Energy and exergy analyses during eggplant drying in a fluidized bed dryer

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Abstract: In this research, energy and exergy loss were analyzed in the laboratory for the drying of eggplant using a fluidized bed dryer. The drying experiment was conducted at inlet temperatures of 40°C, 50°C, and 60°C and air velocities of 3, 5, and 7 m s^{-1} using samples with diameters of 5, 10, and 13 mm and a height of 1 cm. The effects of temperature, velocity of drying air, and sample size on energy consumption and exergy losses were investigated. The results showed that the minimum energy consumption and exergy losses occurred at a diameter of 13 mm, velocity of 3 m s^{-1}, and temperature of 40°C. Meanwhile, the maximum energy consumption and exergy losses occurred at a diameter of 5 mm, velocity of 7 m s^{-1} and temperature of 60°C. Generally, the results demonstrated that higher temperature, velocity, and eggplant samples' lesser diameter increased energy consumption. In addition, exergy losses increased with temperature and velocity increments; however, changes in sample size did not significantly affect exergy losses.

Keywords: energy utilization, exergy losses, eggplant, fluidized bed dryer, temperature, air velocity

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1 Introduction

Thermodynamic analysis, mainly exergy analysis, plays an important role in the design, evaluation, and optimization of thermal systems. Exergy is defined as the maximum amount of work produced by heat and vapor in an equilibrium state. Exergy analysis involves the evaluation of available energy at several points and provides valuable information about desirable design methods and selections in a dryer (Dincer, 2000; Dincer, 2002).

There is a wide range of eggplants with different shapes and colors, including oval or ovoid shapes and colors from white to nearly black, yellow, green, and purple. The eggplant is of great economic value in Asia, Africa, and the tropics (India, Central America); it is also cultivated in some hot and moderate regions of the Mediterranean Sea and South America (Sihachkr et al., 1993). Eggplant is a fruit that is known for being low in calories and for having a mineral composition that beneficial to human health. It is a rich source of potassium, magnesium, calcium, and iron (Zenia and Halina, 2008).

In practice, drying is a process that requires high energy input due to water's latent heat of vaporization and the relatively low efficiency of industrial dryers (Syahrul et al., 2002). Ten percent of the overall energy consumption in food industries is related to the drying of food (Smith, 2007). Thus, food drying represents the most energy-consuming operation in food production, resulting in its high industrial importance (Aghbashlo et al., 2009).

Fluidized bed dryers are widely used to dry wet particles and granular ingredients that can be fluidized; they are even used to dry some solutions and suspensions. Usage of fluidized beds brings important advantages, such as proper mixing of ingredients, high mass and heat transfer coefficients, and easy transfer of ingredients (Mujumdar, 2006).

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Considering the thermal efficiency of the drying process, fluidized bed dryers—with their high heat and mass transfer and drying rates—are widely utilized in food dryings. Moreover, fluidized bed dryers have many applications in the chemistry, metallurgy, and pharmaceutical industries (Bialobrzewski et al., 2008).

By analyzing the energy and exergy of coroba drying with a thin layer dryer, researchers concluded that both energy consumption and the energy consumption ratio increase with increased drying time, while the exergy efficiency decreased. The energy consumption amount and energy consumption ratio were in the range of 0.009-0.65 kJ s^{-1} and 0.00007-0.008, respectively, at temperatures of 71°C-93°C, with an air speed range of 0.82 to 1.18 m s^{-1} (Corzo et al., 2008).

In research on energy and exergy analysis of the drying of chili pepper pieces, it was concluded that the exergy efficiency range of drying was 67.28%-97.92%; moreover, it was observed that energy consumption ratio decreased when the drying temperature increased; meanwhile, the exergy efficiency increased (Akpinar, 2004).

Other researchers found that in drying carrots, the consumed energy and energy consumption ratio increased with drying temperature and bed depth increments, while they decreased with increasing the size of the carrot pieces. The maximum energy consumption and energy consumption ratio occurred at a temperature of 70°C, bed depth of 90 mm, and size of 4 mm, while the minimum values were observed at a temperature of 50°C, bed depth of 30 mm, and size of 10 mm (Nazghelichi et al., 2010).

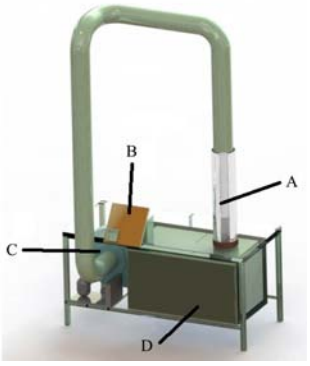
In another study, a fluidized bed dryer with a capacity of 22 tons per hour was designed to dry paddies, and the calculations showed that lesser exergy losses lead to an increase in exergy efficiency. This demonstrated that using the energy in air is effective for the drying process. The exergy balance analysis carried out in this research demonstrated that only 31%-37% of exergy was used for drying rice. This illustrated the purposes of the remaining exergy usage. Exergy usage should be increased by providing enough insulators in the dryer body and by recycling exhaust air; this can be examined in terms of economic efficiency (Sarker et al., 2015). In the energy and exergy analysis of drying native cassava starch in a tray dryer, it was concluded that for starch with contents of 0.76% ash, 0.85% crude protein, 0.16% crude fat, negligible amounts of fiber, an average granule size of 14.1 mm, pH of 5.88, 23.45% amylose content, and a degree of crystallinity of 22.34%, energy utilization and its ratio increased from 1.93 to 5.51 J s^{-1} and 0.65 to 0.6 as the drying temperature increased from 40°C to 60°C (Aviara et al., 2014). In energy and exergy analysis of a solar drying process for pistachios, it was found that the maximum efficiency of exergy usage was obtained when exergy losses were minimal. A maximum amount of exergy flow to the system of 3.718 kJ was obtained; however, exergy losses were elevated by an increase in energy generation in both the shelves and the solar drying chamber (Midilli and Kucuk, 2003).

The aim of the present study is to present a thermodynamic analysis of eggplant drying in different sizes of eggplant and different temperatures and airflow ratios in fluidized bed dryer, and to determine the best conditions for minimum energy utilization and exergy losses during the drying process.

2 Materials and methods

2.1 Material preparation

Freshly harvested eggplants were purchased from a local market and stored in a laboratory refrigerator at 5°C. At the beginning of each test, eggplants were washed, peeled, and cut manually using cylinders with diameters of 5, 10, and 13 mm and a height of 10 mm. The drying experiment was conducted using a laboratory fluidized bed dryer made in the Department of Mechanical Bio-systems of the University of Agricultural Sciences and Natural Resources of Gorgan, Iran.



A- Fluidizing chamber B- heater control C- fan D- heaters

Figure 1 Schematic illustration of testing apparatus

2.2 Experimental procedure

To supply the required air flow, a centrifugal blower with a 3 hp CDF90L_2 three-phase electric motor (KAIJIELI) was used. For outlet temperature measurement, an ST_941 standard multi-meter with an accuracy of ±0.1°C was employed; to measure dryer wind speed, an anemometer (LUTRON, AM-2416) with an accuracy of 0.1 m s^{-1} was utilized. The dryer contained an automated temperature controller with an accuracy of 0.1°C. Samples were weighed every five minutes using a Dj 2000A weigh scale (Shinko electric scale), which had an accuracy of 0.01 g. During drying, the outlet air temperature of the dryer and the airflow ratio were recorded at five minute intervals.

Samples were weighed at the beginning, and after the dryer reached to the desired temperature, eggplants were placed inside the drying cabinet. The experiment was performed at temperatures of 40°C, 50°C, and 60°C and speeds of 3, 5, and 7 m s^{-1}; the eggplants had a cylindrical shape with diameters of 5, 10, and 13 mm and a height of 1 mm. Each treatment was repeated three times and the test was performed at a temperature of 30°C with a relative moisture content of 50%. Variance analysis was carried out using a factorial experiment and a completely randomized design via SAS software (9.1.3 portable).

2.3 Analysis of energy utilization

In this research, energy utilization was expressed using the first law of thermodynamics, as follows Equation (1) (Syahrul et al., 2003).

$$E_u = \dot{m}_{da} \times (h_{dai} - h_{dao}) \quad (1)$$

where, E_u is consumed energy; $\dot{m}_{da}$ is dry air mass flow rate and h_{dai} is inlet air enthalpy and h_{dao} is outlet air enthalpy.

The air mass flow rate was obtained using Equation (2) (Dincer, 2000).

$$\dot{m}_{da} = \rho_a \times v_a \times A_{dc} \quad (2)$$

where, ρ_a is air density; v_a is air speed inside dryer and A_{dc} is the cross section that air crosses it.

Dryer air enthalpy was obtained using Equation (3).

$$h_{ad} = C_{pda} \times (T - T_{\infty}) + h_{fg} \quad (3)$$

where, C_{pda} is specific heat capacity of air; T is outlet temperature; T_{∞} is ambient temperature and h_{fg} is indicative of latent heat of vaporization of water.

Inlet and outlet air-specific heat capacities were calculated with Equation (4) (Corzo et al., 2008).

$$C_{pda} = 1.004 + 1.88 \times w \quad (4)$$

In this equation w is air moisture content ratio and C_{pda} is specific heat capacity of air.

During energy and exergy analysis of the eggplant drying process, Equation (5) was used for transformation of relative moisture content to the air moisture content ratio (kg water/kg dry air) (Topic, 1995).

$$w = 0.622 \times \frac{\varphi \times P_{vs}}{P - P_{vs}} \quad (5)$$

In this equation, φ is relative moisture content, P_{vs} is saturated vapor pressure and P is air pressure.

The inlet and outlet air moisture content ratio was obtained using Equation (6) (Akpinar, 2004).

$$w_{dao} = w_{dai} + \frac{\dot{m}_v}{\dot{m}_{da}} \quad (6)$$

where, w_{dao} is outlet air moisture content ratio; w_{dai} is inlet air moisture content ratio and $\dot{m}_v$ is drying rate.

Moreover, $\dot{m}_v$ was calculated using following Equation (7) (Nazghelichi et al., 2010).

$$\dot{m}_v = \frac{w_t - w_{t+\Delta t}}{\Delta t} \quad (7)$$

where, $\dot{m}_v$ is drying rate; Δt is drying time interval; $w_{(t)}$ is initial weight and $w_{(t+\Delta t)}$ is secondary weight.

2.4 Analysis of exergy

Equation (8) was employed to calculate exergy, representing functional exergy equation with a steady flow (Midilli and Kucuk, 2003).

$$Ex = \dot{m}_{da} \times C_{pda} \times [(T - T_{\infty}) - T_{\infty} \times Ln\frac{T}{T_{\infty}}] \quad (8)$$

where, C_{pda} is air specific heat capacity; T_{∞} is ambient air temperature and $\dot{m}_{da}$ is air mass flow rate.

Exergy losses in the drying chamber were obtained using Equation (9) (Akpinar, 2004)

$$E_{xl} = E_{xi} - E_{xo} \quad (9)$$

where, E_{xi} is inlet and E_{xo} is outlet exergy.

3 Results and discussion

3.1 Energy analysis

The variance analysis results of the effects of temperature, sample size and speed on energy consumed in the eggplant dryer are shown in Table 1. As the table shows, variations in speed and temperature and their interaction with consumed energy were significant at a level of 1%. In addition, the size effect and its interaction with speed were significant at a 5% level. Effect of three parameters was not significant. However, the interaction of size and temperature did not reach a significant difference in consumed energy.

Table 1 Variance analysis for energy utilization under different speed, size and temperature in fluid bed dryer

Source of variation	Degrees of freedom	Sum of squares	Mean square	*F*-value
Speed	2	1956.06	978.03	1646.36**
Temperature	2	221.33	110.66	186.29**
Size	2	5.09	2.54	4.28*
Speed × Temperature	4	13.30	3.32	5.6**
Speed × Size	4	8.17	2.04	3.44*
Temperature × Size	4	0.98	0.24	0.41^{ns}
Temperature × Size × Speed	8	4.91	0.61	1.04^{ns}

Note: ** and * mean significant difference at 1% level ($p<0.01$) and at 5% level ($p<0.05$) respectively, ns means not significant difference.

Temperature and speed interactions affected consumed energy at a 1% level of probability. Thus, an average comparison was attempted using the least significant differences (LSD) method with a completely randomized design, and the results are shown in Figure 2. Figure 2 displays the effect of velocity on energy utilization at different temperatures, indicating that the maximum amount of energy utilization occurred at a temperature of 60°C and a velocity of 7 m s^{-1}. The minimum energy utilization was observed at a temperature of 40°C and a velocity of 3 m s^{-1}. Also Figure 2 shows the effect of speed on energy utilization in different sample sizes. It indicates that the maximum amount of energy utilization occurred at a diameter of 5 mm and a speed of 7 m s^{-1}, while the minimum amount of energy consumption occurred at a diameter of 5 mm and a speed of 3 m s^{-1}.

It can be seen in Figure 3 that drying at temperatures of 40°C and 50°C did not differ statistically in terms of energy consumption; the general trend of this figure indicates that consumed energy increased by increasing temperature, because higher temperatures cause further moisture content reduction. In other words, higher temperatures lead to further mass and moisture content reduction, and this increases energy utilization. Our results are consistent with Aviara et al. (2014) in tray dryer on exergy and energy changes of native cassava.

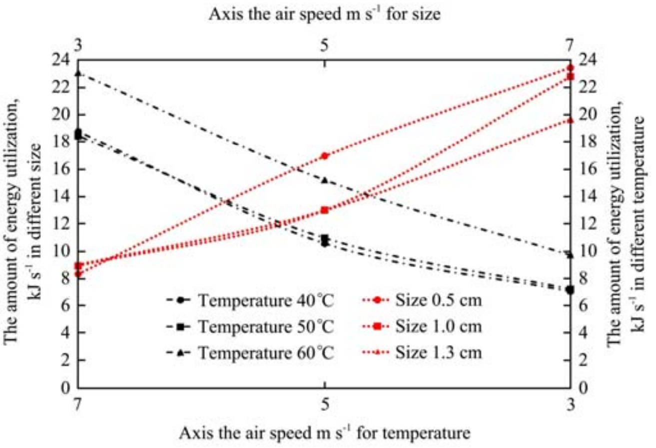


Figure 2 Interaction of air speed and temperature, and air speed and size

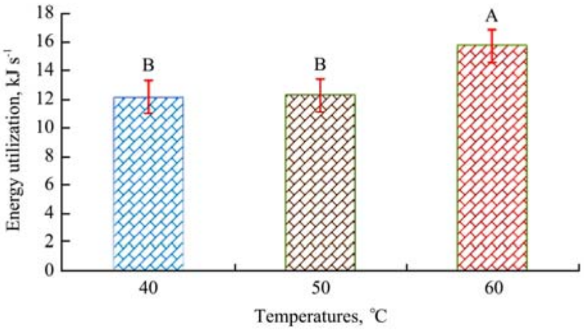


Figure 3 Effects of different temperatures on energy utilization

The same letters in each column represent no significant difference

Figure 4 indicates that energy utilization increased by a decrease in eggplant diameter because the eggplants' interface with flowing hot air elevated by a decrease in size. Consequently, mass and heat transfer occurred as well, and most of the energy produced by the dryer was used to evaporate moisture content from the eggplants. The larger the sample sizes, the more moisture content remained inside the samples for a fixed input of energy. This is because the moisture content evaporation rate slowed down after a while, and the input energy was not able to penetrate the sample and remove moisture content

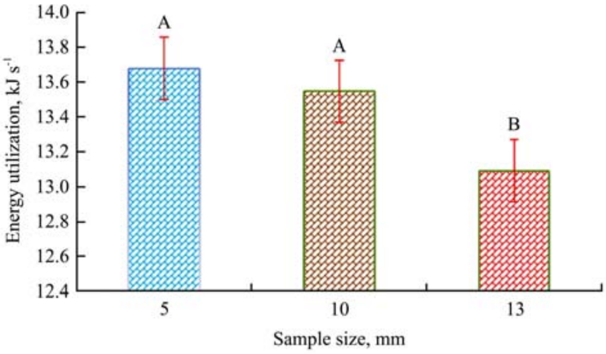


Figure 4 Effects of different size on energy utilization

The same letters in each column represent no significant difference effectively. This matches the results that Nazghelichi et al. (2010) reported in an energy and exergy analysis of drying carrot pieces.

3.2 Exergy analysis

Variance analysis results for the temperature and velocity effects on exergy losses in eggplant drying are shown in Table 2.

Table 2 Variance analysis of exergy loss under different speed, size and temperature in fluid bed dryer

Source of variation	Degrees of freedom	Sum of squares	Mean square	*F*-value
Speed	2	3.46	1.73	44.47^{**}
Temperature	2	109.39	54.69	1405.80^{**}
Size	2	0.19	0.09	2.52^{ns}
Speed × Temperature	4	0.14	0.03	0.89^{ns}
Speed × Size	4	0.25	0.06	1.62^{ns}
Temperature × Size	4	0.08	0.02	0.55^{ns}
Temperature × Size × Speed	8	0.23	0.03	0.75^{ns}

Note: ** and * mean significant difference at 1% level ($p<0.01$), ns means not significant difference.

As summarized in Table 2, there were significant velocity and temperature effects on exergy losses at the 1% level; however, the size of samples did not have a significant effect, and the interactions of these three parameters and effect of three parameters were not significant.

As shown in Figure 5, exergy losses increased with increasing velocity, along with the dryer flow rate. According to Equation (8), there is a direct relationship between flow rate and exergy, and the exergy loss rate increased by increasing the flow rate. This is also in accordance with the results obtained by (Akpinar, 2005) from drying eggplant pieces in a cyclone dryer.

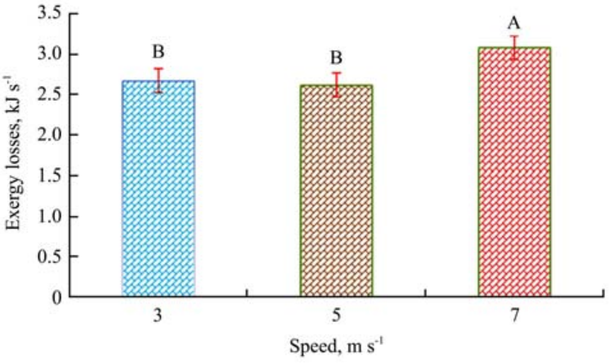


Figure 5 Effects of different speed on exergy losses

The same letters in each column represent no significant difference

Figure 6 shows that exergy losses differed significantly at the three temperatures, and exergy losses were increased with increasing temperature. This was similar to the result with Akpinar (2004). Dryer inlet air with a higher temperature has higher exergy, and this leads to an increase in moisture evaporation and exergy usage; thus, exergy losses are increased (Nazghelichi et al., 2010).

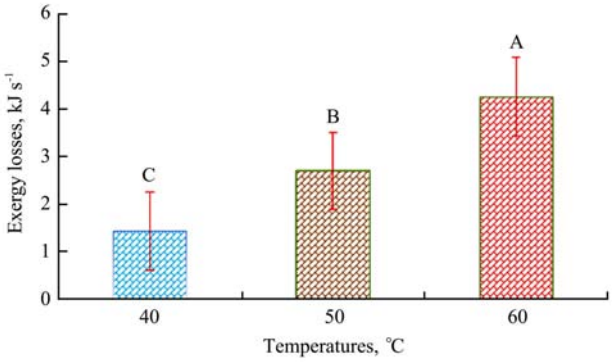


Figure 6 Effects of temperature on exergy losses

The same letters in each column represent no significant difference

4 Conclusion

It was revealed in this experiment that consumed energy increased with increasing temperature and velocity and decreasing sample size. Minimum energy utilization occurred at a velocity of 3 m s^{-1}, and a temperature of 40°C, while maximum energy consumption occurred at a diameter of 0.5 cm, speed of 7 m s^{-1}. Exergy losses increased with increasing temperature and speed; however, no significant changes were observed with variations in sample sizes. Minimum exergy losses occurred with a diameter of 13 cm, velocity of 3 m s^{-1}, and temperature of 40°C, while maximum exergy losses occurred with a diameter of 0.5 cm, speed of 7 m s^{-1}, and temperature of 60°C. Velocity and temperature parameters and the interactions of these two factors had a significantly effect on consumed energy at a 1% level. The diameter of samples and the interaction of size and speed were significant at a 5% level. However, the interaction of size and temperature was not significant. In terms of exergy losses, the factors of temperature and speed were significant at a level of 1%, while the size factor was not significant. None of the three factors' interactions had an effect on exergy losses. Minimum energy utilization and exergy loss occurred in the test treatment with a sample diameter of 1.3 cm, speed of 3 m s^{-1}, and temperature of 40°C. A lower drying temperature and a slower velocity are recommended for drying eggplants using the fluidized bed method.

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