the drying system for durian skin and chili drying were tested. Based on the performance evaluation, a maximum temperature and maximum average temperature of 66°C and 59°C, respectively, was attained in the drying chamber. The drying of chilli with the drying temperature set at 50°C and operating condition of using the ventilation fan and opening the air vent achieved the drying time of 5 days or 45 hours in total, equivalent to 9 hours of drying time per day.

1. Introduction

Tropical fruit crops are one of the significant agricultural products in Malaysia with a yearly production of 1.6 million mg (Department of Agriculture (DOA), 2012). Till date, practices of ignoring post-harvest agricultural waste in landfills or by open burning would bring in serious destruction to the environment and general health standards (Bujang, 2014). In addition, over-supply and its detrimental effect on the farmers’ economic earnings heighten the dire need to concoct and bring in not only a relatively good post-harvest management system but also a channel to bring in value to these abandoned waste streams. Drying is one of the oldest practices to preserve food or non-food products through the process of moisture removal.
Solar dryer is one of the most sustainable technologies in the drying industry that utilize solar energy as a primary heat source to heat up air for drying purpose. This technology is well considered to substitute traditional open sun drying employed by smallholders and rural communities to economically boost up drying rate of the process (Lambert et al., 1980). Besides, open sun drying is not favourable for large scale drying as this technique incorporates several drawbacks such as large area requirement, more manpower, potential contamination by dust and insects, and poor end-product quality characteristics due to inconsistent drying condition (Jambhulkar et al., 2017).

The objectives of this study is to design and fabricated a large-scale hybrid solar dryer of 500 kg drying capacity and to commission the dryer in empty load for performance evaluation. In addition, loaded test will be conducted to observe the performance of solar dryer in drying chillies.

2. Methodology

2.1. Solar dryer design consideration
To design the solar dryer, the assumptions made are presented in Table 1. Solar dryer was designed based on procedure described by Raju et al. (2013).

| Parameters                          | Value         |
|-------------------------------------|---------------|
| Ambient temperature, $T_a$ (°C)     | 30            |
| Drying temperature, $T_d$ (°C)      | 50            |
| Drying period, $t_d$ (hr)           | 8 – 16        |
| Incident solar radiation, $I$ (MJ/m²/day) | 15.87        |
| Density of ambient air, $\rho_a$ (kg/m³) | 1.165        |
| Density of air at 50°C, $\rho_r$ (kg/m³) | 1.109        |
| Solar collector efficiency, $\eta_c$ (%) | 30            |
| Height between each tray interval (m) | 0.2           |
| Tray height (m)                     | 0.1           |
| Base area (m²)                      | 5.4 (3 m x 1.8 m) |

The minimum temperature for the drying of food crops is 30 °C and the maximum temperature is 60 °C (Raju et al., 2013). So 45 °C and above is considered average and normal for the drying of food crops. In this range, 50 °C was chosen. This solar house design was designed for the optimum temperature of solar dryers. Temperature of outlet is 60 °C and the inlet temperature is the ambient temperature, which is 30 °C. For a hot climate passive solar dryer, a gap of 5cm is needed as air inlet.

2.1.1. Solar heat collector. The covering (Perspex sheet) should have 4-5cm thickness. In this project, 5cm thick Perspex sheet was used. The efficiency of the solar collector is around 30% to 50% (Papade & Boda, 2014). For this project, an efficiency of 30% is used. Collector efficiency is defined as the ratio of the useful output of a device to the input of the device. It is not possible to have 100% efficiency. An efficiency of 30% was initially assumed for this project.
First and foremost, the mass of moisture content required to be removed during drying was calculated from equation (1) (ManzoorAhmad et al., 2015).

\[ M_w = \frac{m_i - m_f}{100 - m_f} \times W \]  

(1)

Where, 
- \( m_i \) = Initial moisture content (%) 
- \( m_f \) = Final moisture content (5) 
- \( W \) = Weight of the load (kg) 
- \( M_w \) = Mass of water removed during drying (kg)

Next, the total energy required to eliminate the moisture content was calculated from equation (2) (ManzoorAhmad et al., 2015).

\[ Q = W C_p (T_d - T_a) + M_w \lambda \]  

(2)

Where, 
- \( Q \) = Total energy required (kJ) 
- \( C_p \) = Specific heat capacity of air (kJ kg\(^{-1}\) K\(^{-1}\)) 
- \( T_d \) = Drying temperature (°C) 
- \( T_a \) = Ambient temperature (°C) 
- \( \lambda \) = Latent heat of vaporization (kJ/kg)

Finally, the solar collector area, \( A_c \) was calculated (ManzoorAhmad et al., 2015).

\[ A_c = \frac{\dot{m} C_p (T_d - T_a)}{\eta_c I_g} \]  

(3)

Where, 
- \( A_c \) = Solar heat collector area (m\(^2\)) 
- \( \dot{m} \) = Mass flow rate (kg h\(^{-1}\)) 
- \( I_g \) = Annual average solar radiation (MJ m\(^{-2}\) day\(^{-1}\))

2.1.2. Drying chamber. For a constant exchange of air, the design of the drying chamber was made as spacious as possible. First, the volume of the drying materials was calculated based on equation (4) (ManzoorAhmad et al., 2015).

\[ V = W \times \rho_b \]  

(4)

Where, 
- \( V \) = Volume of drying material (m\(^3\)) 
- \( \rho_b \) = Bulk density (kg/m\(^3\))

Height of the drying material can then be determined as follow:
\[ H = \frac{V}{A_b} \]  \hspace{1cm} (5)

Where,
\[
H \quad = \text{Height of drying material (m)} \\
A_b \quad = \text{Base area (m}^2\text{)}
\]

Steel mesh was used as the dryer trays for an efficient air circulation inside the drying chamber. All the trays have edges. The tray dimensions 1.5m \times 1.8m. Stainless steel was used as frame. The walls of the drying chamber were made up of insulated cement board. This protects the crops to be placed on the trays from direct sunlight. Direct sunlight is able to bleach the color, removes the flavor and causes the crops to dry unevenly.

2.1.3. **Auxiliary heating system.** To determine the power required for the drying processing, assumptions used for calculation are shown in **Table 2.** The data are obtained from previous study of drying chillies in solar dryer.

**Table 2.** Data and assumptions used for calculation of power requirement.

| Parameters                              | Value                |
|----------------------------------------|----------------------|
| Maximum load, W (kg)                   | 500                  |
| Mass of chilli before drying, \( m_i \) (kg) | 30                   |
| Mass of chilli after drying, \( m_f \) (kg) | 8.75                 |
| Drying time, \( t_d \) (s)             | 165,600 (4 hours)    |
| Heat capacity of water, \( C_p \) (kJ/kg \( ^0 \text{C} \)) | 4.19                |
| Latent heat capacity of water, \( \lambda \) (kJ/kg) | 2260                |

The power required can be calculated with the equation below:

\[ P = \frac{Q}{t_d} \]  \hspace{1cm} (6)

2.2. **Experimental set-up**

The first experimental test was performed with non-loaded drying chamber to verify the performance of the solar drying system developed and conduct necessary troubleshooting to ensure effective drying process achieved.

The test was performed based on the experimental matrix as following to establish temperature profile in the chamber:

Combination Test 1: \( T_{\text{set}} = 50^0 \text{C} \), closed fan and closed chimney air vent
Combination Test 2: \( T_{\text{set}} = 60^0 \text{C} \), closed fan and closed chimney air vent
Combination Test 1: \( T_{\text{set}} = 50^0 \text{C} \), open fan and open chimney air vent
Combination Test 1: \( T_{\text{set}} = 60^0 \text{C} \), open fan and open chimney air vent

Drying parameters were measured every two hours, from 8 AM to 5 PM daily. Temperature in the drying chamber was measured at the top, middle and bottom trays, which is tray 1, tray 3 and tray 5.
respectively using thermometer. Whereas, air flow was measured in the surrounding and in the drying chamber (inlet vent) with OMEGA Type K/J Hot Wire Anemometer. Performance of the loaded solar dryer was evaluated using 1 kg of chilli in drying tray of 1, 3 and 5 each. The weight of chili and temperature attained at each drying tray were measured every two hours interval.

3. Results and discussion

3.1. Solar dryer construction
The photography of UMS Eco-Solar House constructed for this study is shown in Figure 1 and a schematic diagram of the solar house that demonstrate chaotic air configuration in the drying chamber is shown in Figure 2. The main components of the solar house are solar heat collector, drying chamber, wind ventilators, suction fan, auxiliary heating elements and a control system. The structure of solar heat collector (3 m x 1 m x 4 m) are made up of galvanized iron and painted black to maximize heat absorption. Four layers of black-painted aluminium bars are stacked on top of each other and placed in the solar collector as a heat absorber. Stainless steel mesh was installed at the inlet of air passage to prevent contamination and thermal intensity of this component was enhanced by using a transparent cover to create greenhouse effect in the collector. The outlet of solar heat collector was connected to the drying chamber with four ducting pipes constructed with rockwool insulated PVC pipes that were painted in black.

The drying chamber (1.5 m x 1.8 m x 3 m) was designed to accommodate 500 kg drying materials and was divided into two compartments to split the utility units and avoid energy wastage. Each compartment was fixed with two ducting pipes at the bottom part. Hence, drying process will be performed in an updraft motion. There are total of five drying trays, a suction fan and a wind ventilated chimney equipped in each compartment. Drying trays were stacked at one another in 7.5 cm interval. Air vents at the inlet and outlet of drying chamber were designed in adjustable window type to provide flexibility in manually regulating the air flow distribution in the chamber based on drying condition desired. Suction fan was installed at the bottom part of drying chamber divider to create forced air movement in the chamber. The skeleton structure of the drying chamber was constructed with 50.8 mm x 25.4 mm metal, support is made of 76.2 mm x 76.2 mm cement and the surface of drying chamber was made up of 12 mm thickness insulated cement board. In order to ensure sufficient heating in the chamber, each side of the drying chamber was fitted with 60 mm infrared halogen heat lamp of 300 watt as an active heating system. A control panel was designed and installed at the drying chamber to control the drying system according to desired temperature, $T_{set}$.

The movement of air through the vents is similar to thermosyphon effect, which creates an updraft of solar heated air laden with moisture out of the drying chamber through the chimney. The air flow in the drying chamber is turbulent flow, thus, air flow distribution in the chamber is not one-directional but scattered all around the chamber. Chaotic air flow pattern produced will then offers uniform distribution of temperature across the chamber. Air movement in the drying chamber can be regulate via opening or closing of air vents.
3.2. Commissioning without load
Based on the test conducted, there are four combinations of temperatures of 50°C and 60°C with operating conditions of closed fan and closed chimney air vent, and open fan and open the top air vent with tied ventilator. The basic idea for the first operating condition is to trap the heated air inside the drying chamber by closing the chimney air vent to prevent the heated air from going out. The closed fan also is to see the chaotic flow of air inside the chamber instead of circulating it with the ventilation fan. While the second operating condition where the fan is turned on to promote the circulation of air and the chimney air vent is open to let the natural flow of heated air.

From the temperature profile shown in Figure 3 to Figure 6, it can be seen that the right chamber have a higher temperature reading than the left chamber with a temperature difference ranged from 1°C to 7°C. This may be caused by the leaking or loosed air gaps in the left chamber that caused the heated air to escape from the chamber. Based on the combination test 1 and test 2 the temperature difference between the right chamber and the left chamber is not significant, where at one point in combination test 2, at 10 am, the average temperature of left chamber is higher than right chamber which 55°C and 54.67°C, respectively.

While in tests with open chimney vent and open fan, the difference between the average temperature of right chamber and left chamber is higher with the highest temperature difference being 7°C. This may be caused by the ventilating fan, where instead of circulating the air in the chamber, the fan promotes the flow of the heated air out of the drying chamber through the opened air vent. Based on the recorded temperature data, it can be seen that the profile of the temperature of a chamber from the bottom tray to the top tray is increasing for both the left and right chamber. From these tests the highest average temperature is 59°C while the highest temperature of tray is 66°C which is the top tray. It can be observed during the 8 am where the temperature of the drying chamber when the $T_{set}$=is 50°C are already reaching the set-point value, while in test with $T_{set}$=60°C, a longer time is needed to achieve the set-point value temperature.
Overall it can be concluded that the temperature profile of the right chamber is higher than the left chamber, and the temperature profile with operating condition of closed fan and closed air vent is higher than the opened fan and opened air vent.

**Figure 3.** Drying chamber temperature profile for combination 1.

**Figure 4.** Drying chamber temperature profile for combination 2.
3.3. Commissioning with load
Drying of chilli was performed in the solar house, under drying condition of combination 3, with drying temperature set at 50°C under continuous ventilation mode. Based on the drying process of chilli, the drying of chilli is complete in 5 days which the drying takes place for 9 hour a day. Thus the total drying time of the chilli is 45 hours. Kaewkiew et al. (2012) reported a total drying time of 3 days for the drying of 500 kg chillies in a mixed mode type solar greenhouse dryer under forced convection. Janjai et al. (2011) reported the use of solar greenhouse to dry 300 kg of chillies from an initial moisture content of 75% to 15% in 3 days. Based on previous study, efficiency of large-scale drying for chillies can be achieved by employing mixed mode solar heating system, where drying materials not only receive heat from the solar heat collector but also through direct solar radiation.
From the graph of average weight reduction between the chambers presented in Figure 7, it can be observed that the average weight in right chamber reduce faster than the left chamber. This also may cause by insufficient drying temperature in the left chamber which can be observed from the average temperature. The highest average temperature in the left chamber for the 5 days of drying is only 49.67°C while the right chamber is 52.67°C. The time for the average temperature in the left chamber to reach the drying temperature which is 50°C is slow and sometimes, it does not reach the required drying temperature at all throughout the day. Based on the recorded weight, tray 1 of the right chamber which is the top tray started to have no change in weight in day 4 and finally reach equilibrium weight at day 5. This tray has the fastest drying while the slowest in reduction of weight is tray 5 at the left chamber, which is the bottom tray.

Figure 7. Comparison of average weight of chilli against time between left and right drying chamber.

4. Conclusion

In this year project, a hybrid system of UMS Eco-Solar House was successfully fabricated and installed. The hybrid system consists of a heating system which is the hydrogen infrared heat lamp and a control panel. The heat lamp installed are 5 in each chamber and a total of 10 heat lamps. The temperature of the drying chamber is recorded with various parameter such as the temperatures and the operating conditions to see the temperature profile of the solar house. The maximum temperature achieve in the drying chambers is 66°C. While the maximum average temperature achieves in the solar house is 59°C. The temperature profile of the right chamber has higher average temperature than the left chamber with range of 1°C to 7°C. The temperature profile of both the chambers from bottom tray to top tray is increasing. The drying of chilli with the drying temperature of 50°C and operating condition of using the ventilation fan and opening the air vent achieved the drying time of 5 days or 45 hours which is 9 hours of drying time per day. More studies are being carried out on a larger amount of samples being dried.
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