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

Hamid Ghasemkhani, Alireza Keyhani, Mortaza Aghbashlo, Shahin Rafiee, Arun S. Mujumdar

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.

© 2015 Elsevier Ltd. All rights reserved.

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. Strumillo 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
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 retro-fitting 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]:

\[
MR = \frac{MC_i - MC_f}{MC_0 - MC_f}
\]

(1)

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

\[
MR = \frac{MC_i}{MC_0}
\]

(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,
condition, calibration, environment, reading and recording, and test planning [26]. Uncertainty analysis was carried out using the methodology developed by Holman [27].

\[
U = \left[ \left( \frac{\partial F}{\partial z_1} u_{1} \right)^2 + \left( \frac{\partial F}{\partial z_2} u_{2} \right)^2 + \cdots + \left( \frac{\partial F}{\partial z_n} u_{n} \right)^2 \right]^{1/2}
\]

(3)

2.5. Theoretical considerations

Fig. 3 shows a schematic illustration of the main features of the drying system including heat exchanger, fan–heater combination, and drying chamber with input and output terms. It was assumed that the dryer operated at a steady-state condition. Moreover, the variations of kinetic and potential exergies were ignored through this research due to their negligible contribution on the magnitude of input and output exergies.

The exergetic efficiencies of heat exchanger, fan–heater combination, and drying chamber were computed using the following equations:

\[
\psi_{HX} = \frac{E_{X_{a,2}} - E_{X_{a,1}}}{E_{X_{a,4}} - E_{X_{a,5}}} \times 100
\]

(4)

\[
\psi_{FH} = \frac{E_{X_{a,3}} - E_{X_{a,4}}}{W_{FH}} \times 100
\]

(5)

\[
\psi_{DC} = \frac{E_{X_{a,4}} + E_{X_{p,7}}}{E_{X_{a,3}} + E_{X_{p,5}} + W_{dm}} \times 100
\]

(6)

The exergy rate of the air at points 1–5 was determined using the following equation [28]:

\[
\dot{E}_{X_a} = \dot{m}_a \left[ C_v + \omega_a C_p \right] (T_a - T_0) - \dot{m}_a \left[ C_v + \omega_a C_p \right] \ln \left( \frac{T_a}{T_0} \right) - \left( R_v + \omega_v R_p \right) \ln \left( \frac{P_v}{P_0} \right) + \dot{m}_a \left[ R_v + \omega_v R_p \right] \ln \left( \frac{P_v}{P_0} \right) + 1.6078 \omega_v R_p \ln \left( \frac{P_v}{P_0} \right)
\]

(7)

Based on mass conversation principle, the following equation can be written for drying air at different points within the drying system:

\[
\dot{m}_{a,1} = \dot{m}_{a,2} = \dot{m}_{a,3} = \dot{m}_{a,4} = \dot{m}_{a,5} = \dot{m}_a
\]

(8)

The recorded relative humidity of air at point 3 was used for computing the humidity ratio of air at points 1–3 as follows [29]:

\[
P_{v_{1,2,3}} = 0.1 \exp \left( 27.014 + \frac{6887}{T_{a,3}} - 5.31 \ln \left( \frac{T_{a,3}}{273.16} \right) \right)
\]

(9)

\[
\omega_{a,1} = \omega_{a,2} = \omega_{a,3} = 0.622 \frac{\partial P_{v_{1,2,3}}}{P - \partial P_{v_{1,2,3}}}
\]

(10)

The humidity ratio of the vented air from drying chamber was obtained using water balance equation for drying process.

\[
\omega_{a,4} = \omega_{a,5}
\]

(11)

and

\[
\omega_{a,4} = \omega_{a,5}
\]

(12)
The power rate consumed by fan–heater combination was computed using the following equations:

\[
W_{F,\text{elec}} = \frac{V_f I_f \sqrt{3}}{1000} \cos \phi \times \eta_{\text{F,elec}} \eta_{\text{F,mech}}
\]

(13)

\[
W_{H,\text{elec}} = \frac{V_h I_h}{1000} \times \eta_{\text{H,elec}}
\]

(14)

\[
W_{\text{FH}} = W_f + W_h
\]

(15)

The power rate utilized by electromotor for rotating the trays was determined as follows:

\[
W_{\text{EM}} = \frac{V_{\text{EM}}}{1000} \eta_{\text{EM,elec}} \eta_{\text{EM,mech}}
\]

(16)

For solid and liquid materials, the specific exergy can be computed as follows:

\[
\dot{E}_{\text{px}} = \dot{m}_p C_p \left[ (T_p - T_0) - T_p \ln \left( \frac{T_p}{T_0} \right) \right]
\]

(17)

The specific heat of the material at the inlet and outlet points was obtained by Choi and Okos' equation [30]:

\[
C_p = \sum X_j C_j
\]

(18)

\[
C_p = C_w X_w + C_{\text{prote}} X_{\text{prote}} + C_{\text{fat}} X_{\text{fat}} + C_{\text{ash}} X_{\text{ash}} + C_{\text{fiber}} X_{\text{fiber}} + C_{\text{case}} X_{\text{case}}
\]

(19)

The equations describing the specific heat capacity of applied components based on temperature are listed in Table 1.

The exergy efficiency of the drying process with heat exchanger was obtained using the following equations:

\[
\psi_{\text{process with HX}} = \frac{\dot{E}_{\text{ev}} + \dot{E}_{\text{p,7}}}{\dot{E}_{\text{a,1}} - \dot{E}_{\text{a,3}} + \dot{E}_{\text{p,5}} + W_{\text{FH}} + W_{\text{EM}}}
\]

(20)

As well, the exergy efficiency of the drying process without heat exchanger was found as follows:

\[
\psi_{\text{process without HX}} = \frac{\dot{E}_{\text{ev}} + \dot{E}_{\text{p,7}}}{\dot{E}_{\text{a,1}} - \dot{E}_{\text{a,4}} + \dot{E}_{\text{p,6}} + W_{\text{FH}} + W_{\text{EM}}}
\]

(21)

The rate of exergy utilized for drying of the product was obtained using the following equation:

\[
\dot{E}_{\text{ev}} = \left( 1 - \frac{T_0}{T_p} \right) Q_{\text{ev}}
\]

(22)

It should be mentioned that the temperature of the product being dried was considered to be equal to that of the wet bulb temperature and drying air temperature at the first and second stages of drying, respectively. The possible error raised from this assumption was negligible since the samples were very thin (3 mm).

The rate of heat transfer due to the evaporation was computed as

\[
Q_{\text{ev}} = (m_w)_{\text{ev}} h_f
\]

(23)

where the mass flow rate of the evaporated water was:

\[
(m_w)_{\text{ev}} = (m_w)_{\text{in}} - (m_w)_{\text{out}}
\]

(24)

The latent heat of vaporization at saturation state based on absolute temperature was determined using the equations developed by Brooker et al. [32].
Table 1
The specific heat capacity of the apple components [31].

<table>
<thead>
<tr>
<th>Component</th>
<th>Equation, T(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrate</td>
<td>$C_{\text{carb}} = 1.5488 + 1.9625 \times 10^{-3}T - 5.9399 \times 10^{-2}T^2$</td>
</tr>
<tr>
<td>Protein</td>
<td>$C_{\text{prot}} = 2.0082 + 1.2089 \times 10^{-3}T - 1.3129 \times 10^{-2}T^2$</td>
</tr>
<tr>
<td>Ash</td>
<td>$C_{\text{ash}} = 1.0926 + 1.8896 \times 10^{-3}T - 3.6817 \times 10^{-2}T^2$</td>
</tr>
<tr>
<td>Fat</td>
<td>$C_{\text{fat}} = 1.9862 + 1.4733 \times 10^{-3}T - 4.8008 \times 10^{-2}T^2$</td>
</tr>
<tr>
<td>Fiber</td>
<td>$C_{\text{fiber}} = 1.8459 + 1.8306 \times 10^{-3}T - 6.5099 \times 10^{-2}T^2$</td>
</tr>
<tr>
<td>Water</td>
<td>$C_{\text{water}} = 4.1762 - 9.8064 \times 10^{-3}T + 5.4731 \times 10^{-2}T^2$</td>
</tr>
</tbody>
</table>

Fig. 3. Schematic of the drying system with input and output terms. 1. fresh air; 2. heated air; 3. hot air; 4. moist air; 5. exhaust air; 6. fresh product; 7. dried product.

h_{lg} = 2.503 \times 10^6 - 2.386 \times 10^4(T - 273.16)  
273.16 \leq T (K) \leq 338.72  
h_{lg} = (7.33 \times 10^2 - 1.60 \times 10^2T^2)^{0.05}  
338.72 \leq T (K) \leq 533.16  

The reference state temperature and pressure were considered to be 25 °C and 101.315 kPa, respectively.

Consequently, the following equation was applied to calculate the exergetic efficiency improvement of drying process at a given drying condition due to the incorporation of heat exchanger into drying system.

\[
\psi = \frac{\psi_{\text{process with HX}} - \psi_{\text{process without HX}}}{\psi_{\text{process without HX}}} \times 100
\]  
(26)

2.6. Qualitative measurements

In order to determine the rehydration ratio of dried product, a given amount of dried apple slices was immersed for 50 min in water at room temperature. In this study, 100 mL of distilled water was used per gram of dried product. Then, the slices were weighed again after draining the water during 2 min. The rehydration ratio of dried apple slices was computed using the following equation [33]:

\[
\text{Rehydration ratio} = \frac{W_r - W_i}{W_i}
\]  
(27)

Toluene displacement method was employed to measure the volume of samples before and after drying. The following equation was applied to calculate the shrinkage of dried samples at the end of drying process [34]:

\[
\text{Shrinkage} = \left(1 - \frac{V_i}{V_f}\right) \times 100
\]  
(28)

As well, the apparent density was determined by measuring the mass of the samples used for shrinkage measurement before and after drying.

A computer vision system was employed to measure the surface color of the samples in CIE L*a*b* space. The detailed information on the apparatus structure was completely explained in Dowlati et al. [35]. A CCD color camera (Canon G9 digital color camera, Tokyo, Japan) with remote capturing capability was used to provide images from the randomly selected dried and wet samples [36]. The images were analyzed according to the methodology comprehensively illustrated in Nadian et al. [37]. Finally, the total color difference of dried apple slices with respect to the fresh state was determined as follows [38]:

\[
\Delta E = \sqrt{(L^* - L_i^*)^2 + (a^* - a_i^*)^2 + (b^* - b_i^*)^2}
\]  
(29)

All the above mentioned measurements were carried out in duplicate.

2.7. Statistical analysis

Statistical evaluation of the results was performed using a 3 x 3 x 2 x 2 split factorial design (three temperatures, three tray rotation speeds, two air velocities, and two modes of heat exchanger) with two replications for each treatment. Analysis of variance was carried out to find the effects (p < 0.05) of air temperature, air velocity, tray rotation speed, and heat exchanger on the exergetic performance and qualitative parameters. Multiple comparison tests were performed using Duncan test at 95% confidence level. All the analyses were carried out using SAS (Statistical Analysis System 9.2) computer program.

3. Results and discussions

Table 2 lists the detailed uncertainty analysis for experimental measurements of parameters and overall uncertainties of predicted values. The results demonstrated that all uncertainties were below an acceptable error level (<5%).

The effect of drying air temperature on the variation of moisture ratio of apple slices at drying air velocity of 1 m/s and tray rotation speed of 6 rpm with application of the heat exchanger is illustrated in Fig. 4. It is obvious from this figure that the drying rate increased as the drying air temperature increased. Similar trends were obtained for other drying experiments. Exergy analysis of the dryer and its main components were carried out by using data obtained from the drying experiments. Fig. 5 indicates the variations in the exergetic performance parameters of the drying system as a function of drying time at drying air temperature of 65 °C, air velocity of 1 m/s, and tray rotation speed of 6 rpm with and without application of the heat exchanger. Similar trends were found for other drying experiments. All data reported in this paper are the mean of the two replications. Obviously, the
Table 2
Uncertainties of the experimental measurements and overall uncertainties for predicted values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Comment</th>
<th>Nominal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental measurements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncertainty in the temperature measurement</td>
<td>°C</td>
<td>±0.905</td>
<td>–</td>
</tr>
<tr>
<td>Uncertainty in the weight measurement</td>
<td>g</td>
<td>±0.141</td>
<td>–</td>
</tr>
<tr>
<td>Uncertainty in the air velocity measurement</td>
<td>m/s</td>
<td>±0.173</td>
<td>–</td>
</tr>
<tr>
<td>Uncertainty in the air relative humidity measurement</td>
<td>%</td>
<td>±2.828</td>
<td>–</td>
</tr>
<tr>
<td>Uncertainty in the time measurement</td>
<td>s</td>
<td>±0.023</td>
<td>–</td>
</tr>
<tr>
<td>Uncertainty in the measurement of moisture content</td>
<td>g</td>
<td>±0.021</td>
<td>–</td>
</tr>
<tr>
<td>Uncertainty in the tray rotation speed</td>
<td>rpm</td>
<td>±0.054</td>
<td>–</td>
</tr>
<tr>
<td>Predicted measurements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total uncertainty for moisture ratio</td>
<td>Dimensionless</td>
<td>±1.21%</td>
<td>0.53</td>
</tr>
<tr>
<td>Total uncertainty for exergy efficiency of fan–heater</td>
<td>Dimensionless</td>
<td>±2.64%</td>
<td>7.05</td>
</tr>
<tr>
<td>Total uncertainty for exergy efficiency of drying chamber</td>
<td>Dimensionless</td>
<td>±3.24%</td>
<td>86.61</td>
</tr>
<tr>
<td>Total uncertainty for exergy efficiency of heat exchanger</td>
<td>Dimensionless</td>
<td>±3.31%</td>
<td>21.00</td>
</tr>
<tr>
<td>Total uncertainty for exergy efficiency of overall drying system</td>
<td>Dimensionless</td>
<td>±4.27%</td>
<td>11.09</td>
</tr>
<tr>
<td>Total uncertainty for exergy efficiency of overall drying process</td>
<td>Dimensionless</td>
<td>±4.11%</td>
<td>1.78</td>
</tr>
<tr>
<td>Total uncertainty for shrinkage</td>
<td>%</td>
<td>±2.12%</td>
<td>74.60</td>
</tr>
<tr>
<td>Total uncertainty for rehydration ratio</td>
<td>Dimensionless</td>
<td>±2.74%</td>
<td>1.78</td>
</tr>
<tr>
<td>Total uncertainty for density measurement</td>
<td>g/cm³</td>
<td>±2.87%</td>
<td>0.616</td>
</tr>
</tbody>
</table>
The effect of drying variables on the exergy efficiency of heat exchanger is exhibited in Fig. 8. Increasing drying air velocity led to an increase \((p < 0.05)\) in the exergy efficiency of heat exchanger because of the effective recovery of the exergy of the vented air from drying chamber based on Eq. \((4)\). Interestingly, the exergetic efficiency of heat exchanger was not significantly influenced \((p > 0.05)\) by the drying air temperature. Moreover, the rotation speed of tray did not affect \((p > 0.05)\) the exergy efficiency of heat exchanger due to an insignificant effect of tray rotation on the temperature of exhaust air from the drying chamber.

The effect of drying variables on the exergy efficiency of the drying process is demonstrated in Fig. 9. The exergy efficiency of drying process varied from a minimum value of 0.43% to a maximum value of 2.19% under the drying conditions investigated, indicating that convective drying process is an exergetically low efficiency process. The considerably small amount of moisture evaporation during convective drying process is responsible for this low exergetic efficiency. It is interesting to note that the inclusion of heat exchanger profoundly improved \((p < 0.05)\) the exergy efficiency of drying process. This can be explained by the fact that some part of outflow exergy from drying chamber was effectively recovered via the heat exchanger. Increasing drying air temperature increased \((p < 0.05)\) the process exergy efficiency because of an increase in the magnitude of moisture evaporation, according to Eqs. \((22)-(24)\). However, the exergy efficiency of the drying process was not significantly affected \((p > 0.05)\) by increasing the rotation speed of tray, This could be ascribed to the fact that the tray rotation marginally increased the mass transfer from the product being dried. On the other hand, the process exergy efficiency decreased \((p < 0.05)\) by increasing the air mass flow rate since the process exergy efficiency is inversely proportional to the exergy rate of inlet drying air.

Fig. 10 illustrates the effect of different drying conditions on the exergetic efficiency improvement of drying process due to the incorporation of heat exchanger into drying system according to Eq. \((26)\). This improvement varied from a minimum value of 23.09% to a maximum value of 96.13% at the drying conditions studied due to the recycling of a considerable amount of outflow exergy. It could be concluded that the incorporation of a simple heat exchanger to the hot air drying system remarkably improved the second law efficiency of the process without high expenditure. Therefore, further surveys should be carried out to increase the exergy recovery from outflow air via efficient heat exchangers and embody low-cost heat exchangers to industrial drying systems for improving the performance.

Table 4 summarizes the measured quality parameters of apple slices dried under different operating conditions. In general, the quality parameters of dried apple slices were significantly influenced \((p < 0.05)\) by the air temperature. However, the other parameters did not significantly affect \((p > 0.05)\) the quality parameters of the dried apple slices. A similar finding has been previously reported by Santos-Sánchez et al. [33] for the effect of air velocity and tray rotation speed on the L* and b* values of tomato slices.
Increasing drying air temperature decreased both shrinkage and density of the dried apple slices because of the rapid moisture removal at higher drying air temperatures. This in turn does not give adequate time to the viscoelastic matrix of the product to shrink back completely into the voids previously filled with water. Similarly, Lewicki and Jakubczyk [45] and Bai et al. [46] found that increasing drying air temperature decreased shrinkage and density of the dried apple. Moreover, the rehydration capacity of apple slices dried at higher temperatures was somewhat better than of those dried at lower temperatures. It could be attributed to the fact that higher drying temperatures lead to dried slices with more porous structure, thereby facilitating the rehydration process [47]. A similar finding was reported by Sacilik and Elicin [48] for hot air drying of apple slices.

It is interesting to note that the normalized lightness of the dried apple slices at higher air temperatures is slightly higher than for those dried at lower air temperatures. It might be due to the degradation of chlorophyll and carotenoids in apple at higher drying air temperature, as discussed by Nadian et al. [37]. Additionally, the normalized redness of the dried apple slices increased remarkably with increasing air temperature due to promotion of the Maillard reaction at higher temperatures. Sacilik and Elicin [48] and Vega-Gálvez et al. [49] found similar results for the effect of drying air temperature on the normalized redness of the dried slices. The
The exergetic performance of a rotating-tray convective dryer fitted with an air-to-air cross-flow plate heat exchanger was assessed via exergy analysis at different drying air temperatures, air velocities, and tray rotation speeds. Furthermore, the effect of the operating variables on the quality of the dried product was evaluated through quantitative measurements of the quality, e.g., rehydration ratio, apparent density, shrinkage, and surface color. The incorporation of a heat exchanger into the system improved the exergetic parameters of the overall system by raising the exergy efficiency of the process. Nevertheless, the quality of the dried product was not unfavorably altered by the use of a heat exchanger. Generally, the exergetic efficiency of the drying process was very poor and lower than the exergy efficiency of the whole drying system due to the lower drying rate. Nevertheless, the process exergy efficiency was found to be a very useful tool for thermodynamic analysis of a drying system compared to the system exergy efficiency. The results of this study can be applied in design and optimization of industrial-scale heat exchangers for recovering the waste heat from exhaust air and improving the performance of convective dryers.

### Table 4: Quality parameters of apple slices dried at different drying conditions.

<table>
<thead>
<tr>
<th>Drying condition</th>
<th>Quality parameter</th>
<th>50°C</th>
<th>65°C</th>
<th>80°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tray rotation speed (rpm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat exchanger mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shelf design</td>
<td>Density (g/cm³)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rehydration ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L* / L**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Acknowledgements

The authors would like to extend their appreciations for financial support provided by the University of Tehran.

Nomenclature

\( \alpha \) * Redness
\( \beta \) * Yellowness
\( C \) Specific heat (kJ/kg K)
\( \dot{E}x \) Exergy flow rate (kJ/s)
\( F \) Function of the independent variables
\( h_{fg} \) Latent heat of vaporization (kJ/kg)

\( I \) Current intensity (Ampere)
\( I^* \) Lightness
\( MC \) Moisture content (wet basis %)
\( MR \) Moisture ration (-)
\( m \) Mass flow rate (kg/s)
\( P \) Pressure (kPa)
\( Q \) Heat transfer rate (kJ/s)
\( R \) Gas constant (kJ/kg K)
\( T \) Temperature (°C or K)
\( U \) Uncertainty in the result
\( V \) Voltage (Volt)
\( W \) Weight (g)
\( W_e \) Electrical work rate (kJ/s)
\( x \) Mass fraction
\( z \) Independent variables
\( \nu \) Volume

Greek letters

\( \psi \) Exergy efficiency
\( \omega \) Humidity ratio
\( \phi \) Relative air humidity
\( \eta \) Efficiency
\( \Psi \) Exergetic efficiency improvement
\( \Delta E \) Total color change

Subscripts

0 Dead state
\( a \) Air
\( ash \) Ash
\( carb \) Carbohydrate
\( d \) Dried
\( DC \) Drying chamber
\( e \) Equilibrium
\( elec \) Electrical
\( ev \) Evaporation
\( EM \) Electrical motor
\( fat \) Fat
\( fiber \) Fiber
\( F \) Fan
\( FH \) Fan–heater combination
\( H \) Heater
\( HX \) Heat exchanger
\( i \) Initial volume
j - Numerator
o - Initial moisture content
prot - Protein
p - Product
r - Rehydrated
t - Drying time
v - Vapor
vs - Saturated vapor
w - Water

References


