Applied Thermal Engineering 94 (2016) 13–23

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Improving exergetic performance parameters of a rotating-tray air dryer *via* a simple heat exchanger

Hamid Ghasemkhani [a], Alireza Keyhani [a], Mortaza Aghbashlo [a,*], Shahin Rafiee [a], Arun S. Mujumdar [b,c]

[a] *Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University College of Agriculture and Natural Resources, University of Tehran, P.O. Box 4111 Tehran, Iran*
[b] *Department of Bioresource Engineering, McGill University, Quebec, Canada*
[c] *School of Agriculture and Food Sciences, University of Queensland, Brisbane, Queensland, Australia*

HIGHLIGHTS

- Exergy analysis of a rotating-tray air dryer fitted with a simple air-to-air heat exchanger.
- effect of drying air temperature and velocity on exergetic efficiency of the dryer.
- Promising improvement of exergetic performance parameters of the dryer using the heat exchanger.
- Potential application of the proposed strategy for recovering waste energy in drying technology.

ARTICLE INFO

Article history:
Received 19 September 2015
Accepted 25 October 2015
Available online 2 November 2015

Keywords:
Air-to-air heat exchanger
Drying
Exergy efficiency
Rotating-tray air dryer
Quality

ABSTRACT

In this study, exergy analysis was applied for a rotating-tray dryer equipped with a cross-flow plate heat exchanger during drying of apple slices. Three drying air temperatures and tray rotation speeds in the range of 50–80 °C and 0–12 rpm, respectively, were employed. Two drying air velocities in the range of 1–2 m/s were adjusted for each drying temperature and rotation speed with and without application of the heat exchanger. The experiments were conducted to assess the effects of the experimental variables on the exergetic performance parameters of the dryer. Also, the effect of drying conditions on the quality of dried apple slices was assessed by determining rehydration ratio, apparent density, shrinkage, and surface color. In general, the exergetic performance parameters of the dryer depended profoundly on the drying air temperature and velocity. Interestingly, the exergetic efficiency of drying process was significantly improved from a minimum value of 23.0% to a maximum value of 96.1% by using the heat exchanger. Furthermore, the incorporation of heat exchanger did not negatively affect the quality of dried product. Therefore, the strategy presented herein could be a promising approach for waste energy recovery in drying without any unfavorable change in the quality of dried product.

1. Introduction

Drying systems are the most ubiquitous components of manufacturing industry to dry wet materials to a desired level of moisture content [1]. However, energy consumption of industrial drying systems is generally very high, which makes the drying process as one of the most energy-intensive unit operations of manufacturing industry. Strumiłło et al. [2] states that industrial drying systems utilize up to 12% of the total national industrial energy used in manufacturing processes. Nowadays, the majority of energy consumed in the drying industry is met by fossil-based fuels. Unfortunately, the widespread utilization of such fuels has led to the greenhouse gas emissions and has consequently brought about environmental concerns such as global warming, climate changes, acid rain, and stratospheric ozone exhaustion [3–6].

Furthermore, the commonly used convective or conductive drying methods suffer from various shortcomings such as long processing time and high energy costs. The energy issue of drying systems could be overcome to a large extent if energy saving strategy is applied to recover a portion of the energy in the waste outflow. This is ascribed to the fact that the major component of energy losses in conventional drying systems occurs because of the exhaust of moist air from dryers [7]. One of the most promising technologies in this regard is the application of heat-pump assisted drying system. However, the heat-pump assisted drying systems suffer from several drawbacks such as higher capital and operational costs, possibility of refrigerant leak and consequent environmental issues, and the need for regular maintenance [8]. Another approach to reuse the

* Corresponding author. Tel.: +98 2612801011; fax: +98 261 2808138.
E-mail address: maghbashlo@ut.ac.ir (M. Aghbashlo).

http://dx.doi.org/10.1016/j.applthermaleng.2015.10.114
1359-4311/

waste energy from exhaust is to mix a known portion of outlet air with fresh incoming air. However, the exhaust is humid which lowers the driving force for moisture evaporation. Often the outflow air is contaminated and hence must be cleaned. Thus, there is an increasing demand for innovative engineering approaches and new drying techniques to save energy and minimize production costs in the drying operation. Fortunately, it is well-documented that the costly waste of thermal energy of convective dryers can be remarkably avoided by installing a simple heat recovery systems and then utilizing the recovered energy to preheat fresh inlet air [9]. It is possible to recover a part of the heat in exhaust air. Nevertheless, advanced engineering tools can be employed to assess the sustainability and efficiency of the heat recovery equipment in industrial drying systems.

Traditionally, various energy conversion processes in industry are often assessed *via* energy analysis. However, energy analysis based on the first law of thermodynamics does not give information on the quality of different energy forms [10,11]. Analysis based on the second law of thermodynamics, namely exergy analysis, overcomes limitations of the first law analysis [12]. As well, it has emerged as a tool for designing, analyzing, optimizing, and retrofitting energy-intensive unit operations. Exergy analysis utilizes the concepts of conservation of mass and energy together with the second law of thermodynamics. Several studies have been published on the use of exergy analysis for various drying processes and systems [13–23]. The outcomes of previously published researches indicate that drying processes can be satisfactorily designed and optimized using exergy analysis. However, very little information is available on exergy analysis of convective drying systems fitted with heat recovery systems to reuse a portion of the thermal energy in the exhaust. It is worth pointing out that air-to-air cross-flow plate heat exchangers can be a low-cost way of reducing the heating load in commercial air flow dryers. The objective of this study was to present exergy analysis for a rotating-tray convective dryer for apple slices fitted with an air-to-air cross flow plate heat exchanger. Some qualitative measurements such as rehydration ratio, apparent density, shrinkage, and surface color of dried product were made to evaluate the effect of drying variables. It is worth pointing out that a rotating-tray design avoids the problem of non-uniformity in air flow distribution often encountered in conventional cabinet dryers.

2. Material and methods

2.1. Sample preparation

Apples (Golden Delicious variety) purchased from a local market were stored in a refrigerator at 4 °C prior to the drying experiments. The apples were washed, peeled, and cut into 3 mm slices, after 1 h of stabilization period at the ambient temperature of 25 °C. At the start of each experiment, 750 g of apple slices was weighed and uniformly distributed on the trays in thin layers. The initial moisture content of the samples was determined by drying a known amount of the apple slices at 105 °C in a vacuum oven for 24 h. The average moisture content of the samples was found to be 84 ± 0.3% (wet basis %).

2.2. Drying equipment

A rotating-tray convective dryer fitted with an air-to-air cross-flow heat exchanger was designed and fabricated to recover waste heat from outflow air and improve air distribution within the drying chamber (Fig. 1). The dryer consisted of an adjustable centrifugal blower, a heat exchanger, an electrical heater, a control panel, a drying chamber, a closure, air flow pipes, a shaft and two bearings, an inverter, and a DC electric motor.

The cylindrically-shaped drying chamber with 86 cm diameter and 40 cm height was constructed using 1.2 mm thick stainless steel sheet. The closure was created on the drying chamber to place and remove the sample trays during drying experiments. The closure was sealed with a gasket to prevent the heat loss from drying chamber. Four screened stainless steel trays having dimension of 30 × 30 cm were located within the drying chamber with an angle of 90° relative to each other. The shaft was rotated using a 24 V DC electromotor and the tray rotation speed was adjusted *via* voltage control. The drying air was heated using nine U-type electrical elements having capacity of 4.5 kW (9 × 500 W). The air mass flow rate was regulated by controlling the speed of the blower's motor using a frequency modulation device. The air-to-air cross-flow flat-plate heat exchanger was developed to recover waste heat from the outflow air for preheating the inflow air (Fig. 2). The aluminum-made flat plates having dimension of 40 × 40 cm and thickness of 0.3 mm were placed in parallel on a square frame with 6 mm distance.

The whole body of the dryer was completely insulated with glass wool wrapped with aluminum foil to avoid undesirable heat loss. The air velocity was measured using a hot film sensor with accuracy of ±0.1 m/s placed in the connection pipe between the heater and the drying chamber. As well, the relative humidity of drying air was recorded at this point with accuracy of ±2% RH. Furthermore, various SHT15 temperature sensors having an accuracy of ±0.4 °C were installed on different positions of the dryer to control drying process and record the required data for exergy analysis. Weight loss of the samples was measured by means of two aluminum single point load cells (Zemic, model L6D) located under the bearings with an accuracy of ±0.1 g. The control of drying process was performed using an AVR microcontroller. Labview software was used to communicate with the dryer, observe drying process, and save the required data for exergy analysis including temperatures, relative humidity, air velocity, and samples mass with 30 s time intervals. The microcontroller was interfaced to a PC. Generally, the temperature of drying air was controlled with an accuracy of ±1 °C during drying experiments using the developed controller and the temperature sensor located at the middle of the heater and drying chamber connection pipe.

2.3. Experimental procedure

Experiments were performed at air temperatures of 50, 65 and 80 °C, air velocities of 1 and 2 m/s, tray rotation speeds of 0, 6, and 12 rpm with and without application of the heat exchanger. Each experiment was repeated twice. The dryer was run for one hour in order to achieve desirable steady-state conditions before each drying experiment. Drying process was continued until the samples reached the moisture ratio of 0.1. It is worth mentioning that the moisture ratio of wet products during drying process can be determined using the following equation [24]:

$$MR = \frac{MC_t - MC_e}{MC_o - MC_e} \quad (1)$$

However, due to the high moisture content of fresh fruits, the above-mentioned can be written as follows [24]:

$$MR = \frac{MC_t}{MC_o} \quad (2)$$

Moreover, the heat exchanger was detached from drying system during non-heat exchanger trials using the connection pipe between the drying chamber and heat exchanger.

2.4. Experimental uncertainty

Uncertainty analysis is required to demonstrate the repeatability and accuracy of the experimental data [25]. The experimental errors and uncertainties can occur due to the instrument selection,