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Experimental investigation of an indirect-mode forced convection solar dryer for drying thymus and mint

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ABSTRACT

An indirect-mode forced convection solar dryer was designed and fabricated. The thermal performance of the solar dryer under Tanta (latitude, 30° 47′ N and longitude, 31° E) prevailing weather conditions was experimentally investigated. The system consists of a double pass v-corrugated plate solar air heater connected to a drying chamber. A blower was used to force the heated air to the drying chamber. Drying experiments were performed for thymus (initial moisture content 95% on wet basis) and mint (initial moisture content 85% on wet basis) at an initial temperature of 29 °C. The final moisture contents for thymus and mint were reached after 34 and 5 h, respectively. Fourteen mathematical models of thin layer drying were tested to specify the suitable model for describing the drying behavior of the studied products. It was found that, Midilli and Kucuk model is convenient to describe the thin layer solar drying of mint. However, the Page and modified Page models were found to be the best among others for describing the drying curves of thymus.

1. Introduction

Solar dryers were classified as direct solar dryers, indirect solar dryers, mixed mode and hybrid solar dryers. Solar drying systems were also categorized into two general groups: natural and forced convection solar dryers. The indirect-mode forced convection solar dryer (IMFCSD) essentially consists of an air heater, drying chamber and a blower to duct the heated air into the drying chamber. Many designs of indirect-mode forced convection solar dryers had been fabricated in order to improve the thermal performance of solar dryers. Al-Juamily et al. [1] constructed and tested an indirect-mode forced convection solar dryer for drying fruits and vegetables in Iraq. The solar dryer consisted of two identical double pass solar air collectors with single glass cover and an air blower was used to duct the air inside the solar drying cabinet. A solar drying system employing a V-grooved solar collector was also developed and tested by Kadam and Samuel [2] for drying cauliflower. Karim and Hawlader [3] investigated the V-grooved, fins and flat-plate solar collectors for crop drying applications. The reported results indicated that the efficiency of the V-grooved collector is 7–12% higher than that of flat-plate collectors. The thermodynamic performance of a solar dryer with an evacuated tube collector was studied by Lamnatou et al. [4]. They used their dryer for drying apples, carrots and apricots. They concluded that the evacuated tube collector is suitable for solar drying applications without preheating the outlet air. Banout et al. [5] introduced a new design of the double-pass solar dryer (DPSD) for drying a red chillies. They compared the performance of the DPSD with that of a typical cabinet dryer and a traditional open-air sun drying for drying of red chillies. Energy and exergy analysis of the thin layer drying process of mulberry in a forced convection solar dryer were studied by Akbulut and Durmus [6]. They concluded that the energy utilization ratio and exergy loss are decrease with increasing the mass flow rate of the drying air; while, the exergetic efficiency increases with increasing the mass flow rate of the drying air. El-Beltagy et al. [7] developed a mathematical model of the thin layer drying of strawberry using an indirect forced convection solar dryer. The dryer consisted of the drying chamber and a solar collector with W-corrugated black aluminum sheet to absorb most of the available solar radiation. They reported that the solar collector with W-corrugated plate provides a drying air of temperature around 47 °C at peak conditions which is considered adequate for strawberry drying. They also found that the Newton or exponential model fits very well the experimental data and can be further applied to predict the thin layer solar drying behavior of strawberry. Dissa et al. [8] introduced mathematical model and experimental validation of thin layer solar drying of mango slices. Mohanraj and Chandrasekar [9] designed, fabricated and tested an indirect-mode forced convection solar dryer for drying copra. The moisture content of the dried copra was reduced from 51.8% to 7.8% and 9.7% in 82 h for the trays at the bottom and top of the cabinet,

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Nomenclature

I	global solar radiation incident on a tilted surface (W/m^2)
$IMFCSD$	indirect-mode forced convection solar dryer
k	drying constant (s^{-1})
M	moisture content (dimensionless)
M_o	initial moisture content (dimensionless)
M_{od}	initial moisture content on dry basis (dimensionless)
M_{ow}	initial moisture content on wet basis (dimensionless)
M_e	equilibrium moisture content (dimensionless)
M_f	final moisture content (dimensionless)
M_t	instantaneous moisture content on dry basis (dimensionless)
MR	moisture ratio (dimensionless)
$MR_{\exp,i}$	experimental moisture ratio (dimensionless)
$MR_{pre,i}$	predicted moisture ratio (dimensionless)
$\dot{m}$	mass flow rate of air (kg/s)
T	temperature (°C)
T_{fid}	temperatures of flowing air at the inlet of the drying chamber (°C)
T_{fod}	temperatures of flowing air at the outlet of the drying chamber (°C)
T_{fol}	temperature of flowing air at the outlet of lower channel of the heater (°C)
T_{fou}	temperature of flowing air at the outlet of upper channel of the heater (°C)
$T_{mint(max)}$	the maximum temperature of mint (°C)
$T_{mint(av)}$	the average temperature of mint (°C)
$T_{thymus(max)}$	the maximum temperature of thymus (°C)
$T_{thymus(av)}$	the average temperature of thymus (°C)
t	duration of drying time (s)
W_o	initial weight of the product (kg)
W_d	the weight of the dried product (kg)
W_t	the weight of the product at any time (kg)

Subscripts

a	ambient
av	average
i	inlet
l	lower
max	maximum
o	outlet
u	upper

respectively. Singh and Kumar [10] constructed laboratory models of direct, indirect and mixed mode solar dryers to perform no-load steady state experiments for natural and forced circulation of the drying air. The dryers were operated under indoor simulation conditions for absorbed thermal energy and air flow rate in the ranges of 300–800 W/m^2 and 1–3 m/s, respectively. They developed correlations of the convective heat transfer coefficient from the absorber plate to the flowing air in terms of the dimensionless numbers for each dryer operating under natural and forced convection modes.

Due to the intermittent nature of the solar energy, the energy storage materials were used to store excess energy during the peak time of solar radiation to be used in off sun hours or when the energy availability is inadequate. The storage materials improve the energy systems by smoothing the output and thus increasing the reliability. Esakkimuthu et al. [11] investigated the feasibility of using a latent heat storage unit with HS 58 (an inorganic salt based phase change material) to store the excess thermal solar energy and release it overnight as well as during poor weather conditions. Experiments were conducted to evaluate the charging and discharging characteristics of the storage unit by the authors of Ref. [11]. The effects of inlet flow rate during the charging and discharging regimes were measured and reported. It was indicated that, the mass flow rate of 200 kg/h is convent to provide a near uniform rate of heat transfer during charging and discharging processes. Further, low mass flow rates are able to utilize the maximum capacity of the storage system and to supply heat for a longer duration. An indirect type natural convection solar dryer was designed, constructed and investigated experimentally by El-Sebaii et al. [12]. Grapes, figs, apples, green peas, tomatoes and onions were dried successfully with and without using storage materials. They concluded that the final moisture content M_f for seedless grapes is reached after 60 and 72 h when the system is used with and without storage material, respectively.

Numerous research work concerning the mathematical modeling and kinetics of the drying process of various agricultural products for describing the thin layer drying of the dried products were reported; such as those concerning mint [13,14], figs [15,16], grapes [17], and Pistachios [18]. The drying characteristics for chillies pepper using open sun and solar drying were investigated by Akintunde [19]. The thin layer silk cocoon drying in a forced convection type solar dryer was studied by Singh [20]. Drying kinetics of orange peels in a forced convection solar drying were studied by Ben Slama and Combarnous [21]. Mathematical modeling of the thin layer solar drying of apricot in an indirect forced convection solar dryer consisting of solar air heater with conical concentrator and a drying cabinet was introduced by Togrul and Pehlivan [22].

A new type solar dryer using double pass solar air collector, heat pump and photovoltaic unit was experimentally studied by Sevik [23]. The performance of the dryer had been tested for carrot drying. Carrot slices were dried at 220 min by using double-pass solar air collector in solar-heat pump dryer.

Mint leaves are rich in calcium and phosphorus. Therefore, mint leaves can be used as a medicinal and aromatic plant. Mint leaves are refreshing, antiseptic, anti-asthmatic, diaphoretic, stomachic and antispasmodic where it helps in colds, flu, fever, poor digestion, motion sickness, food poisoning, rheumatism, hiccups, stings, ear aches, flatulence and for throat and sinus ailments. Because of high water content (78–82%, w/w), mint is ordinarily dried for market, in order to inhibit microorganisms growth and prevent degradation because of biochemical reactions. Also, drying brings about substantial reduction in weight and volume, minimizing packaging, storage and transportation costs [24,25]. On the other hand, thymus species are commonly used as herbal tea, flavoring agents (condiment and spice) and medicinal plants [26]. Therefore, the main objective of the present study was to investigate the thermal performance of an indirect-mode forced convection solar dryer for drying thymus and mint. For the first time, as far as the authors know, thymus will be dried using an indirect-mode forced convection solar dryer. Fourteen thin layer drying mathematical models were tested in order to evaluate the most suitable model that could be used for describing the drying curves of thymus and mint.

2. Drying analysis

In this section, the fundamental principles and basic definitions governing the drying process is presented. The moisture content on