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Experimental investigation and evaluation of hybrid solar/thermal dryer combined with supplementary recovery dryer

Tadahmun A. Yassen *, Hussain H. Al-Kayiem

Mech. Eng. Dept., Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia

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A B S T R A C T

The common practice in the hybrid solar dryers which are backed up with thermal source is to exhaust the flue gas to the ambient. This flue gases are still hot and carry considerable amount of thermal energy as waste. In the present work, the thermal energy of flue gas from a biomass thermal backup unit was utilized in terms of heat recovery criteria. A prototype of hybrid solar-thermal drying system was coupled with recovery dryer to yield a combination of the main dryer and the recovery dryer. The combination was investigated experimentally to evaluate the enhanced performance compared to the system without recovery. The investigations were conducted under two operational modes, hybrid mode (day and night) and thermal mode alone (night). Red chili was utilized as drying material. The results of the thermal mode showed that the overall drying efficiency of the dryer was increased from 9.9% without recovery dryer to 12.9% with the recovery dryer. The overall drying efficiency of the hybrid drying without recovery dryer was 10.3%, while it was increased to overall drying efficiency of 13% in the case of using hybrid dryer and recovery. The enhancement of the overall drying efficiency due to the recovery dryer was 25.84% in the hybrid day and night drying, and was 29.7% in the night thermal drying mode. This validated enhancement encourages the use of sub dryer as thermal recovery to optimize the utilization of fuel, and to increase the system capacity.

1. Introduction

In many rural locations, grid-connected electricity and supplies of other non-renewable sources of energy are either unavailable, unreliable or, for many farmers, too expensive. Thus, in such areas, crop drying systems that employ motorized fans and/or electrical heating are inappropriate. The large initial and running costs of fossil fuel powered dryers present such barriers that they can rarely be adopted by small scale farmers. Solar energy has great potential for many low temperature applications, especially the drying of agricultural products (Singh and Kumar, 2012). The traditional open sun drying utilized widely by rural farmers has inherent limitations: high crop losses ensue from inadequate drying, fungal attacks, insects, birds and rodents encroachment, unexpected down pour of rain and other weathering effects. In such conditions, solar-energy crop dryers appear increasingly to be attractive as commercial propositions.

Various drying techniques are employed to dry different food products. Each technique has its own advantages and limitations. Choosing the right drying techniques is thus important in the process of drying of the perishable products. To reduce its dependence on solar radiation for operation and to improve the quality of drying, a biomass stove was incorporated with solar drier (Bena and Fuller, 2002; Tarigan and Tekasakul, 2005; Prasad and Vijay, 2005). It has extended the period of drying beyond sunshine hours, and perhaps during night as well, while drying high-value products. Biomass (especially fuel wood) is a dominant source of energy, and commonly is burned using inefficient technologies in most developing countries (Bena and Fuller, 2002; Kaygusuz and Türker, 2002).

Prasad and Vijay (2005) have investigated experimentally an integral type natural convection solar dryer coupled with a biomass stove. The design consists of single glazing (2 mm thickness) having an inclination of 28.58 Experiments have been conducted to test the performance of the dryer by drying of ginger, turmeric and Guduchi during the summer climate in Delhi. The dryer has three drying trays of perforated wire mesh base and drying area covered by each tray is 0.991 m^2. The biomass stove is having a dimension of 650 mm × 600 mm × 550 mm. The overall drying efficiency of the solar-biomass hybrid dryer for ginger drying was obtained as 15.59%. The efficiency of the dryer when using only biomass as the heat source was calculated to be 7.1%.

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* Corresponding author.
E-mail addresses: tadamun_77@yahoo.com (T.A. Yassen), hussain_kayiem@petronas.com.my (H.H. Al-Kayiem).

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An indirect type natural convection solar dryer with integrated collector-storage solar and biomass-backup heaters has been designed, constructed and evaluated by Madhlopa and Ngwalo (2007). The major components of the dryer are biomass burner (it is composed of drum, rectangular duct and flue gas chimney), collector- storage thermal mass and drying chamber (with a conventional solar chimney). The temperature inside dryer had been maintained at 41–56 °C. The overall drying efficiency of the solar-biomass hybrid dryer for drying fresh pineapples was obtained as 13%. The efficiency of the dryer when using only biomass as the heat source was calculated to be 11%.

Tarigan and Tekasakul (2005) have studied experimentally a mixed-mode natural convection solar collector with biomass burner and heat storage back-up heater. For back up heating system for the solar collector, a biomass burner with total dimension of 1750 mm × 900 mm × 1500 mm, was constructed from concrete as the wall, and filled up with bricks as heat storage. In the biomass burner, a free space of 750 mm × 500 mm × 1000 mm was occupied, including 2.5 mm extruded wall to outside of the burner, for space for burning fuels. They have utilizing 50 kg wood per night and temperature recorded in drying chamber was 65 °C. From a series of evaluation trials of the system, the capacity of the dryer was found to be 60–65 kg of unshelled fresh harvested groundnuts.

Bena and Fuller (2002) have investigated experimentally a hybrid drying system. The dryer consists of a direct-type natural convection solar drying cabinet mounted on top of a brick chamber that encloses a simple biomass burner. A dryer and a simple biomass burner have been combined to demonstrate a drying technology suitable for small-scale processors of dried fruits and vegetables in non-electrified areas of developing countries. The outside base dimensions of this dryer are 1.2 m by 1.2 m. There are three drying trays, all with a wire mesh base with area 3 m^2. The biomass burner, designed primarily for fuel wood, was constructed from a 0.2-m drum laid on its side. The exhaust air exits via a 0.09 m diameter 1.8 m long flue pipe. The volumetric flow rate of air exit from drying chamber was 0.025 $m^3\,s^{-1}$ at a maximum dryer temperature 65 °C. For evaluation of the system, the overall drying efficiency of the hybrid solar biomass mode for drying fresh pineapples was 8.6%. The overall efficiency for biomass mode of drying fresh pineapples was 6%.

A hybrid dryer system, which combines an unglazed transpired solar collector, rock bed, and a biomass gasifier stove with heat exchanger, was studied experimentally by Leon and Kumar (2008). The system was evaluated by drying chili using air at 60 °C and 90 m^3/h. The chili was dried from 76.7% moisture (w.b.) to 8.4% over 32.5 h of continuous drying. The dryer reduced the drying time by 66% compared to open sun drying and provided 91.6% load fraction during the 24-h operation. The temperature of hot air supplied was stable at 60 ± 3 °C for about 21 h during the entire drying time. The overall drying efficiency of drying chili was 11.06%.

A natural convection solar dryer coupled with a biomass thermal back-up heater was studied experimentally by Lokeswaran and Eswaramoorthy (2013). They found that to reduce the moisture content from 53.4% to 9.2% for drying coconut requires 26 h in a hybrid solar biomass mode, 30 h in biomass mode, 44 h in a solar mode and 88 h in open sun drying. López-Vidaña et al. (2013) have experimentally studied hybrid solar-gas dryer. The hybrid drying system comprises of solar air heater, drying chamber and gas burner. They found that the dryer temperature could be maintained between 55 and 65 °C using the gas burner.

It is obvious that the use of thermal backup to support the hybrid drying is leading to a considerable enhancement in the overall dryer efficiency, but there is considerable amount of thermal energy waste in the exhausted flue gases to the ambient. Madhlopa and Ngwalo (2007) have suggested recirculating the exhaust gases around the chimney of the dryer to avert reverse thermo-siphoning at night or during period of low insolation. Bena and Fuller (2002) suggested diverting of the exhaust gases through the drying chamber to utilize more of the heat losses. Both suggestions have not been justified or tested experimentally. It is not practical way utilize the flue gasses of the exhaust because through the period of burning the drying chamber is hot enough. There is no need to add the heat of flue gases.

The objective of the present work is to present a new drying enhancement idea in terms of thermal energy recovery from the hot flue exhaust gasses using additional recovery dryer. Hence, a thermal energy recovery unit was designed, fabricated and attached to the main hybrid dryer body. The enhancement of the performance in the new system was investigated experimentally using Chili as drying crop. The investigations were carried out in two different operational modes, namely, thermal mode alone (or night drying mode), and hybrid solar-thermal mode (or day and night drying mode).

2. Methodology

This section presents the system description, operational principal, experimental setup, and the measuring instrumentations. The system is a hybrid solar-thermal dryer consists of solar collector, drying chamber, thermal back-up unit, and a recovery dryer.

2.1. Hybrid solar thermal drying system description

The hybrid solar thermal drying system in the present work was constructed from a mixed mode natural convection solar dryer, natural convection thermal back-up unit, and recovery dryer. Zaman and Bala (1989) have reported that the mixed mode natural convection solar crop-dryer is potentially most effective and it appears to be particularly promising in tropical humid areas where climatic conditions favor sun drying of agricultural products. The natural convection solar dryer was constructed from single pass double flow solar air heater with the roughened absorber plate and drying chamber. The recovery dryer was a hybrid dryer constructed from a direct type natural convection solar dryer and rectangular duct. The thermal back-up unit comprises of gas-to-gas heat exchanger and fuel burner.

2.1.1. Solar collector

The solar collector of single pass double flow was fabricated from galvanized plate and aluminum angles. The gap between the cover and the absorber was set to 60 mm, and the gap between absorber and the back was set to 30 mm. The external dimensions of the solar collector are 1750 mm (length) × 1100 mm (width) × 140 mm (depth). The internal dimensions are 1750 mm (length) × 1000 mm (width) × 90 mm (depth). The solar collector insulated from back, left edge and right edge by a glass wool with a thickness of 50 mm. The absorber with artificial roughness was made of aluminum plate with gage of 1 mm and it is painted with a black color to increase the absorptivity. The artificial roughness of the absorber was pin shaped with base of 4 mm in diameter and 2 mm in height. The pines were arranged as a staggered shape. The dimension of the absorber was (1750 mm × 1000 mm). The solar collector tilt angle was 40 degrees from horizontal facing to the south. In the free convection solar air collector, Mathu and Mathur (2006) reported that the optimum inclination at any place varies from 40° to 60° depending on the latitude. Al-Kayiem and Yassen (2015) reported that the optimum inclination angle for free convection solar air heater was 50° compared with 30° and 70°.