Ashdin Publishing
Journal of Fundamentals of Renewable Energy and Applications
Vol. 2 (2012), Article ID R120302, 5 pages
doi:10.4303/jfrea/R120302

Review Article

Solar Drying Technology: Potentials and Developments*

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Received 26 February 2012; Accepted 6 March 2012

Abstract This paper presents developments and potentials of solar drying technologies for drying of fruits, vegetables, spices, medicinal plants, and fish. Previous efforts on solar drying and recent developments of different types of solar dryers for drying of cereal grains, fruits, vegetables, spices, medicinal plants, and fish in the rural areas of the tropics and subtropics are critically examined in terms of drying performances and product quality, and economics. Experimental performances of different types of solar dryers which have demonstrated their potentialities for drying of fruits, vegetables, spices, medicinal plants, and fish in the tropics and subtropics are addressed. Simulated performances of solar tunnel dryer were assessed for drying fruits, vegetables, spices, medicinal plants, and fish. The agreement between the simulated and experimental results was very good. Energy and exergy analyses of solar drying of jackfruit leather in a solar tunnel dryer are also presented. A multilayer neural network approach to predict the performance of the solar tunnel dryer is presented. The prediction of the performance of the dryer was found to be excellent after it was adequately trained. Finally, prospects of solar dryers for drying of fruits, vegetables, spices, medicinal plants, and fish in the tropics and subtropics are discussed.

Keywords solar dryers; experimental and simulated results; drying efficiency; exergy; neural network

1 Introduction

Solar drying can be considered as an elaboration of sun drying and it is an efficient system of utilizing solar energy [2,3,22]. The tropics and subtropics have abundant solar radiation. Hence, the obvious option for drying would be the natural convection solar dryers. Many studies on natural convection solar drying of agricultural products have been reported [7,8,11,16,18]. These dryers have been widely tested in the tropical and subtropical countries. Considerable studies on simulation and optimization have also been reported [7,8,19]. The success achieved by indirect natural convection solar dryers has been limited, the drying rates achieved to date not having been very satisfactory [17]. Furthermore, natural convection dryers are not suitable for a small-scale industrial production of fruits, vegetables, spices, fish, and medicinal and herbal plants. These prompted researchers to develop forced convection solar dryers. These dryers are (i) solar tunnel dryer, (ii) indirect forced convection solar dryer, (iii) greenhouse-type solar dryer, (iv) roof integrated solar dryer, and (v) solar assisted dryer. Numerous tests in the different regions of the tropics and subtropics have shown that fruits, vegetables, cereals, grain, legumes, oil seeds, spices, fish, and even meat can be dried properly in the solar tunnel dryer [5, 6,10,15]. The purpose of this paper is to present (i) the developments and potentials of solar drying technologies for drying fruits, vegetables, spices, medicinal plants, and fish, (ii) the experimental performances of the solar dryers for drying of fruits, vegetables, spices, medicinal plants, and fish, (iii) simulated performances of solar tunnel dryer for drying of chilli, (iv) energy and exergy analysis of solar drying of jackfruit leather, and (v) neural network prediction of the performance of the solar tunnel dryer for drying of jackfruit and jackfruit leather.

*This article is a part of a Special Issue on the International Conference on Energy Security, Global Warming and Sustainable Climate (SOLARIS 2012).

2 Solar drying systems

Different types of solar dryers have been designed, developed, and tested in the different regions of the tropics and subtropics. The major two categories of the dryers are natural convection solar dryers and forced convection solar dryers. In the natural convection solar dryers the airflow is established by buoyancy induced airflow while in forced convection solar dryers the airflow is provided by using a fan either operated by electricity/solar module or fossil fuel.

2.1 Natural convection solar drying

Natural convection solar drying has advantages over forced convection solar drying, one of which is that it requires a lower investment. Due to low cost and simple operation

Figure 1: Solar tunnel dryer.

and maintenance, natural convection solar dryer appears to be the obvious option and popular choice for drying of agricultural products. Natural convection solar dryer can be classified as follows: (i) indirect natural convection solar dryer, (ii) direct natural convection solar dryer, and (iii) mixed mode natural convection solar dryer.

Indirect natural convection solar dryer consists of a separate solar collector with a transparent cover on the top and a drying unit with an opaque cover on the top. These are connected in series. In such a dryer, the crop is contained within a cabinet in a relatively thin bed, air flows as a result of the buoyancy forces resulting from the temperature differences up through the crop bed. The drying rates achieved to date with these dryers have not, generally, been very satisfactory. Many attempts to develop such indirect free or natural convective solar crop dryers have been made [7, 8, 20]. Bala and Woods [7] reported a mathematical model to simulate the indirect natural convection solar drying of rough rice and Bala and Woods [8] also developed a technique for optimization of natural convection solar dryers.

Direct-type solar dryer called cabinet-type solar dryer is essentially a solar hot box, in which the desired product can be dried on a small scale. It consists of a quadrilateral-shaped cabinet, trays for the product and single layered transparent plastic/glass at the top. Holes are drilled through the base to permit fresh ventilating air entry into the cabinet. Outlet posts are located on the upper parts of the cabinet side and rear panels. The capacity of the dryer is 30 kg to 50 kg per batch. It is concluded that the cabinet-type dryer may be useful for domestic applications for drying fruits and vegetables in developing countries [18]. An extensive study has been conducted on solar drying of agricultural products using cabinet/box-type and tent-type solar dryers [21]. Sodha et al. [21] developed an analytical model for predicting temperature and moisture content during drying of fruits in cabinet/box-type solar dryer.

The mixed-mode solar dryer consists of a separate solar collector and a drying unit, both having a transparent cover on the top. The dryer is composed of 3 main components, namely, the solar collector, the product box, and the chimney. The solar collector consists of a matt-black substance spread on the ground and provided with transparent top and side covers. Although the mixed mode dryer produced quality dried product, this dryer is not in use in Bangladesh and even in the tropics and subtropics. Many studies have been made to develop mixed solar dryer [19]. The basic concepts involved in modeling of such dryers are discussed by Simate [19] and the computer simulation model is combined with the cost of the dryer materials and a search technique to find the optimal dimensions of such dryers. This model is based on the concept of optimal design of solar dryers developed by Bala and Woods [8].

2.2 Forced convection solar drying

The success achieved by the indirect natural convection solar dryer has been very limited due to low buoyancy induced air flow rate. Therefore, adding a small fan powered by a photovoltaic system to provide the required air flow will give drying rates much higher than those achieved by an indirect natural convection solar dryer. The required air flow can be supplied by using fan either operated by electricity/solar module or fossil fuel. The PV operated system has the advantage that it can be operated independent of electrical grid. Such dryers can be used to dry fruits, vegetables, spices, and even fish for a small-scale industrial production of quality dried products. Several versions of PV ventilated forced convection solar dryers have been developed such as (i) solar tunnel dryer with plastic cover, (ii) solar tunnel dryer with polycarbonate cover, (iii) greenhouse solar dryer, and (iv) roof integrated solar dryer. Solar tunnel dryer and greenhouse solar dryer which have demonstrated their potentialities for small-scale agro-industrial applications are discussed below.

Solar tunnel dryer

Solar tunnel was developed at the University of Hohenheim, Germany and it consists of a flat plate air heating collector and a tunnel drying with a small fan to provide the required air flow over the product to be dried. The collector and the drying unit are covered with UV stabilized plastic sheet and these are connected in a series as shown in Figure 1. Solar tunnel dryer can be operated by one 40 Watt photovoltaic module independent of electrical grid. The photovoltaic system has the advantage that temperature of the drying air could be automatically controlled by the solar radiation.

Greenhouse solar dryer

A PV-ventilated greenhouse solar dryer was developed at Silpakorn University [13]. The dryer essentially consists of a parabolic-shape greenhouse with a black concrete floor

Figure 2: Greenhouse-type solar dryer with polycarbonate sheet.

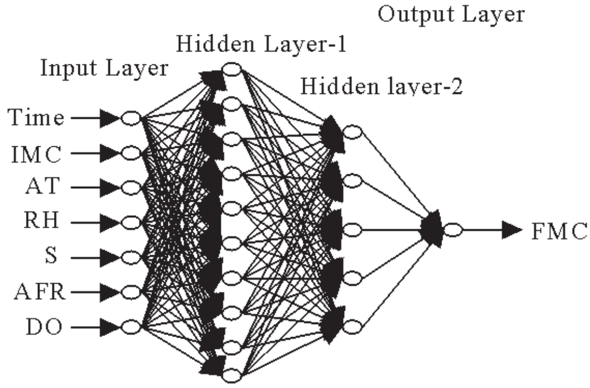

Figure 3: The structure of the ANN solar tunnel dryer model for drying jackfruit bulb and jackfruit leather.

with an area of $5.5 \times 8.0\,\mathrm{m}^2$ (Figure 2). The parabolic cross-sectional shape helps to reduce the wind load in case of tropical rain storms. The structure of the dryer is made of galvanized iron bars. The roof of the dryer is covered with polycarbonate plates. The products to be dried are placed in a thin layer on two arrays of trays. These arrays of trays are placed on single-level raised platforms with a passage at the middle for loading and unloading the products inside the dryer. Three fans powered by a solar cell module of 50 W were installed in the wall opposite to the air inlet to ventilate the dryer. With this PV model, the dryer can be used in the rural areas without access to electrical grids.

3 Experimental and simulated studies

Large-scale field level studies were conducted at Bangladesh Agricultural University, Mymensingh, Bangladesh and Silpakorn University at Nakhon Pathom, Thailand to demonstrate the potentiality of the solar dryers for production of high quality solar dried fruits, vegetables, spices, medicinal plants, and fish. Packages of technology for solar drying of fruits, vegetables, spices, medicinal plants, and fish have also been developed at Bangladesh Agricultural University, Mymensingh, Bangladesh.

Mathematical models are useful for predicting performance and optimal designs of solar drying systems. The fundamentals of heat and mass transfer during drying are given in Bala [2]. The details of heat and mass transfer during drying of chilli in a solar tunnel dryer, roof integrated solar dryer, and greenhouse solar dryer are given by Hossain [12] and Janjai et al. [13, 14], respectively.

4 Energy and exergy analysis

The overall drying efficiency is defined as the ratio of energy output of the dryer to the total energy input. Thus, overall efficiency of the system is

$$\mathrm{Efficiency}_{\mathrm{overall}} = \frac{\mathrm{Output}_{\mathrm{dryer}}}{\mathrm{IA}_{\mathrm{collector}} + \mathrm{IA}_{\mathrm{module}} + \mathrm{IA}_{\mathrm{dryer}}}. \tag{1}$$

The second law of thermodynamics introduces the useful concept of exergy in the analysis of thermal systems. Exergy analysis evaluates the available energy at different points in a system. Based on the second law of thermodynamics, total exergy inflow, outflow, and losses of the drying systems are estimated. The exergetic efficiency of collector can be defined as the ratio of the product exergy to exergy inflow for the drying chamber as follows:

$$\text{Exergetic efficiency} = \frac{\text{Exergy inflow} - \text{Exergy loss}}{\text{Exergy inflow}}. \tag{2}$$

Exergetic efficiency for the dryer can be calculated as follows:

$$\text{Exergetic efficiency} = 1 - \frac{\text{Exergy loss}}{\text{Exergy input}}. \tag{3}$$

The details of the computation of energy and exergy are given by Choudhury et al. [9].

5 Neural network computing

The neuro-computing techniques are shaped after biological neural functions and structures. In such a modeling approach, there is no need to formulate an analytical description of the process. Instead, a black-box process model is constructed by interacting the network with representative samples of measurable quantities that characterize the process. An independent multilayer ANN model of solar tunnel dryer has been developed to represent the drying system of jackfruit bulb and jackfruit leather [4]. Network of both models is 4-layered and has a large number of simple processing elements, called neurons. The input layer of the model consists of seven neurons which correspond to the seven input variables, and the output layer has one neuron, which represents the final moisture content (FMC) in the model (Figure 3). The ANN dryer models are trained by backpropagation algorithm so that application of a set of input would produce the desired set of output.

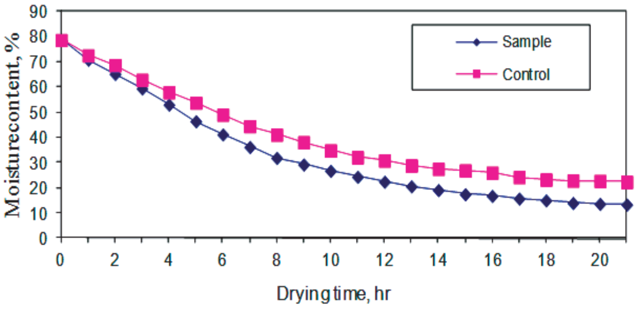

Figure 4: Variations of moisture content with time during solar drying of mango.

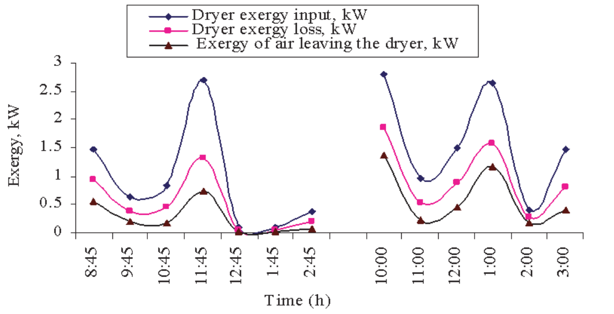

Figure 6: Variations of dryer exergy input, exergy loss, and exergy outflow from the dryer.

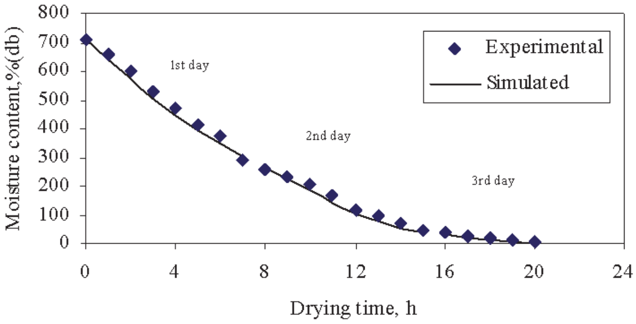

Figure 5: Experimental and simulated moisture content during drying of green chilli.

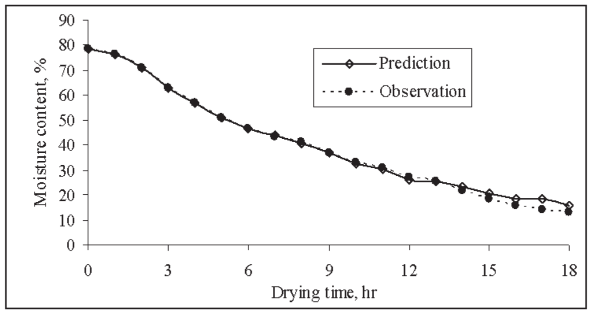

Figure 7: Variation of predicted and observed moisture content of jackfruit leather with drying time.

6 Results

Experimental results

Comparison of the moisture contents of mango dried in the solar tunnel dryer with those obtained by the traditional method of drying for a typical experimental run at Chapai Nawabganj, Bangladesh is shown in Figure 4. The solar tunnel drying required 3 days to dry mango samples from 78.87% (WB) to 13.47% as compared to 78.87% to 22.48% in 3 days.

Simulated results

The mathematical model developed was validated against the experimental data of chilli in Bangladesh. Figure 5 shows the experimental and simulated moisture content during solar drying of green chilli in a solar tunnel dryer.

Energy and exergy analysis

The overall efficiency of the solar tunnel dryer was within the range of 39.18% to 48.13% while the overall efficiency for natural convection solar dryer was within the range of 12% to 18% [1]. The variations in dryer exergy input, exergy loss, and exergy of outflow from the dryer with drying time are shown in Figure 6. Exergy input, exergy loss, and exergy outflow follow similar patterns. The exergetic efficiency of collector varies between 32% to 69% and the mean value of exergetic efficiency of dryer was 41.42%.

Neural network prediction

Comparison between the observed and neural network prediction of the performance of solar tunnel dryer for drying of jackfruit leather is shown in Figure 7. The agreement between the predicted and observed moisture contents is very good.

7 Discussion and/or conclusions

In all the cases, the use of solar dryer leads to a considerable reduction of drying time in comparison to the sun drying, and the quality of the product dried in the solar dryer was of quality dried products as compared to sun dried products. The agreement between the experimental and simulated moisture contents was found to be good.

The overall higher efficiency of the solar tunnel dryer compared to natural convection solar dryer was due to the fact that the solar tunnel dryer operated as a forced convection solar dryer and the drying unit received energy from both the collector and incident radiation. The variations in exergy input, exergy loss, and exergy outflow of the dryer resulted from the variations in daily solar radiation. On an average of 50.50% and 58.58% of the available energy are wasted in the collector and dryer, respectively. Hence there is significant potentials to optimize the solar drying systems to increase actual efficiency and reduce the exergy losses. The neural network prediction of the model has been found very good. If the neural network model is adequately trained, it can appropriately represent the solar tunnel drying system very well.

Field-level tests demonstrated that PV ventilated solar dryers are appropriate for production of quality dried fruits, vegetables, spices, and fish. The photovoltaic system has the advantage that the temperature of the drying air is automatically controlled by the solar radiation.

The solar dryer can be operated by a photovoltaic module independent of electrical grid. The photovoltaic driven solar dryers must be optimized for efficient operation.

Exergy is a measure of quality of energy and it can clearly take into account the loss of availability of heat in the solar drying systems. Therefore, exergy analysis should be used to design solar drying systems with the highest possible thermodynamic efficiencies.

Neural network model can be used to predict the potential of the dryer for different locations and can also be used in a predictive optimal control algorithm.

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