Renewable Energy 105 (2017) 764–773

Contents lists available at ScienceDirect

Renewable Energy

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

Energy and exergy analyses of the solar drying processes of ghost chilli pepper and ginger

D.K. Rabha, P. Muthukumar*, C. Somayaji

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam, 781039, India

A R T I C L E I N F O

Article history:
Received 1 August 2016
Received in revised form
13 December 2016
Accepted 4 January 2017
Available online 7 January 2017

Keywords:
Solar drying
Energy
Exergy
Ghost chilli pepper
Ginger

A B S T R A C T

A forced convection solar tunnel dryer integrated with a shell and tube based latent heat storage module was designed and fabricated. Ghost chilli pepper and sliced ginger were successfully dried in the dryer in 42 h and 33 h in the drying air temperature range of 42–61 °C and 37–57 °C, respectively. Energy and exergy analyses of the drying processes of the two products were performed. The results showed that the thermal efficiencies of the first and the second solar air heaters varied between 22.10% and 40.24% and 9.64% and 19.50%, respectively. The average overall thermal efficiency of the air heaters array varied between 22.95% and 23.30%. The specific energy consumptions of the ghost chilli and the ginger were 18.72 kWh/kg and 8.82 kWh/kg, respectively. When the ghost chilli was dried, the exergy efficiency of the drying chamber was in the range of 21%–98% with an average of 63%, and it was 4%–96% with an average of 47%, while the ginger was dried. The exegetic efficiency increased with advancing in drying time, and high exergetic efficiency was recorded in the last few hours of the drying operation of the consecutive drying days.

1. Introduction

Drying is one of the widely used methods of food preservation, and it has been used by humankind around the world over several decades. It is a moisture removal process from the natural and industrial products to reach the standard safe storage moisture content [1]. It involves the application of heat to vaporise moisture. The heat energy requirement for the drying operation is met by burning fossil fuels, biomass, and also by solar energy. It is an energy intensive operation. The energy cost accounts for a major operational cost of the industrial dryers [2]. It is increasing day by day owing to continuous depletion of the fossil fuels resources and high prices of energy. In view of this, the available renewable energy sources have to be used efficiently and judiciously to reduce energy consumption as well as environmental impact without compromising the quality of dried products.

Solar energy is one of the widely used renewable energy sources in drying. It is used through solar thermal route and electrical route (solar photovoltaic). In spite of many disadvantages like contamination, longer drying time, difficult to control the drying process, losses of natural colours and minerals, losses of product due to insect and bird, large area requirement, high labour cost, etc., associated with the sun drying, it is widely practised in the rural areas for drying agricultural products. Solar drying can alleviate these shortcomings. It is an efficient way of utilising solar energy in which products are dried in an enclosed space at an elevated temperature thereby increasing the vapour pressure of the moisture content of the product sufficiently and decreasing the relative humidity of the drying air [3]. It is considered as a promising alternative to the traditional sun and industrial dryers for the sunny areas during the harvest seasons [4].

In this study, a solar dryer was developed, and the performance of the dryer was evaluated by energy and exergy analyses with an objective to improve its performance. Exergy analysis plays a vital rule in optimising drying conditions and improving the performance of drying systems. The energy analysis based on the first law of thermodynamics has some limitations. It determines only the quantity of energy required but it does not provide any information about the quality of energy and the direction of a thermodynamic process [5,6]. The exergy analysis provides more realistic views of a thermodynamic process. It determines the causes and magnitude of irreversibility in any thermodynamics process [7] and identifies the locations, causes, and sources of deviations of the actual process from the ideal one [8]. The energy and exergy efficiencies can be

* Corresponding author.
E-mail addresses: pmkumar@iitg.ernet.in, pmuthukkumar@yahoo.com (P. Muthukumar).

http://dx.doi.org/10.1016/j.renene.2017.01.007

improved by selecting optimum drying conditions and identifying the causes of inefficiency and accordingly, taking corrective measures.

The exergy analysis of the drying system helps in accounting losses of availability due to heat losses such as wall heat loss, heat loss with the exhaust, and heat loss with the product in the drying chamber. The performance of the drying system can be determined in more meaningful way by the exergy analysis compared to the energy analysis. The energy analysis identifies the wastage of energy in a drying system while the exergy analysis gives information about the potential for the utilisation of the energy.

One of the major energy losses in the drying chamber is the energy loss with the exhaust. This energy can be recovered to some extend if it is recirculated in the drying chamber. The simple energy analysis quantifies only the energy loss in the exhaust but it does not give any information whether the exhaust air can be recirculated or not. However, the exergy analysis gives information about the potential of the recirculation of the exhaust air since high exergy in the exhaust air for a fixed air flow rate and the product quantity indicates high exhaust air temperature. The exhaust of a drying chamber at high temperature has the potential for reutilisation in the drying system. Any energy form with high exergy is more useful than the energy form with low exergy. Therefore, it is essential to perform exergy analysis of a drying system.

A number of studies have been performed on the energy and exergy analyses of the solar drying process of agricultural products. Midilli et al. [9] presented energy and exergy analyses of the drying process of shelled and unshelled pistachios in an indirect-type forced convection solar dryer consisting of solar air heater of the area of 4.5 m^2 and a cross flow drying cabinet. They reported that the unshelled pistachios consumed more energy than the shelled pistachios. The exergetic efficiency increased with progressing of the drying time, and the maximum exergetic efficiency was obtained during the shelled pistachios drying. Celma and Cuadros [10] performed the energy and exergy analyses of the drying process of olive mill waste water in an indirect-type natural convection solar dryer consisting of a solar air heater and a cross flow drying cabinet. They observed that the exergetic efficiency of the drying chamber decreased with an increase in the dryer inlet air temperature and the drying time. More exergy losses took place in the second day of the drying period. The exergetic efficiency ranged from 53.24% to 100% and 34.4%–100% during the first and the second days, respectively. Akbulut and Durmus [11] presented energy and exergy analyses of the thin layer drying process of mulberry in an indirect-type forced convection solar dryer consisting of a solar air heater, a cross flow drying chamber, and a fan. The authors observed that the energy utilisation ratio and the exergy losses decreased with increase in the mass flow rate of air. Akpinar [12] investigated the thin layer drying kinetics of mint leaves dried in a forced convection solar dryer. The drying system consisted of a single cover solar air heater with finned absorber plate, a cross flow drying chamber, and a fan. The investigator also carried out energy and exergy analyses to investigate the performance of the dryer and observed that the exergetic efficiency of the drying cabinet varied between 34.76% and 87.71%. The exergetic efficiency increased with increasing drying time. Boukadoum et al. [13] dried mint leaves in a natural convection cabinet dryer consisting of a single cover heater and a cross flow drying cabinet and carried out energy and exergy analyses of the drying process of the mint leaves. They observed that most of the exergy losses occurred in the second day of drying. Chowdhury et al. [14] presented energy and exergy analyses of a mixed-mode type solar tunnel dryer consisting of a solar air heater connected in series with a transparent drying chamber. Jackfruit leather was dried in the dryer. The investigators reported that the energy efficiency of the heater and the drying chamber varied between 27.45% and 42.50% and 32.34% and 65.30%, respectively. The efficiency of the solar air heater varied linearly with the solar radiation. The exergy inflow and losses of the dryer depended on the solar radiation intensity and increased with increase in the solar radiation. Sami et al. [15] developed a mathematical model of an indirect-type forced convection solar cabinet dryer based on the energy and exergy analyses and performed parametric study. Fudholi et al. [16] developed and tested an indirect-type forced convection solar dryer integrated with an array of double-pass solar air heaters with finned absorber plate and an auxiliary heater, and cross flow drying cabinet by drying red seaweed, and evaluated the performance of the dryer by the energy and exergy analyses. The exergetic efficiency of the dryer was in the range of 1–93% with an average of 30%. Fudholi et al. [17] dried red chilli in the same dryer developed by Fudholi et al. [16] and investigated the performance of the drying system by conducting energy and exergy analyses. The average thermal efficiency of the solar heater was 28%. The average thermal and exergetic efficiencies of the drying chamber were 13% and 58%, respectively. Fudholi et al. [18] dried oil fronds in the same solar dryer used by Fudholi et al. [16] and performed the energy and exergy analyses. They observed that the efficiency of the solar heater was high at the low solar radiation intensity, and it varied between 9% and 48%. The exergetic efficiency was in the range of 10–73%.

In view of the above, one can conclude that there is no profound study on the energy and exergy analyses of the solar drying processes of the ghost chilli pepper and the sliced ginger dried in a forced convection solar dryer with a parallel flow drying chamber reported in the literature. Therefore, the main objective here is to perform the energy and exergy analyses of the drying process of the ghost chilli pepper and the sliced ginger dried in a newly developed forced convection solar tunnel dryer.

2. Materials and description of the experimental layout

2.1. Materials

North Eastern Region (NER) of India comprising the states of Assam, Arunachal Pradesh, Mizoram, Meghalaya, Manipur, Sikkim, and Tripura produces variety of high value organic spices such as large cardamom, ginger, turmeric, chillies, black, pepper, etc. The climatic condition of this region is characterised by frequent rainfall, high relative humidity, and the low annual average solar radiation (4.5 W/m^2). The ghost chilli pepper, one of the hottest chilli peppers in the world, is grown only in this region. It has a very high heat level of 855,000 Scoville heat units. It was rated as the world's hottest chilli in the Guinness World Records in 2007 [19,20]. The ghost chilli pepper (Capsicum Chinense Jacq.) is locally known as the Bhut Jolokia or Naga Jolokia [21]. The hilly regions of the NER with subtropical climate are suitable for growing wide varieties of gingers. The ghost chilli and the ginger were selected for carrying out the drying experiments as there was no study reported in these items.

2.2. Description of the experimental layout

The prototype of the newly developed solar dryer is an indirect-type forced convection solar tunnel dryer. It consists of a parallel flow tunnel dryer, two solar air heaters, a shell and tube based energy storage, and a blower. The schematic of the drying system is shown in Fig. 1(a). Two double pass-type solar air heaters of the same size (2.04 m × 1.04 m) and structure are connected in series and oriented towards the south at the local latitude of 26.18° for supplying the hot air to the drying chamber. The ambient air first passes through the solar air heater-1 (SAH-1) and is heated up to a