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PERFORMANCE OF A FORCED CONVECTION SOLAR DRIER INTEGRATED WITH GRAVEL AS HEAT STORAGE MATERIAL FOR CHILI DRYING

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Abstract

An indirect forced convection solar drier integrated with different sensible heat storage maternal has been developed and tested its performance for drying chili under the metrological conditions of Pollachi, India. The system consists of a flat plate solar air heater with heat storage unit, a drying chamber and a centrifugal blower. Drying experiments have been performed at an air flow rate of 0.25 kg/s. Drying of chili in a forced convection solar drier reduces the moisture content from around 72.8% (wet basis) to the final moisture content about 9.1% in 24 h. Average drier efficiency was estimated to be about 21%. The specific moisture extraction rate was estimated to be about 0.87 kg/kWh.

Keywords: Solar drier, Chili drying, Heat storage materials.

1. Introduction

In India, sun drying is the most commonly used method to dry the agricultural materials like grains, fruits and vegetables. In sun drying, the crop is spread in a thin layer on the ground and exposed directly to solar radiation and other ambient conditions. The rate of drying depends on various parameters such as solar radiation, ambient temperature, wind velocity, relative humidity, initial moisture content, type of crops, crop absorptivity and mass of product per unit exposed area [1]. This form of drying has many drawbacks such as degradation by wind-

Nomenclatures

A	Cross section area of the pipe connecting the drying chamber, m^2
DR	Drying rate, kg of water/ kg of dry matter. h
h_{fg}	Latent heat of vaporization of water, kJ/kg
k	Drying constant
M_d	Final mass of the sample at any time , g
M_e	Equilibrium moisture content, %
M_o	Mass of the sample at t=0, g
M_t	Initial mass of the sample at any time , g
M_{wb}	Moisture content (wet basis), %
m_a	Mass flow rate of air, kg/s
m_w	Moisture evaporated in time t, kg/s
P_d	Blower power, kWh
R	Calculated parameter
$SMER$	Specific moisture ratio, kg/kWh
T_d	Drying air temperature, ^oC
$T_{fHS,}$	Final temperature of heat storage materials
T_i	Temperature of at solar air heater inlet, ^oC
T_{iHS}	Initial temperature of heat storage materials, ^oC
T_o	Temperature of at solar air heater outlet, ^oC
w_r	Total uncertainty
$x_1\ x_2.....x_n$	Independent variables
Greek Symbols	
η_{th}	Drier thermal efficiency, %

blown, debris, rain, insect infestation, human and animal interference that will result in contamination of the product. Drying rate will reduce due to intermittent sunshine, interruption and wetting by rain.

Solar driers using natural convection or forced circulation have been investigated to overcome these problems [2]. For commercial applications, the ability of the drier to process continuously throughout the day is very important to dry the products to its safe storage level and to maintain the quality. Normally thermal storage systems are employed to store thermal energy, which includes sensible heat storage, chemical energy storage and latent heat storage.

The solar drier is an energy efficient option in the drying processes [3]. Many experimental studies reported the various methods used for drying of agricultural materials using solar drier [4-6] for copra drying, for onion drying [7], and for pineapple drying [8]. Use of forced convection solar driers seems to be an advantage compared to traditional methods and improves the quality of the product considerably [9, 10]. Use of forced convection solar driers seems to be an advantage and improves the quality of the product considerably [11]. Normally thermal storage systems are employed to store the heat, which includes sensible and latent heat storage [12]. Common sensible heat storage materials used to store the sensible heat are water, gravel bed, sand, clay, concrete, etc. [13].

The objective of the present work is to develop a forced convection solar drier integrated with heat storage material for drying of chili under the metrological conditions of Pollachi, India. The experiments were conducted during the period from January 2008 to April 2008. The performance of a forced convection solar drier with gravel as heat storage material and drying characteristics of chili are discussed in this paper.

2. Materials and Methods

2.1. Experimental set-up

A schematic diagram of the forced convection solar drier is shown in Fig. 1 and its pictorial view in the Fig. 2. The solar drier consists of flat plate solar air heater of area (2×1) m^2 connected with drying chamber. The solar air heater has 2 mm thick copper absorber plate coated with black paint to absorb the incident solar radiation. The absorber plate is placed directly behind the transparent cover (glass) with a layer of air separating it from the cover. The air to be heated passes between the transparent cover (glass) and the absorber plate. To increase the temperature of air by green house effect, a glass cover of 5 mm thickness was placed. The gap between the glass and the absorber surface was maintained at 25 mm for air circulation. One side of the collector was connected to the blower with the help of reducer and the other side was attached with drier cabin. The 100-mm gap between the absorber and insulation was filled with sand mixed with aluminium scraps to store the heat during sunshine hours and to obtain hot air during off sunshine hours. The drying chamber is made up of mild steel sheet of 2 mm thickness with width, depth and height of (1×1×1.5) m respectively. The drier is capable of holding about 50 kg of chili per batch. The drying chamber was insulated with glass wool of 10 mm thickness. The solar air heater was tilted to an angle about 25^o with respect to horizontal [14]. The system is oriented to face south to maximize the solar radiation incident on the solar collector. On the basis of measurements, Pollachi (latitude of 10.39^o N, longitude of 77.03^{o}E), where the experiment was conducted had about 11 hours 30 min of sunshine, but potential sunshine duration was about 8 hours per day only.

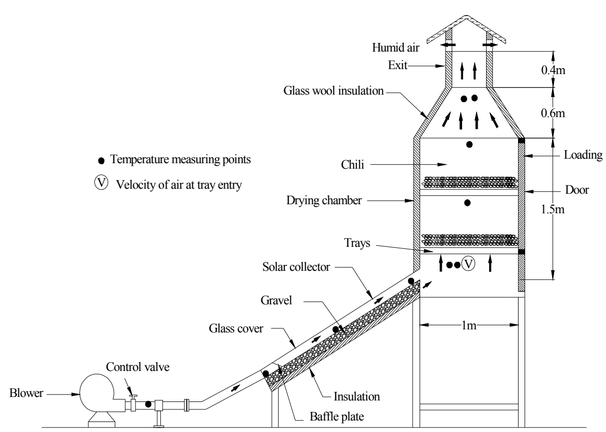

Fig. 1. Schematic View of Experimental Setup.

Eight pre calibrated RTD (Pt 100) temperature sensors with ± 0.5°C accuracy were fixed at different locations (as shown in Fig.1) of the solar drier are connected to a digital temperature indicator (having 0.1°C resolution) through a rotary switch. Energy consumption to the blower was measured with an energy meter having ± 0.5 kW.h accuracy. The solar intensity was measured using solar intensity meter having accuracy of about ± 10W/m^2. The humidity at entry and exit of the drier was measured with the help of humidity meter having accuracy of ±1%. The relative humidity of the ambient air was calculated from the measured wet and dry bulb temperatures using two mercury thermometers of sensitivity 0.5°C, one covered with wetted cloth. The velocity of air at inlet of the tray was measured with the help of vane type anemometer having ±0.01 m/s accuracy. A digital electronic balance of 1 kg capacity having an accuracy of ±0.01 g was used to weigh the samples.

Fig. 2. Pictorial View of Experimental Setup.

2.2. Experimental procedure

Only good quality chilies were used in the experiments. About 40 kg of fresh chilies were dried as whole fruits, without any chemical pre-treatment, until the required final moisture content was attained. The fresh chilies were loaded over the trays of drier chamber having about 90% perforation. The initial moisture content was calculated by taking five different samples. Then the air blower was switched on and the air flow rate through the solar flat plate collector was adjusted to 0.025 kg/s [15]. The velocity of air at inlet of the tray was measured with the help of vane type anemometer. Solar intensity was measured using solar intensity meter. During sunshine hours the air flow over the absorber plate gets heated and simultaneously the heat storage material (gravel) packed in the collector stores the heat energy. During off sunshine hours, the stored energy was used to heat the air. Temperatures at inlet and outlet of the solar collector and drying chamber were measured at every one-hour interval. The experiments with heat storage material were conducted for 8 h during potential sunshine hours and 4 h during lean or off sunshine hours. During idle conditions, the chilies were covered with polyethylene sheet to avoid deabsorption of moisture. All the experimental observations were made after the drier attains the steady state condition. The experiments were repeated thrice and an average value was considered. The drying characteristics of chilies such as moisture content, drying rate, specific moisture extraction rate and drier thermal efficiency were determined by using Eqs. (1) to (4), respectively.

2.3. Determination of moisture content

The quantity of moisture present in a material can be represented on wet basis and expressed as percentage. About 10 g samples were taken and kept in a convective electrical oven, which was maintained at 105±1°C until constant weight has reached. The initial and final mass, M_t, and final mass, M_d,of the samples were recorded with the help of electronic balance. The moisture content, M_{wb}, on wet basis was calculated by using Eq. (1). The procedure was repeated for every one hour interval till the end of drying.

$$M_{wb} = \frac{(M_t - M_d)}{M_t} \times 100 \tag{1}$$

2.4. Determination of drying rate

The drying rate, *DR*, should be proportional to the difference in moisture content between material to be dried and the equilibrium moisture content [16]. The concept of thin layer drying was assumed for the experiments as reported by Eq. (2).

$$DR = \frac{dM}{dt} = -k(M_t - M_e) \tag{2}$$

2.5. Determination of specific moisture extraction rate

The specific moisture extraction rate, which is the energy required for removing one kg of water. *SMER* was calculated using Eq. (3) as reported by Shanmugam and Natarajan [11]

$$SMER = \frac{m_d}{P_d} \tag{3}$$

2.6. Determination of drier thermal efficiency

The thermal efficiency of the solar air heater was estimated using Eq. (4) as reported by Shanmugam and Natarajan [11]

$$\eta_{th} = \frac{m_w h_{fg}}{m_a c_{pa}(T_o - T_i) + P_d + m_a c_{pa}(T_{iHS} - T_{fHS})} \times 100 \tag{4}$$

2.7. Uncertainty analysis

Detailed uncertainty analysis of the various calculated parameters are estimated according to Holman [17]. In the present study, temperatures, relative humidity, solar radiation, energy consumption and velocity were measured with instruments as mentioned in the previous section. The uncertainties arising in calculating a result due to several independent variables is given by the following equation

$$w_r = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots\ldots\ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \quad (6)$$

The total uncertainties for the calculated parameters such as moisture content, drying rate, specific moisture extraction rate and drier thermal efficiency are about 3.3, 3.1, 2.5 and 4.5% respectively.

3. Results and Discussions

The variations of temperature of air at solar collector outlet and ambient temperature for a typical day during drying of copra are shown in Fig. 3. The average drying air temperature recorded at inlet of the drier was about 50.4^{o}C. The maximum and minimum drying air temperatures recorded at the drier inlet were measured to be about 68 and 43^{o}C during peak and off sun sunshine hours respectively.

Figure 4 shows the variation of solar intensity and ambient relative humidity during experimentation. Maximum solar intensity recorded was about 950 W/m^2 during peak sunshine hours. The average dry and wet bulb temperatures recorded were 31^{o}C and 26^{o}C respectively. In the drying chamber outlet, a high relative humidity of about 78% was recorded during initial stages of drying and gradually reduced to about 36% at the end of drying.

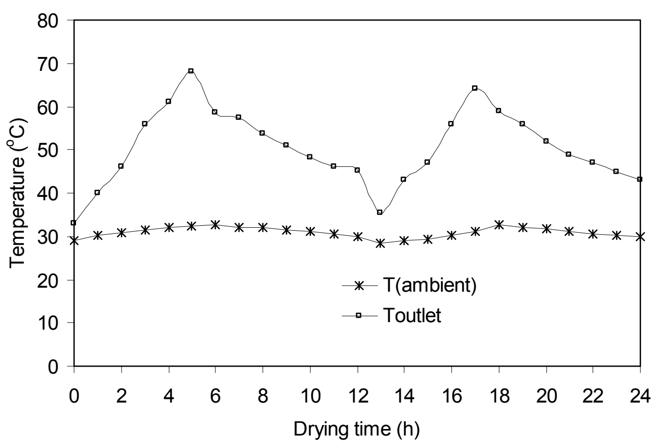

Fig. 3. Variation of Ambient and Drier Outlet Temperatures against Drying Time.

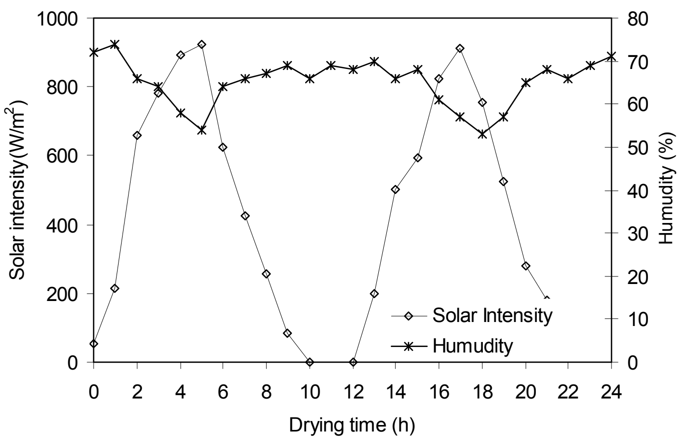

Fig. 4. Variation of Solar Intensity and Relative Humidity against Drying Time.

The variation of moisture content (wet basis) with drying time is illustrated in Fig. 5. The average moisture content of the chili was reduced from about 72.8% to 9.1% and 9.8% in bottom and top tray respectively after 24 h. The higher moisture reduction during the initial stages of drying was observed due to evaporation of free moisture from the outer surface layers and then gets reduced due to internal moisture migration from inner layers to the surface, which results in a process of uniform dehydration. The reduction in moisture content at bottom tray was about 4 to 6% higher than that of top tray.

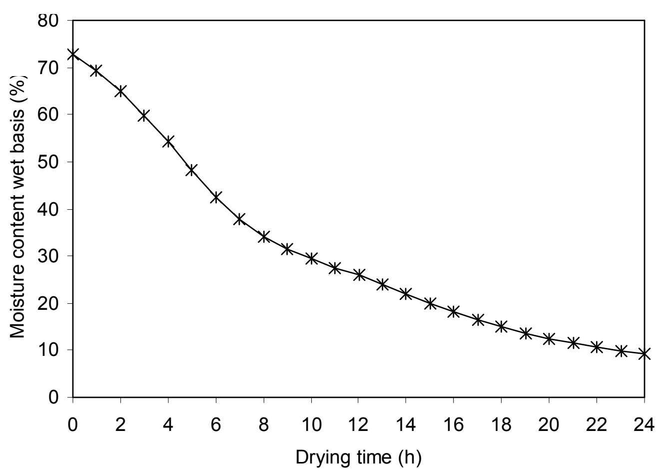

Fig. 5. Variation of Moisture Content against Drying Time.

Temperature inside drier was higher than ambient temperature and corresponding relative humidity in the drier was lower than ambient relative humidity. As a result, drying rate of chili in a force convection drier was found to be higher than that of open sun drying. Figure 6 shows the variation of drying rate against drying time. High drying rate (of about 6.2 kg/kg of dry matter h) was observed during the initial stages of drying. Drying rate gets decreased with increase in drying time. Drying occurs in the falling rate period with steep fall in moisture content in initial stages of drying and becomes very low in the later stages. The reason for sudden increase in drying rate during second day is due to increase in collector out let temperature. During off sunshine hours and nights, drier utilizes the heat stored in heat storage materials. Drying rate decreases due to decrease in collector outlet air temperature and gets increased due to increase in collector outlet air temperature.

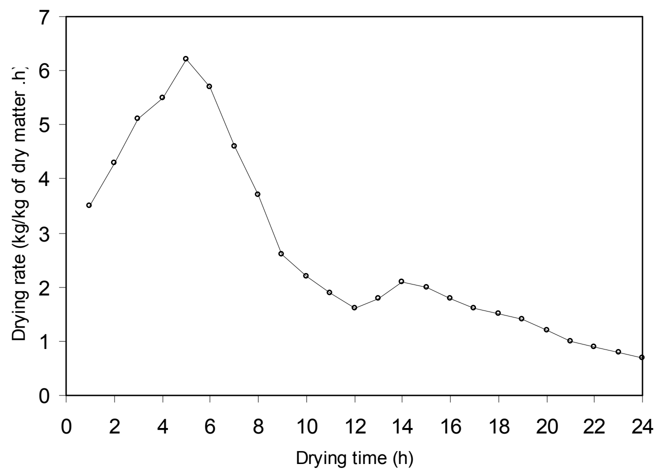

Fig. 6. Variation of Drying Rate against Drying Time.

The variation of humidity of air at the drier exit with drying time is shown in Fig. 7. It is observed that the humidity of the air at drier exit is higher during the initial stages of drying and gets decreased with drying time as drying proceeds and became constant in the final stage of drying. Maximum humidity of about 89% was observed during initial stages of drying and was gradually reduced to about 60% at the end of drying. This is because the higher drying rate of the chili during initial stage of drying results in release of more moisture in the drying air. The effect of decrease in air temperature at the drier inlet was also affecting the humidity of air at drier outlet. The specific moisture extraction rate was estimated to be about 0.87 kg/kWh by using Eq. (4). The average drier thermal efficiency was calculated to be about 21% using Eq. (5). The quality of the final dried chili was found to better compared to open sun drying. The use of heat storage material maintains consistent air temperature inside the drier even during fluctuations in solar intensity. The drying time can also be extended to 4 hours during off sunshine. Use of solar drier with the integration of heat storage materials will improves the efficiency of the drier and reduces the dependency of conventional energy sources, which reduces indirect global warming.

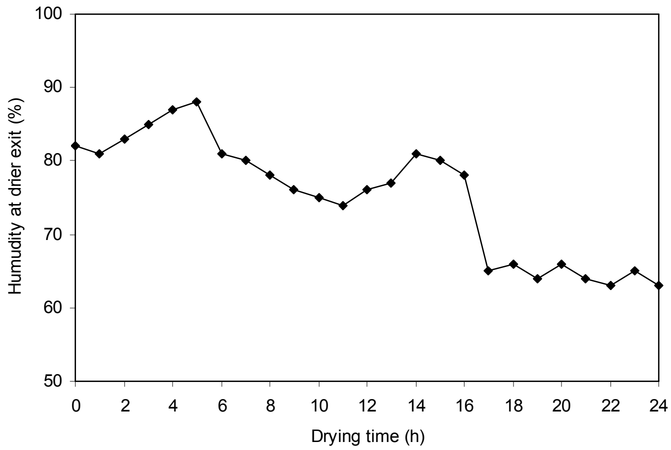

Fig. 7. Variation of Drying Rate against Drying Time.

4. Conclusions

The performance of an indirect forced convection solar drier integrated with heat storage material was designed, fabricated and investigated for chili drying. The drier with heat storage material enables to maintain consistent air temperature inside the drier. The inclusion of heat storage material also increases the drying time by about 4 h per day. The chili was dried from initial moisture content 72.8% to the final moisture content about 9.2% and 9.7% (wet basis) in the bottom and top trays respectively. It could be concluded that, forced convection solar drier is more suitable for producing high quality dried chili for small holders. Thermal efficiency of the solar drier was estimated to be about 21% with specific moisture extraction rate of about 0.87 kg/kW h.

References

1. Jain, D.; and Tiwari, G.N. (2003). Thermal aspects of open sun drying of various crops. *Energy,* 28(1), 37–54.
2. Ong, K.S. (1999). Solar dryers in the Asia-pacific region. *Renewable Energy*, 16 (1-4), 779-784.
3. Pangavhane, D.R.; and Sawhney, R.L. (2002). Review of research and development work on solar driers for grape drying. *Energy conversion and management*, 43 (1), 45 –61.
4. Mohanraj, M.; and Chandrasekar, P. (2009). Performance of a solar drier with and without heat storage material for copra drying. "Special issue on Recent trends in solar energy technology" *Int. J. of Global energy issues*, 32 (2), 112-121.
5. Mohanraj, M.; and Chandrasekar, P. (2008). Drying of copra in a forced convection solar drier. *Bio systems Engineering*, 99(4), 604-607.

6. Mohanraj, M.; and Chandrasekar, P. (2008). Comparison of drying characteristics and quality of copra obtained in a forced convection solar drier and sun drying. *Journal of Scientific and Industrial Research*, 67(5), 381-385.
7. Sarsavadia, P.N. (2007). Development of a solar-assisted dryer and evaluation of energy requirement for the drying of onion. *Renewable Energy,* 32(15), 2529–2547.
8. Jain, D.; and Jain, R.K. (2004). Performance evaluation of an inclined multi-pass solar air heater with in-built thermal storage on deep-bed drying application. *Journal of Food Engineering* 65(4), 497–597.
9. Sodha, M.S.; Dang, A.; Bansal, P. K.; and Sharma, S.B. (1985). An analytical and experimental study of open sun drying and a cabinet type dryer. *Energy Conversion Management,* 25 (3), 263-271.
10. Midilli, A. (2001). Determination of pistachio drying behavior and conditions in a solar drying system. *International Journal of Energy Research,* 25(8) 715-725.
11. Shanmugam, V.; and Natarajan, E. (2007). Experimental study of regenerative desiccant integrated solar dryer with and without reflective mirror. *Applied Thermal Engineering*, 27(8-9), 1543-1551.
12. Hawlader, M.N.A.; Uddin, M.S.; and Khin, M.M. (2003). Microencapsulated PCM thermal energy storage system. *Applied Energy*, 74 (I-2), 195-202.
13. Ahmad, A.; Saini, J.S.; and Varma, H.K. (1996). Thermohydraulic performance of packed bed solar air heaters. Energy conversion and Management 37 (2), 205-214.
14. Shariah, Adnan; Al-Akhras, M-Ali; and Al-Omari, I.A. (2002). Optimizing the tilt angle of solar collectors. *Renewable Energy* 26 (4), 587–598.
15. Hegazy, A.A. (1999). Optimum channel geometry for solar air heaters of conventional design and constant flow operation. *Energy Conversion and Management*, 40 (7) 754-774.
16. Ekechukwu, O.V. (1999). Review of solar energy drying systems 1: An overview drying principles and theory. *Energy Conversion and Management*, 40 (6), 593-613.
17. Holman J.P. (2007). Experimental methods for engineers (7^{th} Ed.). New Delhi: Tata Mcgraw hill Publishing Company.