Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 83 (2009) 1472–1484
SOLAR ENERGY
www.elsevier.com/locate/solener

Improvement in greenhouse solar drying using inclined north wall reflection

V.P. Sethi [a,*], Sadhna Arora [b]

[a] Department of Mechanical Engineering, Punjab Agricultural University, Ludhiana 141004, Punjab, India
[b] Department of Processing and Food Engineering, Punjab Agricultural University, Ludhiana 141004, Punjab, India

Received 16 September 2008; received in revised form 12 February 2009; accepted 7 April 2009
Available online 7 May 2009

Communicated by: Associate Editor I. Farkas

Abstract

A conventional greenhouse solar dryer of 6 m^2 × 4 m^2 floor area (east–west orientation) was improved for faster drying using inclined north wall reflection (INWR) under natural as well as forced convection mode. To increase the solar radiation availability onto the product (to be dried) during extreme summer months, a temporary inclined wall covered with aluminized reflector sheet (of 50 μm thickness and reflectance 0.93) was raised inside the greenhouse just in front of the vertical transparent north wall. By doing so, product fully received the reflected beam radiation (which otherwise leaves through the north wall) in addition to the direct total solar radiation available on the horizontal surface during different hours of drying. The increment in total solar radiation input enhanced the drying rate of the product by increasing the inside air and crop temperature of the dryer. Inclination angle of the reflective north wall with vertical (β) was optimized for various selective widths of the tray W (1.5, 2, 2.5 and 3 m) and for different realistic heights of existing vertical north wall (h) at 25°N, 30°N and 35°N latitudes (hot climatic zones). Experimental performance of the improved dryer was tested during the month of May 2008 at Ludhiana (30.56°N) climatic conditions, India by drying bitter gourd (*Momordica charantia Linn*) slices. Results showed that by using INWR under natural convection mode of drying, greenhouse air and crop temperature increased by 1–6.7 °C and 1–4 °C, respectively, during different drying hours as compared to, when INWR was not used and saved 13.13% of the total drying time. By using INWR under forced convection mode of drying, greenhouse air and crop temperature increased by 1–4.5 °C and 1–3 °C, respectively, during different drying hours as compared to, when INWR was not used and saved 16.67% of the total drying time.

Keywords: Crop drying; Solar dryer; Greenhouse dryer; North wall reflection; Natural convection; Forced convection

1. Introduction

Agricultural greenhouses are primarily used for increasing crop production during off-season. However, due to higher air temperature inside these greenhouses in hot climatic zones, these cannot be used for raising crops during extreme summer months and remain unused for about three months of May, June and July. During these months, this empty greenhouse can be used as a crop dryer (Condori and Saravia, 1998). This dual use of greenhouse for crop production and as a crop dryer improves its economic viability (Condori et al., 2001). Greenhouse drying has been practiced since more than two decades. Naturally ventilated greenhouses for drying applications have been reported in the past (Sadykov and Khairiddinov, 1982; Muthuveerapan et al., 1985). A solar tunnel dryer was used for drying grapes (Muhlbauer, 1983). It was reported that the dryer produced high quality dried grapes up to the desired moisture content level. In another study, a greenhouse type dryer for multi-crop solar drying was used in natural as well as forced convection mode for drying

* Corresponding author. Address: Department of Mechanical Engineering, Punjab Agricultural University, Ferozepur Road, Ludhiana 141004, Punjab, India. Tel.: +91 161 2502643.
E-mail address: vpsethi68@yahoo.co.in (V.P. Sethi).

0038-092X/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2009.04.001

Nomenclature

h	height of the existing vertical north wall, m
h_1	height of the inclined reflective north wall, m
h_2	extended length of the reflective north wall on both sides of the tray, m
I_g	global solar radiation intensity, W m^{-2}
I_{r1}	incident sun ray on the reflective north wall
M_{crop}	mass of crop sample, g
N	day of the year starting from January 1
R_{r1}	reflected sun ray from the reflective north wall
t_{solar}	local time of the day, h
T_{air}	temperature of air inside the greenhouse dryer, °C
$T_{ambient}$	temperature of ambient air, °C
T_{crop}	Surface temperature of crop sample, °C
V_a	velocity of air, m s^{-1}
w	gap between the vertical and inclined north walls, m
W	width of the drying tray, m

Greek letters

β	inclination angle of the reflective north wall with vertical, °
δt_{air}	air temperature difference between inside and outside the greenhouse dryer, °C
δt_{crop}	crop temperature difference between inside and outside the greenhouse dryer, °C
δm_{out}	moisture content of the crop sample placed in open sun, % db
δm_{in}	moisture content of the crop sample placed inside the greenhouse dryer, % db
δ	declination angle of the sun, °
θ_z	zenith angle of the sun, °
ϕ	north latitude angle of the location, °
ω	hour angle of the sun, °

bamboo (Ong, 1996). It was reported that the moisture content of bamboo could be brought down to about 19% wb from 90% wb in 17 days by operating the dryer over 8 h each day. However, under natural ventilation drying conditions, the final moisture content reached to only 22% wb. Similarly, a greenhouse solar dryer was used to dry vanilla pods (Abdullah and Mursalim, 1997). A fiber reinforced plastic (FRP) hybrid solar drying house was effectively used for brown rice drying (Rachmat et al., 1998). In another study, a greenhouse was used for alfalfa drying considering the differences in drying behavior between stems and leaves of alfalfa (Rachmat and Horible, 1999). A three-tier drying rack was used in a greenhouse type solar dryer for multi-tiered drying of mustard under natural as well as forced convection conditions (Manohar and Chandra, 2000). The performance of another solar tunnel dryer was also studied for drying pineapple slices (Bala et al., 2003). The proximate analysis indicated that the pineapple dried in a solar tunnel dryer was a good quality product for human consumption. Peas and cabbage were dried inside the greenhouse under natural and forced convection and mathematical models were also developed. The predictions of crop temperature, greenhouse room air temperature and rate of moisture evaporation were made on the basis of solar intensity and ambient temperature (Jain and Tiwari, 2004). In another study, a thermal model of a natural convection greenhouse drying for jaggery was also developed (Kumar and Tiwari, 2006). It was shown that analytical and experimental results matched well. Recently a mixed mode type forced convection solar tunnel dryer was developed to dry hot red and green chillies (Hossain and Bala, 2007).

Experiments inside a wind tunnel were conducted to study the drying of red pepper in open sun and greenhouse conditions (Kooli et al., 2007) where solar radiation was simulated by a 1000 W lamp. Effect of drying parameters on moisture content and drying time were determined. A simple drying model of red pepper related to water evaporation process was developed and verified.

A mathematical model for drying agricultural products in a mixed-mode natural convection solar crop dryer was presented (Forson et al., 2007). The governing equations of the drying air temperature and humidity ratio; the material temperature and its moisture content; and performance criteria indicators were derived. Results of simulation runs using the model were presented and compared with the experimental data. It was shown that the model could predict the performance fairly accurately.

Feasibility studies of a solar chimney to dry agricultural products were also performed (Ferreira et al., 2008). A prototype solar chimney was built. The constructed chimney generated a hot airflow with a yearly average rise in temperature (compared to the ambient air temperature) of 13 ± 1 °C. In the prototype, the yearly average mass flow was found to be 1.40 ± 0.08 kg/s, which allowed a drying capacity of approximately 440 kg.

It is known that inside a fully closed single polyethylene (PE) cover greenhouse (east–west orientation), air temperature rises about 12–16 °C above the ambient air temperature (38–42 °C) during the extreme summer months (Sethi, 2009). However, for lowering the inside moisture, side and top ventilators have to be opened in natural convection mode or an exhaust fan has to be used in forced convection mode. Due to the opening of ventilators, rise in the inside air temperature of the greenhouse is limited to about 10–12 °C (under natural convection mode). On the other hand, use of exhaust fans for expelling the inside hot and moist air further lowers the inside air temperature rise to only