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Comparison of solar dryer and solar-assisted heat pump dryer for cassava

M. Yahya[a,*], Ahmad Fudholi[b,*], Hadyan Hafizh[c], Kamaruzzaman Sopian[b]

[a] Fakultas Teknologi Industri, Institut Teknologi Padang, Indonesia
[b] Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[c] Department of Mechanical Engineering, City University College of Science and Technology, 46100 Petaling Jaya, Selangor, Malaysia

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A B S T R A C T

The performance of a solar dryer (SD) and a solar-assisted heat pump dryer (SAHPD) for drying of cassava chips have been investigated. The SD and SAHPD decreased the mass of cassava from 30.8 kg to 17.4 kg within 13 and 9 h at average temperatures of 40 °C and 45 °C, respectively. The moisture content of cassava decreased from 61% (wet basis) to 10.5%, with a mass flow rate of 0.124 kg/s. The average thermal efficiencies were 25.6% and 30.9% for SD and SAHPD respectively. The average drying rate (DR) and specific moisture extraction rate (SMER) were 1.33 kg/h and 0.38 kg/kW h, respectively, for SD as well as 1.93 kg/h and 0.47 kg/kW h, respectively, for SAHPD. The pick-up efficiencies varied from 3.9% to 65.8% and 15.9% to 70.4% for SD and SAHPD, with average values of 39.3% and 43.6%, respectively. The average solar fractions were 66.7% for SD and 44.6% for SAHPD. The coefficient of performance of the heat pump ranged from 3.23 to 3.47, with an average of 3.38.

1. Introduction

In Indonesia, cassava is the fourth important staple food after rice, maize, and soybean (Setyopratomo et al., 2009). This root crop is grown in all provinces in Indonesia, with Java and Sumatera as the main production areas (Saediman et al., 2015). Annual cassava production reaches approximately 26.7 million ton (AFSIS, 2015). Cassava contains high moisture (61%, wet basis) after harvesting and is therefore dried for long-term storage (Rahmi et al., 2008).

Drying, an energy-intensive process, is traditionally used to preserve food or biologically active products. Drying is primarily performed to decrease the moisture content of food to levels at which spoilage caused by various reactions is minimized (Szentmarjay et al., 1996). This process can also improve stability, decrease shipping mass and costs, and minimize packing requirements of food (Ruiz-Lopez et al., 2008).

Sun drying and artificial drying (using electric or fuel dryer) are commonly used in developing countries to dry food or biologically active products. Sun drying is a simple and inexpensive method but requires long drying times and generates products of low quality. Artificial drying using electricity or fuel consumes much energy and causes pollution.

Several studies used either a solar dryer (SD) or a heat pump dryer to overcome the limitations of sun and artificial drying. A SD is used as an alternative to sun drying because it generates good-quality products, requires short drying time, does not cause pollution, and consumes low energy. Various solar drying systems with air- and water-based solar collectors have been developed. The performances of solar dryer with air-based solar collectors are shown in Table 1 (Fudholi et al., 2015a,b). Many studies also reported the use of SD to dry agricultural and marine products; these products include palm oil fronds (Fudholi et al., 2015c), red chili (Fudholi et al., 2014a, 2013; Banout et al., 2011; Kaewkiew et al., 2012; Mohanraj and Chandrasekar, 2009; Hossain and Bala, 2007; Hossain et al., 2005), seaweed (Fudholi et al., 2014b), fish (Bala and Janjai, 2012, 2005; Bala and Mondal, 2001), banana (Janjai et al., 2009), cassava (Ghaba et al., 2007), green peas (Shanmugam and Natarajan, 2006), onion (Sarsavadia, 2007), cash crops (Purohit et al., 2006), herbs and spices (Yahya et al., 2009; Janjai et al., 2008; Janjai and Tung, 2005), and fruits and vegetable (Al-Juamily et al., 2007). However, drying cannot be continued or conducted during cloudy or rainy days and at night time because of the absence or low amount of sunlight.

A heat pump dryer is used as alternative to dry foods or biologically active products because it consumes less energy and does not cause pollution; this method also involves low relative humidity, low temperature, and good quality of product. A solar-assisted heat pump dryer (SAHPD) can also be used to dry foods or biologically

* Corresponding authors.
E-mail addresses: yahya_err@yahoo.com (M. Yahya), a.fudholi@gmail.com (A. Fudholi).

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Nomenclature

A_C	area of the collector (m^2)
C_{Pair}	specific heat of air (J kg^{-1} $°C^{-1}$)
COP	coefficient of performance
E_b	electrical energy consumed by the blower (kW)
E_{Comp}	electrical energy consumed by the compressor (kW)
E_{evap}	energy used for moisture evaporation (kW)
E_{input}	energy input to the drying system (kW)
$E_{R,Cond}$	thermal energy released by the condenser (kW)
E_s	energy incident in the plane of the solar collector (kW)
E_{Ucoll}	useful heat gain by the solar collector (kW)
H_{fg}	latent heat of vaporization of water (kJ/kg)
G	solar radiation incident on the collector (W/m^2)
I	current (A)
M_C	moisture content
M_f	final moisture content on wet basis (%)
M_i	initial moisture content on wet basis (%)
m_d	mass of the bone dry (kg)
m_p	initial mass of the product (kg)
m_W	mass of water (kg)
m_{water}	mass of water evaporated (kg)
$\dot{m}_{air}$	air mass flow rate (kg/s)
$\dot{m}_{da}$	mass flow rate of dry air ($kg_{dry\,air}$/s)
$\dot{m}_{water}$	drying rate (kg/s)
$T_{i,\,coll}$	air temperatures at the inlet (°C)
$T_{o,\,coll}$	outlet of the solar collector (°C)
$T_{i,cond}$	air temperatures at the inlet of the condenser (°C)
$T_{o,cond}$	temperatures at the outlet of the condenser (°C)
$T1$	dry bulk ambient temperature or evaporator dry bulk inlet air temperature of heat pump (°C)
$T2$	wet bulk ambient temperature or evaporator wet bulk inlet air temperature of heat pump (°C)
$T3$	evaporator dry bulk outlet air temperature of heat pump (°C)
$T4$	evaporator wet bulk outlet air temperature of heat pump (°C)
$T5$	condenser dry bulk inlet air temperature of heat pump (°C)
$T6$	condenser wet bulk inlet air temperature of heat pump (°C)
$T7$	condenser dry bulk outlet air temperature of heat pump (°C)
$T8$	condenser wet bulk outlet air temperature of heat pump (°C)
$T9$	solar collector inlet air temperature (dry bulk) (°C)
$T10$	solar collector outlet air temperature (dry bulk) (°C)
$T11$	drying chamber dry bulk inlet air temperature (°C)
$T12$	drying chamber wet bulk inlet air temperature (°C)
$T13$	drying chamber dry bulk outlet air temperature (°C)
$T14$	drying chamber wet bulk outlet air temperature (°C)
t	drying time (s)
SF	solar fractions
SMER	specific moisture extraction rate
V	voltage (V)
Y_{as}	adiabatic saturation humidity of air that enters the drying chamber (kg_{water}/kg_{dryair})
Y_i	absolute humidity of air that enters the drying chamber (kg_{water}/kg_{dryair})
$\cos\varphi$	power factor
η_{Pickup}	pick-up efficiency
η_{th}	thermal efficiency

active products to solve the limitations of existing drying methods. This dryer comprises a heat pump and a solar drying system. SAHPD consumes low energy and does not cause pollution. This dryer can also perform continuous drying operation, produces high-quality products, and increases the drying air temperature. Several studies used SAHPD to dry agricultural and marine (Goh et al., 2011; Daghigh et al., 2010). However, to our best knowledge, the performance of SAHPD for drying of cassava chips has not been reported yet, and the use of SD for drying of this root crop has been rarely investigated. Moreover, limited studies have compared solar drying with SAHPD. The objective of this study was performed to compare the experimental performance of SAHPD with SD for drying of cassava chips.

Table 1 Performances of a solar dryer (SD) with air-based solar collector (Fudholi et al., 2015a,b).

2. Materials and methods

The SAHPD consists of a solar collector array, heat pump, drying chamber, and blowers (Fig. 1). The solar collector consists of several main parts: a transparent cover glass material; absorbent finned plate made from aluminum and black-painted opaque; angular iron frame; inside and outside collector coated with 1 mm-thick aluminum; and insulation using fiber glass materials. Two solar collectors are connected in series with an area of 1.8 m^2 each. The heat pump consists of evaporator, condenser, compressor, and expansion valve. The compressor has an electrical capacity of 0.746 kW. The cabinet-type drying chamber has a dimension of 1.0 m (width) × 1.0 m (length) × 1.35 m (height). The chamber contains drying trays with adjustable racks to place the cassava sample. The triple-layer walls of the chamber consist of an aluminum sheet as outside layer, insulated glass fiber material as middle layer, and aluminum sheet as inner layer (Fig. 2). Drying air was circulated using a blower with an electrical capacity of 0.75 kW.

Experiments were performed at the Institut Teknologi Padang, West Sumatra, Indonesia. Freshly harvested cassava was obtained from Padang. The cassava roots were washed, peeled, and cut into 2–3 mm chips. The chips (approximately 30.8 kg) were placed into the drying chamber. The air temperatures at the inlet and outlet of the solar collector, heat pump, and drying chamber were measured using a thermocouple. Solar radiation was measured using a pyranometer, and air flow rate was determined using a flowmeter. Changes in the mass of cassava chips were measured using scales. Cassava chips were weighed every 1 h, and temperature was measured every 0.5 h.

The drying experiments were performed to evaluate the dryer performance under two different operating modes: SD and SAHPD. Heat pumps were not used for solar mode of operation (Fig. 3a). Solar collectors and heat pumps were employed for SAHPD (Fig. 3b).

T-type thermocouples with an accuracy of ±0.1 °C were used in the drying experiment to measure air temperature. Solar radiation during drying was measured with an LJ-200 pyranometer with ±0.1 W/m^2 accuracy. Air velocity was measured within 0–30 m/s by using an HT-383 anemometer, with an accuracy of ±0.2 m/s. Air temperature and solar radiation were recorded by an AH4000 data logger, with a reading accuracy of ±0.1 °C. The mass of the product was measured within 0–15 kg range by using a TKB-0.15 weighing scale, with an accuracy ±0.05 kg. An experimental uncer-