Solar Energy 174 (2018) 1058–1067

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Performance and economic analyses on solar-assisted heat pump fluidised bed dryer integrated with biomass furnace for rice drying

M. Yahya[a,*], Hendriwan Fahmi[a], Ahmad Fudholi[b,*], Kamaruzzaman Sopian[b]

[a] Fakultas Teknologi Industri, Institut Teknologi Padang, Indonesia
[b] Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

ARTICLE INFO

Keywords:
Heat pump
Fluidised bed
Solar and biomass energy

ABSTRACT

This study is concerned with the performance and economic analyses on solar-assisted heat pump fluidised bed dryer integrated with biomass furnace for rice drying. The dryer decreased the moisture content of rice from 32.85% (dry basis) to 16.29% (dry basis) in 22.95 min, with a mass flow rate of 0.1037 kg/s at an average temperature of 80.9 °C and average relative humidity of 8.14%. The specific moisture extraction rate varied from 0.13 kg/kWh to 0.40 kg/kWh, with an average value of 0.24 kg/kWh. The specific energy, specific thermal energy and specific electrical energy consumptions varied in the range of 2.50–2.62, 0.98–3.03 and 0.90–2.78 kWh/kg, with average values of 4.76, 1.86 and 1.71 kWh/kg, respectively. The thermal dryer, pickup and exergy efficiencies varied in the range of 8.4%–25.6%, 23.7%–73.4% and 13.6%–61.8%, with average values of 15.4%, 43.8% and 41.3%, respectively. Improvement potential varied from 223.3 W to 1391.2 W, with an average value of 630.6 W. The payback period of the dryer was approximately 1.6 years. Furthermore, the experimental dimensionless moisture content data fitted well with the Page's model.

1. Introduction

With the current trends towards scare and expensive fossil fuel, as well as the uncertainty regarding future cost and availability, the use of solar energy in drying of agricultural products will probably increase, and it may become highly economically feasible in the future. Solar energy is a major renewable energy source that can supply daily energy without polluting the environment. In addition, solar energy is vital to ensure the continuity of energy resources to satisfy the demands of human energy. Solar energy is also the ultimate heat energy that is most readily available. Nowadays, the use of solar energy has been developed for use in air or water heater systems, air conditioning systems, drying, hydrogen production and electricity because this energy is a natural renewable source and environmentally friendly. Hence, the advancement on active solar energy activation has begun, and it will continue to increase mainly in developing countries. Solar energy has been used to dry food, agricultural produce, marine products and herbs. Currently, the drying process is widely used in industries, such as fabric industry, paper industry and ceramics. Drying can be achieved either by direct sunlight or by using dryers (indirect drying). The use of direct sunlight, also known as open sun drying, is a traditional method of preserving agricultural products in tropical and subtropical countries. Considerable savings can be made with this type of drying because the energy source is free and sustainable. Traditional drying, which is low cost, can be performed easily. However, open sun drying suffers from many disadvantages, such as degradation by rain, storm, wind-blown debris, dust, insect infestation, rodents, human and animal interference which can contaminate the product. The drying time required for a given commodity can also be considerably long and result in post-harvest losses. Solar drying system is introduced to expedite the drying process. Solar drying system is much better than traditional drying. Solar drying systems offer several advantages as follows: (i) no need for a large area, (ii) nondependent on weather conditions, (iii) clean and guarantees the quality of commodities, (iv) high drying efficiency without damaging yield quality, (v) avoids the threat of insects and animals and (vi) controllable drying process (Nazri et al., 2018; Fudholi and Sopian, 2018a, 2018b, 2018c; Fudholi et al., 2018d, 2018e).

Indonesia is a tropical country and the third largest rice-producing country worldwide with its annual production of approximately 78 million tons (BPS, 2015). Rice after harvest normally contains high moisture (20%–25% wet basis) (Inprasit and Noomhorm, 2001). Therefore, to secure long-term storage, rice should be dried quickly to achieve a moisture content in the range of 12%–14% wet basis (Bonazzi et al., 1997). Fluidised bed dryer provides an alternative to the use of traditional sun drying and fixed bed dryer for rice drying. Fluidised bed dryer presents several advantages, such as low initial and maintenance

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

https://doi.org/10.1016/j.solener.2018.10.002
Received 27 May 2018; Received in revised form 5 September 2018; Accepted 1 October 2018
0038-092X/

Nomenclature

A_{SC}	area of the solar collector (m^2)
BF	biomass fraction (%)
C_C	capital cost (Rp)
C_p	production cost (Rp)
C_{Pair}	specific heat of air ($J\,kg^{-1}\,°C^{-1}$)
CV_{bmf}	caloric value of biomass fuel (kcal/kg)
COP_{hp}	coefficient of performance
E_{Bcyc}	electrical energy consumed by the blower of cyclone (W)
E_{Bfd}	electrical energy consumed by the blower of fluidized bed (W)
E_{bmf}	heat energy generated by the combustion of the biomass fuel (W)
E_{Comp}	electrical energy consumed by the compressor (W)
E_{Ubf}	useful heat by the biomass furnace (W)
E_{Uchp}	useful heat by the condenser of heat pump (W)
E_S	energy incident in the plane of the solar collector (W)
E_{Usc}	useful heat by the solar collector (W)
Ex_{dci}	exergy input to the drying chamber (J/s)
Ex_{dco}	exergy output to the drying chamber (J/s)
Ex_{loss}	exergy losses (J/s)
H_{fg}	laten heat of vaporization of water (kJ/kg)
I	current (A)
IP	improvement potential (W)
I_T	solar radiation incident in the solar collector (Wm^{-2})
MBE	mean bias error
M_e	equilibrium moisture content in dry basis (%)
$M_{wb,f}$	final moisture content in wet basis (%)
$M_{wb,i}$	initial moisture content in wet basis (%)
M_o	initial moisture content in dry basis (%)
M_t	moisture content at any time in dry basis (%)
$\dot{m}_{air}$	air mass flow rate (kg/s)
$\dot{m}_{bmf}$	biomass fuel consumption rate (kg/s)
$\dot{m}_{da}$	mass flow of dry air ($kg_{dry\ air}/s$)
M_{wb}	moisture content wet basis (%)
M_{db}	moisture content dry basis (%)
m_{dp}	mass of bone dry of the paddy (kg)
m_{wetp}	mass of wet paddy (kg)
$\dot{m}_{water}$	drying rate (kg/s)
m_{water}	mass of the water evaporated (kg)
MR	dimensionless moisture content
NPV	net present value
ROR	return of capital
PP	pay back period (Year)
PR	profit (Rp)
$T_{in,\,chp}$	condenser inlet air tempetarure (°C)
$T_{out,\,chp}$	condenser outlet air tempetarure (°C)
$T_{in,\,sc}$	solar collector inlet air tempetarure (°C)
$T_{out,sc}$	solar collector outlet air tempetarure (°C)
	biomass furnace inlet air tempetarure (°C)
$T_{out,\,bf}$	biomass furnace outlet air tempetarure (°C)
T_{dcai}	drying chamber inlet air temperature (°C)
T_{dcao}	drying chamber outlet air temperature (°C)
T	temperature (°C)
T_1	dry bulk ambient temperature or evaporator dry bulk inlet air temperature of heat pump (°C)
T_2	wet bulk ambient temperature or evaporator dry bulk inlet air temperature of heat pump (°C)
T_3	evaporator dry bulk outlet air temperature or condenser dry bulk inlet air temperature of heat pump (°C)
T_4	evaporator wet bulk outlet air temperature or condenser wet bulk inlet air temperature of heat pump (°C)
T_5	condenser dry bulk outlet air temperature of heat pump (°C)
T_6	condenser wet bulk outlet air temperature of heat pump (°C)
T_7	solar collector inlet air temperature (dry bulk) (°C)
T_8	solar collector outlet air temperature (dry bulk) (°C)
T_9	biomass furnace inlet air temperature (dry bulk) (°C)
T_{10}	biomass furnace outlet air temperature (dry bulk) (°C)
T_{11}	drying chamber dry bulk inlet air temperature (°C)
T_{12}	drying chamber wet bulk inlet air temperature (°C)
T_{13}	drying chamber dry bulk outlet air temperature (°C)
T_{14}	drying chamber wet bulk outlet air temperature (°C)
RMSE	root mean-square error
SEC	specific energy consumption (kWh/kg)
STEC	specific thermal energy consumption (kWh/kg)
SEEC	specific electrical energy consumption (kWh/kg)
SF	solar fraction (%)
SMER	specific moisture extraction rate (kg/kWh)
V	voltage (V)
Y_{as}	adiabatic saturation humidity of air ($kg_{water}/kg_{dry\ air}$)
Y_{in}	absolute humidity of air ($kg_{water}/kg_{dry\ air}$)
$\cos\varphi$	power factor
η_{BF}	thermal efficiency of the biomass furnace (%)
η_{Ex}	exergy efficiency for the drying chamber (%)
η_P	pick-up efficiency (%)
η_{SC}	thermal efficiency of the solar collector (%)
η_{th}	thermal efficiency of the drying system (%)

costs, high drying rate, uniform product moisture content and less drying time. Fluidised bed dryers are extensively used in drying high-moisture grains, such as rice, brown rice, wheat, soybean, maize (corn) and green peas. Fluidised bed dryer also offers advantages, such as uniform product moisture content, high drying rate, less drying time, easy material transport and low initial and maintenance costs (Sivakumar et al., 2016). Many studies have been reported on the use of fluidised bed dryers for drying of high-moisture grains, such as rice (Soponronnarit et al., 1995; Swasdisevi et al., 1997; Izadifar and Mowla, 2003; Karbassi and Mehdizadeh, 2008; Prachayawarakorn et al., 2009; Sarker et al., 2014a, 2015; Ibrahim et al., 2015; Sivakumar et al., 2016; Yahya et al., 2017), brown rice (Cheevitsopon and Noomhorm, 2011), wheat (Giner and De Michelis, 1988; Ozbey and Soylemez, 2005; Xiang et al., 2011; Assari et al., 2013), soybean (Soponronnarit et al., 2001; Prachayawarakorn et al., 2006; Meeso et al., 2011; Khoshtaghaza et al., 2013), corn (Doymaz and Pala, 2003; Syahrul et al., 2003), maize and green peas (Hatamipour and Mowla, 2003). However, most fluidised bed dryers, which are used to dry high-moisture grains, are types of hot air dryer. This type suffers from several disadvantages as follows. (1) Drying rate and drying time depend on the drying air temperature, that is, drying rate and decrease drying time can be increased by increasing the drying air temperature. High drying air temperature may cause cracking of the rice kernel which causes breakage during milling, thereby reducing head rice yield. (2) Most of the energy used to heat the drying air is fossil fuel. Fossil fuel sources are limited, and their prices are high and steadily increasing. These sources can also cause air pollution. (3) Energy consumption is high.

The combination of heat pump dryer with renewable energy (solar energy and biomass energy) provides a solution to the hot air dryer type or the current drying techniques. This combination also displays the following advantages: less energy consumption, abundant reserves, safety and good product quality. Many studies have been reported on the combined use of heat pump dryers and solar energy to dry agricultural products or biologically active products, such as using solar-assisted fluidised bed dryer integrated with a heat pump to dry mint leaves (Ceylan and Gurel, 2016) and solar-assisted heat pump dryer