Performance evaluation of a novel multi-pass solar air heating collector

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Abstract

In this present investigation, the performance of a new solar air heating collector of multi-pass mode is presented. The solar air heating system is theoretically modelled by applying energy balance expressions to reflect the network of convection and radiation heat flows. The theoretical analysis of the active air heater is supported by SIMSCAPE\textsuperscript{TM} numerical tool while the proposed multi-pass solar collector system was tested under the meteorological condition of Seri Iskandar, Malaysia (4.385693° N and 100.979203° E). These techniques were used to audit the solar energy balance of the solar dryer system. The performance indices of the drying system were evaluated and the system thermodynamic correlations were obtained. Daily maximum temperature gradient between ambient and the system collector was 30.42°C. The thermal collector efficiency and optical efficiency were 59.96\% and 72.26\%, respectively. Improvement on system thermal delivery by the sensible porous matrix of 9.37\% was achieved. The predicted performance level was compared with the test result and a relatively fair agreement was obtained. However, the instantaneous thermodynamic properties of air at the system boundary need to be defined to accomplish better accuracy on the relevant correlations.

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1. Introduction

Strategic transformation in securing the environment from further degradation by fossil fuel has been spelt out in the sustainable development goals (SDG) adopted by the United Nations in 2015. Therefore, the performance and reliability of renewable energy, especially solar energy are on test to meet the global energy demand. Open sun drying is still a common practice among farmers in developing countries. This has reflected in reduced quality and quantity of dried product, which is unable to meet international market standard. In addition, this traditional drying approach is characterised by low drying rate, high labour involvement, rain and rodent attack.

| Nomenclature          | Description                                      |
|-----------------------|--------------------------------------------------|
| $M$                   | Moisture (g)                                     |
| $n, k$                | Drying parameters                                |
| $T$                   | Temperature (°C)                                 |
| $t$                   | Time (s)                                         |
| $RH$                  | Relative humidity (%)                            |
| $C$                   | Specific thermal capacity (J(kg.°C)$^{-1}$)      |
| $m$                   | Air mass flow rate (kgs$^{-1}$)                  |
| $x$                   | Length (m)                                       |
| $I$                   | Solar energy flux (Wm$^{-2}$)                    |
| $U$                   | Thermal energy (W(m$^2$.°C)$^{-1}$)              |
| $F'$                  | Collector performance factor                     |
| $A$                   | Area (m$^2$)                                     |
| $h$                   | Heat transfer coefficient (W(m$^2$.°C)$^{-1}$)   |

| Greek Symbols         | Description                                      |
|-----------------------|--------------------------------------------------|
| $\alpha$              | Absorptivity                                     |
| $\tau$                | Transmissivity                                   |

| Subscripts            | Description                                      |
|-----------------------|--------------------------------------------------|
| $R$                   | Ratio                                            |
| $eq$                  | Equivalent                                       |
| $f$                   | Fluid                                            |
| $p$                   | Collector plate                                  |
| $r$                   | Radiation                                        |
| $c$                   | Convection                                       |
| $amb$                 | Ambient                                          |
| $dk$                  | Drying deck                                      |
| $g$                   | Glass                                            |
| $ch$                  | Drying chamber                                   |

Drying technology involves a means of generating hot air to dehydrate a substance that contains a certain percentage of moisture in its composition. Therefore, a mass transfer of water molecule occurred in the process of drying operation. Different successful approaches have been used to produce hot air such as electrical filament, burning of fossil fuel, chemical adsorption and desorption. Although, many of these are not sustainable in nature, while some are adversely affecting the environment. Therefore, a relatively free and eco-friendly option of modernised (indirect) solar drying is a way out of these deficiencies.

Significant achievement has been made on the performance of single pass and double pass collectors. Recently, Fudholi et al. [1] designed a forced convective double pass solar air heater with six pieces of solar collector plates made of aluminium and a transparent cover. They optimised their solar air heater to achieve collector, pickup and
drying efficiency of 31%, 67% and 19% respectively, while exergy efficiency range of 10-73% was recorded. In another study conducted on hot air solar collectors by Mahmood et al. [2] attained an optimum performance efficiency of 62.5% and 55% for both double pass and single pass that are assisted with meshed wire, respectively.

Many drying models have been investigated such as Newton, Page, Henderson and Pabis, and Logarithmic which remain famous and benchmark models in drying operation [3, 4]. Pakowaki and Mujumdar [5] stated that four independent partial differential expressions to model the changes that occur during drying operation of a substance such as moisture content, temperature of dried product, relative humidity and the temperature of air provided the changes in fluid concentration remains constant when compared with the changes in solid phase. A mathematical model was investigated by Forson et al. [6] under a steady state regime. They used diathermal wall on the system boundary of their solar air heater to determine the chamber wall temperature. In serial tests, they obtained a range of 45.4-70%, 11-22.5% and 17.5-28.2% for the collector, drying and pick-up efficiencies of the drying system, respectively. Cadafalch and Cònsul [7] listed transparent cover, absorber, back insulation, upper and lower airways as essential parts in modelling a solar system. They presented both numerical and experimental means of solving solar collector using multilayer analysis of one-dimensional dynamic approach.

Rahman et al. [8] studied a solar drying system with a payback period of 4 years and 3 months with 50°C, 1.25 m² and 0.036 kg/s as the drying temperature, system aperture and air mass flow rate, respectively. These parameters were combined to achieve optimum performance in Singapore with solar collector facing geographical south at 10° angle of inclination which they affirmed suitable for solar harvest. A banana solar dryer was designed and tested by Amer et al. [9] in Germany. They valued the initial moisture content of banana as 82%, whereas the final moisture content was evaluated as 18%, while the drying temperature was 27°C more than the ambient temperature. The banana dryer takes between 8-10 h for its operation depending on the enhancement accessories used such as auxiliary thermal source. They established that recycle of drying air can improve the dryer performance in the neighbourhood of 65%.

Many studies have been previously investigated to scale up the performance of the solar air heating collector based on single pass and double pass modes, which are either supported by auxiliary heater or pebble beds as sensible thermal mass. Despite the energy reservoir used in augmenting the double pass, the thermal delivery of the system is still low. Hence the present study proposed a multi-pass solar dryer without traditional back insulation plate with improved performance efficiency.

2. Physics of the model

The multi-pass solar air heater is predicated on the principles of energy law. The energy law is employed to analyse the collector performance.

Basunia and Abe [10] demonstrated the relevance of employing Page’s equation as shown in Eqn. (1) to describe the thing layer characterization of drying grain in a passive dryer. They used Modified Chung-Pfost equation already established as ASAE Standard (D245.4, 1995) shown in Eqn. (2). They derived equations for and with correlation of determinations of 0.86 and 0.8 as shown in Eqn. (3) and Eqn. (4), respectively.

\[ M_R = \frac{M - M_{eq}}{M_0 - M_{eq}} = \exp(-kt^n) \]  

\[ M_R = 29.3940 - 4.6015 \ln[(-(T + 35.703) \ln(RH))] \]  

where \( M_R \) is the moisture ratio; \( M \) is the instantaneous content, % dry basis (d.b); \( M_0 \) is the initial moisture content, % d.b; \( M_{eq} \) is moisture content at equilibrium of grain, % d.b; \( t \) is the duration of drying (min), while \( k \) and \( n \) are drying parameters.

where \( RH \) is the relative humidity and \( T \) is the temperature.
Kong et al. [11] applied the expression in Eqn. (5) to solve the solar collector system under dynamic condition. Although, the steady state is guided by some strict limitations and its process is costly. However, they emphasised that steady state evaluation of collector is not complex like dynamic situation. This made many of the previous studies to employ steady state.

\[
C \dot{m} \left[ T_f(x + \delta x, t) - T_f(x, t) \right] = \alpha \pi I (\delta x \delta y) F^x - C \dot{m} \left( \frac{\delta T_f(x, t)}{\delta t} \right) - U_{loss} F^x \left[ T_f(x, t) - T_p(t) \right] \delta A
\]

Equation (5) can be reduced to the expression in Eqn. (6) as the heat loss to the ambient through the back plate is not significant in the designed multi-pass solar collector.

\[
C \dot{m} \left[ T_f(x + \delta x, t) - T_f(x, t) \right] = \alpha \pi I (\delta x \delta y) F^x - C \dot{m} \left( \frac{\delta T_f(x, t)}{\delta t} \right)
\]

3. SIMSCAPE model

The heat transfer around the multi-pass solar dryer was modelled by the SIMSCAPE™ tool of version 3.13 (R2015a). The system is composed of network of mathematical blocks that represent the physical feature of the system and the meteorological situation of the environment where the facility is located. The heat source, temperature source, flow process and sink of the open system are modelled by ideal source block, sensor blocks and heat transfer elements, respectively. The model solver is based on ordinary differential equation (ODE15s) with a relative tolerance of 0.001.

Table 1. Solar dryer modeling variables.

| Parameter                  | Symbol | Value  |
|----------------------------|--------|--------|
| Irradiance, $I$           | Wm$^{-2}$ | 0-900  |
| Ambient temperature, $T_f$ | °C     | 29-34  |
| Collector area, $A$       | m$^2$  | 1.75   |
| Specific thermal capacity, $C$ | J(kg.°C)$^{-1}$ | 1005 |
| Relative humidity, $RH$   | %      | 54-98  |
| Inlet air velocity, $V$   | ms$^{-1}$ | 0-1.2  |
| Air mass flow rate, $\dot{m}$ | kgs$^{-1}$ | 0.01-0.07 |
4. Experimental setup

The facility of this experiment was erected on the Solar Research Site (SRS), Universiti Teknologi PETRONAS (4.385693° N and 100.979203° E). The solar air heater was tested in August, 2015. The schematic diagram of the energy flow around the system is shown in Fig. 1. The air with ambient temperature enters the system through the inlet between first and second transparent covers. The air later passes through the absorber (upper and lower surfaces), the sensible thermal mass and eventually enters the drying compartment, which consists of four decks of drying trays (deck-1 to deck-4). The air experience temperature differential as it passes through the planes of covers, collector and thermal mass. This stage involves energy conversion and thermal transfer.

The drying operation involves the removal of moisture composition of the dried product. Therefore, mass transfer of moisture is evaluated at this stage. The drying operation is generally segmented into constant and falling rate periods. Although, there are no clear distinction between the constant drying rate period and falling drying rate period of some drying operation which was affirmed [10, 12]. The modes of thermal transfer of multi-pass air dryer are shown in the facility sketch, while the humidified air flow out of the system with the help of exhaust fan at the centre of the drying chamber floor.

![Schematic diagram of the system energy flow.](image)

5. Results and discussion

The outcome of the thermal transfer during the testing of the multi-pass solar dryer is presented in this section based on the local weather condition of Seri Iskandar, Malaysia. A meteorological data (Fig. 2a) monitored for 24:00 h on a clear day of August, 2015 reflected maximum value of solar energy flux and system inlet air velocity with 848.35 Wm\(^{-2}\) and 0.63 ms\(^{-1}\), respectively. The weather profile shows 8:00 h to 17:00 h as the active solar period of the day, whereas the inlet velocity rapidly improved upon the activation of exhaust fan in the morning and a range
of 0.48-0.63 ms\(^{-1}\) was maintained throughout the day.

The environmental temperature and relative humidity as dependent variables on solar energy flux is presented in Fig. 2b. A low temperature range 25.6-28.4\(^\circ\)C and high humidity range 82-98% were experienced at the early part of the day when irradiance was less than 150 Wm\(^{-2}\). This trend reached climax when the energy flux attained 200 Wm\(^{-2}\), while a reversal in trend was observed as the humidity was dropping and upsurge was reflected in the ambient temperature until the peak value of irradiance was attained.

The multi-pass solar collector dryer system temperature profile is depicted in Fig. 3a. The materials that are relevant to evaluation of system thermal level are the transparent covers, the thermal energy storing mass and the solar collector. The temperatures of these materials are used in determining the performance efficiency of the dryer, while the ambient temperature acts as reference temperature. The graph revealed maximum value of 64.19\(^\circ\)C, 49.19\(^\circ\)C, 55.49\(^\circ\)C, 47.47\(^\circ\)C and 33.77\(^\circ\)C for collector, first glass, second glass, sensible energy thermal storing mass and ambient temperature, respectively. The second (inner) glass is closer to the solar thermal energy converter of the system, which is the solar collector. This made the inner glazing cover to attain higher temperature compare to the first (outer) cover. This was in line with reported study [13]. However, the peak of temperature is skewed towards late hours of the day. The contribution of thermal mass is shown between 17:00 h and 24:00 h of the study day. It reflects a temperature gradient range of 4-15\(^\circ\)C above the ambient temperature.
Fig. 3 (a) Multi-pass solar drying system temperature profile; (b) Performance profile of the system.

The system solar collector performance efficiency curve is presented in Fig. 3b. Both theoretical and experimental profiles are presented. The theoretical curve is emanated from the simulation of the dryer system using SIMSCAPE tool, whereas the test conducted on the experimental rig was analysed to obtain the experimental curve.

The temperature profile of the system was integrated as shown in Fig. 4 to reflect the source contribution of the first-pass, second-pass, multi-pass and the sensible thermal energy storing mass that is determined by their temperatures in relation to the local ambient temperature. The ambient temperature serves as reference temperature.

The improvement of multi-pass and double pass over single pass are 7.05% and 14.18%, respectively, while 9.37% of the system energy enhancement that was contributed by sensible thermal matrix was achieved. The overall collector thermal performance was ranged between 28.4-59.96% depending on the utilization mode.

Fig. 4. Integrated energy profile of the solar dryer.
6. Conclusion

Measured and predicted analyses of solar dryer have been done in reference to the weather data of Seri Iskandar, Malaysia. The outcome has formed a database for further study on the tested facility and solar air heaters. The performance efficiency of the system collector was evaluated as 59.96% under forced convective mode. Sensible thermal mass improved the performance of the system by 9.37% when the maximum daily system inlet air velocity and environmental temperature were 0.63 ms\(^{-1}\) and 33.77\(^{\circ}\)C, respectively.

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