Renewable Energy 63 (2014) 511–518

Contents lists available at ScienceDirect

Renewable Energy

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

Analysis of the heat transfer and airflow in solar chimney drying system with porous absorber

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ARTICLE INFO

Article history:
Received 21 March 2013
Accepted 1 October 2013
Available online

Keywords:
Porous absorber
Heat transfer and airflow
Solar chimney
Numerical analysis

ABSTRACT

In this paper, the chimney is assembled with porous absorber for the indirect-mode solar dryer. Local thermal non-equilibrium (LTNE) exists in the porous absorber, so the double energy equations and Brinkman–Forchheimer extended Darcy model are employed to analyze the heat transfer and flow in the solar porous absorber, and the k-ε turbulent model coupled with the above equations are also used to investigate the influences of the porous absorber inclination and the height of drying system on the heat transfer in the solar dryer. The specific heat capacities (ρc) and thermal conductivity k_s have remarkable effects on the average temperature of solar porous absorber in the drying system. The mean temperature of the higher (ρc) Aluminous solar absorber is lower and the top temperature of porous absorber delays due to lower thermal conductivity k_s. The inclined angle of porous absorber influences the airflow and temperature field in the solar dryer greatly. With the height of solar dryer changing from 1.41 m to 1.81 m, the higher airflow velocity and the lower temperature at chimney exit can be achieved. The simulations agree with the published experimental data. All these results should be taken into account for the promotion and application of the solar chimney dryer with porous absorber.

1. Introduction

Solar dryers used for food and crop drying are very useful devices. They not only save energy but also occupy less area, improve quality of the product, make the process more efficient, and also protect the environment. Solar drying can be used for the entire drying process reducing the total amount of fuel energy required. Natural convection solar crop dryers are normally reported to perform inefficiently [1,2]. This is attributed to poor ventilation, which results in excessively high temperatures in the drying chamber. The use of solar dryers with improperly designed airflow mechanism leads to the crops being partially cooked rather than dried. So far, the natural ventilation enhanced by chimney has been put into application in solar drying system. A chimney operates by increasing the buoyancy force to aid the airflow through a structure. This buoyancy force is directly proportional to the difference between the mean air density within the chimney and the density of outside air.

The solar dryers can be classified in three forms [3], based on their mode of operation. The indirect-mode dryer is equipped with a separate absorber to absorb solar irradiation and preheat the drying air [4]. The dryer has opaque drying-chamber walls, thus the dryer contents have no contact with irradiation. A new specific prototype of an indirect active hybrid solar–electrical dryer for agricultural products was constructed at LENREZA Laboratory, University of Ouargla (Algerian Sahara) by Boughali et al. [5]. An indirect type natural convection solar dryer was designed and the various storage materials were inserted under the absorber plate to improve the drying process, which were constructed and investigated experimentally by El-Sebaii et al., under Tanta prevailing weather conditions. It was also found that the storage and chemical pretreatment caused significant decrease in the drying time for all the investigated crops [6]. In the direct-mode dryer, the walls of drying chamber are transparent and the contents serve as the main absorber, and there is no air pre-heater. A direct-type natural convection solar dryer and a simple biomass burner were combined by Benon Bena and Fuller to demonstrate a drying technology suitable for small-scale processors of dried fruits and vegetables in non-electrified areas of developing countries [7]. A direct type natural convection solar dryer was designed, constructed using local materials (wood, blades of glass, and metals) and then tested experimentally in foodstuffs drying (cassava, bananas, and mango) by Gbaha et al. [8]. The mixed-mode dryer has a device for preheating the air and also transparent walls of chamber for

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http://dx.doi.org/10.1016/j.renene.2013.10.006

Nomenclature

a_{sf}	specific surface area, m^{-1}
c	specific heat,J kg^{-1} K^{-1}
c_1	constant for the turbulence model
c_2	constant for the turbulence model
c_μ	constant for the turbulence model
C	inertia coefficient, see Eq. (3)
d	diameter, m
D	diameter of chimney, m
f	friction coefficient
g	gravitational acceleration vector m s^{-2}
G_k	turbulence model coefficient
G_{sun}	rate of solar flux, W m^{-2}
h_{sf}	fluid-to-solid heat transfer coefficient, W m^{-2} K^{-1}
H	height of drying system, m
k	turbulence kinetic energy
K	permeability of porous media, m^2
$k_{eff,f}$	effective thermal conductivity of fluid, W m^{-1} K^{-1}
$k_{eff,s}$	effective thermal conductivity of solid, W m^{-1} K^{-1}
k_f	fluid thermal conductivity, W m^{-1} K^{-1}
K_i	local losses coefficient of chimney inlet
K_o	local losses coefficient of chimney outlet
k_s	solid thermal conductivity, W m^{-1} K^{-1}
L	Length of dryer wall from the inlet to outlet, m
P	pressure, Pa
Pr	Prandtl number
q_w	rate of solar flux absorbed by the absorber surface, W m^{-2}
q_f	heat transfer from the absorber surface to airflow, W m^{-2}
q_s	heat transfer from the absorber surface to porous solid matrix, W m^{-2}
S	source term
T	temperature, K
t	time, s
u	velocity component in x-direction, m s^{-1}
$\lvert\vec{v}_d\rvert$	mean velocity($=\sqrt{u_d^2+v_d^2}$) m s^{-1}
v	velocity component in y-direction, m s^{-1}
x	horizontal coordinate, m
y	vertical coordinate, m

Greek symbols

β	thermal expansion coefficient, K^{-1}
ε	dissipation rate of turbulent kinetic
σ_ε	constant for the turbulence model
σ_k	constant for the turbulence model
σ_T	constant for the turbulence model
μ	dynamic viscosity, kg (m s)$^{-1}$
μ_{efft}	effective dynamic viscosity for the turbulence model, kg (m s)$^{-1}$
ρ	density, kg m^{-3}
φ	porosity of the porous medium,
τ	transmittance
η	absorptivity

Subscripts

c	cold wall
d	Darcy
eff	effective property
f	fluid
i	inlet of dryer
o	outlet of dryer
p	porous
s	solid
t	turbulent
T	temperature

Superscripts

$\rightarrow$	vector

maximum radiant energy absorption. A mixed mode natural convection solar crop dryer was analyzed and experimental studied by Forson FK [9,10]. However, the large size of the air heater makes the mixed-mode dryer too expensive for the normal rural farmer in a developing country. A direct-mode dryer depends on the contents of the drying chamber for air heating and airflow. The air circulation is normally poor. Some reports on chimneys have also shown that properly designed chimneys can boost the flow of air through an enclosure [11–13]. Compared with flat plate absorber, the more interface area and higher coefficients of heat transfer can be achieved in the porous absorber while airflow passes through the absorber. As a result, more heat can be supplied for the drying chamber by the airflow and the heat flux in the absorber is dispersed rapidly. The uses of solar chimney in building to enhance natural ventilation and the porous absorber for solar collection have been studied by researchers [14,15].

The temperature, relative humidity and airflow velocity are the main influencing factors on the drying performance in the system. The temperature also affects the relative humidity of airflow. The relative humidity of airflow decreases with an increase in temperature under the same absolute humidity of airflow in dryer, which facilitates the drying process. In this paper, the chimney is assembled with solar porous absorber for the indirect-mode dryer. Due to the natural ventilation enhanced by the chimney with solar porous absorber, the temperature and the airflow velocity in the dryer influence each other. The drying chamber has different airflow and temperature fields with the change of chimney height and the inclined angle of porous absorber. There are great different characteristics of the solar collection and heat transfer within porous absorber while the absorber has various materials and porosities. So, the influences of the material, porosity, and inclination of absorber and the height of dryer on the performance of heat transfer and airflow within the drying system have been analyzed in this paper. The simulations agree with the published experimental data. All these results should be taken into account for the design and optimization of the solar chimney drying with porous absorber.

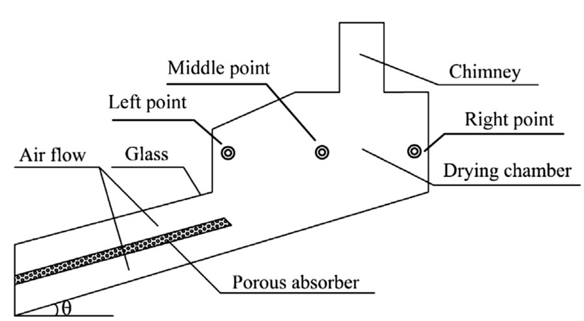

Fig. 1. Schematic diagram of solar chimney dryer with porous absorber.