Energy and Exergy Aanalyses of Drying of Eggplant Slices in a Cyclone Type Dryer

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In this paper, the energy and exergy analyses of the drying process of thin layer of eggplant slices are investigated. Drying experiments were conducted at inlet temperatures of drying air of 55, 65 and 75℃ and at drying air velocities of 1 and 1.5 ms^{-1} in a cyclone type dryer. Using the first law of thermodynamics, energy analysis was carried to estimate the ratios of energy utilization. However, exergy analysis was accomplished to determine type and magnitude of exergy losses during the drying process by applying the second law of thermodynamics. It was deduced that eggplant slices are sufficiently dried in the ranges between 55-75℃ of drying air temperature and at 1 and 1.5 ms^{-1} of drying air velocity during 12000-21600 s despite the exergy losses of 0-0.739 kJs^{-1}.

Key Words: Drying, Energy and Exergy Analyses, Eggplant

Nomenclature

A : Area, (m^2)
c_p : Specific heat, ($kJkg^{-1}K^{-1}$)
$\bar{c}_p$: Mean specific heat, ($kJkg^{-1}K^{-1}$)
E : Emissive power, energy utilization, (Js^{-1})
EUR : Energy utilization ratio ; (%)
Ex : Exergy, ($kJ\ s^{-1}$)
F : Shape factor
g : Gravitational acceleration, (ms^{-2})
g_c : Constant in Newton's law
h : Enthalpy, $kJkg^{-1}$
J : Joule constant
$\dot{m}$: Mass flow rate, (kgs^{-1})
N : Number of species
P : Pressure, (kPa)
$\dot{Q}$: Net heat, (kJs^{-1})
$\dot{Q}_{gda}$: The energy gained to drying air by heater, kJs^{-1}
Q_{Lcp} : The heat loss throughout the connection pipe between heater and drying chamber, kJs^{-1}

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s : Specific entropy, ($kJkg^{-1}K^{-1}$)
T : Temperature, (K)
u : Specific internal energy, ($kJkg^{-1}$)
v : Specific volume, (m^3kg^{-1})
V : Velocity, (ms-1)
w : Humidity ratio, (gg^{-1})
$\dot{W}$: Energy utilization, ($kJ\ s^{-1}$)
z : Altitude coordinate, m

Subscripts

a : Dry air
c : Chemical
cp : Connection pipe
da : Drying air (fresh air)
dc : Drying chamber
f : Fan
i : Inlet, inflow
L : Loss
mp : Moisture of product
o : Outlet, outflow
sat : Saturated
tr : Tray
∞ : Surrounding or ambient

Greek symbols

ϕ : Relative humidity, (%)
η_{Ex} : Exergetic efficiency, (%)
μ : Chemical potential, (kJkg-1)

1. Introduction

Drying is widely used in a variety of thermal energy applications ranging from food drying to wood drying. Utilization of high amount of energy in the drying industry makes drying one of the most energy-intensive operations with a great industrial significance. The objective of the dryer is to supply the product with more heat than is available under ambient conditions. Thus, sufficiently increasing the vapor pressure of the moisture held within the product to enhance moisture migration from within the product and significantly decreasing the relative humidity of the drying air to increase its moisture carrying capability and to ensure a sufficiently low equilibrium moisture content (Dincer, 2002).

During the past few decades, thermodynamic analysis, particularly exergy analysis, has appeared to be an essential tool for system design, analysis and optimization of thermal systems. From a thermodynamic point of view, exergy is defined as the maximum amount of work, which can be produced by a stream of matter, heat or work as it comes to equilibrium with a reference environment (Dincer, 2000).

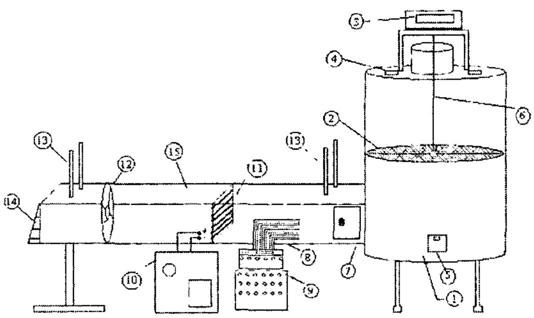
The exergy method can help further the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. Therefore, exergy analysis can reveal whether or not and by how much it is possible to design more efficient thermal systems by reducing the sources of existing inefficiencies. Increased efficiency can often contribute in a major way to achieving energy security in an environmentally acceptable way by the direct reduction of irreversibilities that might otherwise have occurred. This makes exergy one of most powerful tools to provide optimum drying conditions. Exergy analysis becomes more crucial, especially for the industrial (large-scale) high-temperature drying applications (Dincer and Sahin, 2004).

It is important to highlight that the exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change. A thorough understanding of exergy and the insights it can provide into the efficiency and environmental impact of drying systems, are required for engineers or researchers working in the area of drying technology. During the past decade, the need to understand the connections between exergy and energy impact has become increasingly significant (Dincer, 2002; Dincer and Sahin, 2004; Syahrul et al., 2002a, 2002b; Szargut et al., 1988; Rosen and Dincer, 2001).

Although numerous studies on the energy and exergy analysis of thermal systems and applications and industrial systems have recently been undertaken by some researchers, e.g., (Bejan et al., 1998; Kim, 1998; Noh et al., 2001; Bayrak et al., 2003; Kim et al., 2003; Verkhivker and Kosoy, 2001), very few papers have appeared on the energy and exergy analyses of drying systems and processes of fruits and vegetables (Dincer and Sahin, 2004; Syahrul et al., 2002a, 2002b; Midilli and Kucuk, 2003; Akpinar, 2004, Akpinar et al., 2005). Thus, the primary objective of this paper is to present energy and exergy analyses of drying process of eggplant slices in a cyclone type dryer.

2. Experimental Set-up

Figure 1 shows a schematic diagram of the cyclone type dryer. It consists of fan, resistance



1. Drying chamber, 2. Tray, 3. Digital balance, 4. Observed windows, 5. Digital thermometer, 6. The balance bar, 7. Control panel, 8. Thermocouples, 9. Digital thermometer and channel selector, 10. Rheostat, 11. Resistance, 12. Fan, 13. Wet and dry thermometers, 14. Adjustable flab, 15. Duct

Fig. 1 Experimental set-up

and heating control systems, air-duct, drying chamber in cyclone type, and measurement instruments. Air fan has a power of 0.04 kW. The airflow was adjusted through a variable speed blower and manually operated an adjustable flab in entrance. The heating system consisted of an electric 4000 W heater placed inside the duct. A rheostat, adjusting the drying chamber temperature, was used to supply heating control. The drying chamber was constructed from sheet iron in 600 mm diameter and 800 mm height cylinder. Drying air was tangentially entered in drying chamber. In this way, the samples were dried in swirl flow in place of uniform flow (Akpinar et al., 2003a ; Akpinar et al., 2003b).

In temperature measurements, J type iron-constantan thermocouples with the accuracy of ±0.1℃ were used with a manually controlled 20-channel automatic digital thermometer (Elimko 6400, Ankara, Turkey). A thermo hygrometer (Extech 444731, Shenzhen, China) with an accuracy of ±0.1 RH was used to measure humidity levels at various locations of the system.

The velocity of air passing through the system was measured with 0-15 m/s-capacity vane probe anemometer- (Lutron AM-4201, Taipei, Taiwan), with an accuracy of ±0.1 m/s. In the velocity measurements, the values of the velocity in the center of the drying chamber were taken into account. The tangential airflow was across the layer during drying process. Moisture loss was recorded at 20 min intervals during drying for determination of drying curves by a digital balance (Bel, Mark 3100, Monza, Italy). The measurement range was 0-3100 g with an accuracy of ±0.01 g. The effect of airflow on the weight measurements was little. Therefore, this effect was calibrated (Akpinar et al., 2003a ; Akpinar et al., 2003b ; Akpinar et al., 2003c).

2.1 Experimental procedure

Before drying process, the eggplants were cut into slices of 6 mm thickness and 30 mm diameters with a mechanical cutter. After the dryer is reached at steady state conditions for operation temperatures, the eggplant slices are put on the tray of dryer and left for drying. The initial and final moisture content of the eggplant slice specimens were determined at 80℃ by using a METTLER Infrared Moisture Analyser (Mettler LJ16, Greifensee, Switzerland) with an accuracy of ±0.001 g. This temperature value was taken from the drying studies in the literature (Togrul and Pehlivan, 2002). Generally, the initial and final moisture content of vegetables and fruits is determined at 80℃. Drying experiments were carried out at 55, 65, and 75℃ drying air temperatures and 1 and 1.5 ms^{-1} drying air velocities. The velocities and temperatures were measured in the center of drying chamber. External air temperatures changed between 21 and 23℃ and relative humidity of ambient air changed between 40% and 43%. The relative humidity of the drying air was determined as 15% at 55℃, 9% at 65℃ and 5% at 75℃. Drying of the eggplant slices started with an initial moisture content around 10.627 g water/g dry matter and continued until no further changes in their mass were observed, e.g. to the final moisture content of about 0.04 g water/g dry matter. The times to reach 0.04 g water/g dry matter moisture content from the initial moisture content at the various drying air temperature and velocity of the eggplant slices were found to be between 1200 and 21600 second. The drying time is shorter when the temperature is higher, which is explained by the increase in the drying rate. This increase is due to the increased heat transfer potential between the air and the eggplant slices, thus favouring the evaporation of the water from the eggplant slices. During the experiments, ambient temperature and relative humidity, inlet and outlet temperatures of drying air in the dryer chamber were recorded. Drying air at chamber went out from a flue in 200 mm diameter. The humidity and temperature of drying air were measured in the center of flue. The outlet temperature of drying air increased continuously with drying time. However, the outlet humidity of drying air decreased continuously with drying time.

3. Analysis

A thermodynamic model for energy and exergy

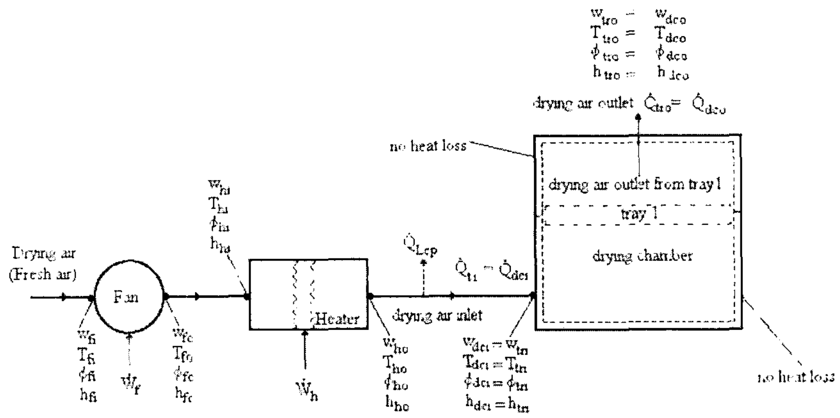


Fig. 2 Schematic illustration of the drying chamber, the tray and the connection pipe

analysis of drying process proposed by Midilli and Kucuk was applied to this study (Midilli and Kucuk, 2003). Drying process was considered as a steady-flow process in these analyses (Midilli and Kucuk, 2003). To benefit at the energy and exergy analysis was drawn schematic illustration of the drying chamber, the tray and the connection pipe (Figure 2).

3.1 The first law analysis: energy utilization

The air conditioning process throughout the drying of eggplant slices includes the processes of heating, cooling, and humidification. The air conditioning processes can be modelled as steady-flow processes that are analysed by applying the steady-flow conservation of mass (for both dry air and moisture) and conservation of energy principles. General equation of mass conservation of dry air (Midilli and Kucuk, 2003):

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} \tag{1}$$

General equation of mass conservation of moisture:

$$\sum(\dot{m}_{wi} + \dot{m}_{mp}) = \sum \dot{m}_{wo} \quad \text{or} \quad \sum(\dot{m}_{ai}w_i + \dot{m}_{mp}) = \sum \dot{m}_{ai}w_o \tag{2}$$

General equation of energy conservation:

$$\dot{Q} - \dot{W} = \sum \dot{m}_o\left(h_o + \frac{V_o^2}{2}\right) - \sum \dot{m}_i\left(h_i + \frac{V_i^2}{2}\right) \tag{3}$$

The changes in kinetic energy of air through the fan were taken into consideration while the potential and kinetic energy in other parts of the process were neglected. During the energy and exergy analyses of eggplant slices drying process, the following equations were generally used to compute the relative humidity and enthalpy of drying air. The relative humidity:

$$\phi = \frac{wP}{(0.622 + w)P_{sat@T}} \tag{4}$$

Where, w denotes the specific humidity, P atmospheric pressure, $P_{sat@T}$ the saturated vapor pressure of drying air.

The enthalpy of drying air:

$$h = c_{pa}T + wh_{sat@T} \tag{5}$$

Where, c_{pa} defines the specific heat of dry air, T drying air temperature and $h_{sat@T}$ enthalpy of the saturated vapor (Midilli and Kucuk, 2003).

3.1.1 Determination of the fan outlet conditions

The enthalpy equation of the fan outlet was derived (Cengel and Boles, 1994 ; Midilli and Kucuk, 2003) by using Eqs. (1-3) as below:

$$h_{fo} = \left[\left(\dot{W}_f - \frac{V_{fo}^2}{2*1000}\right)\left(\frac{1}{\dot{m}_{da}}\right)\right] + h_{fi} \tag{6}$$

Where, h_{fi} characterizes the enthalpy of drying air at the inlet of the fan, h_{fo} the enthalpy at the outlet of the fan, V_{fo} the drying air velocity at the outlet of the fan, $\dot{W}_f$ fan energy and $\dot{m}_{da}$ mass flow of drying air. Considering the values of dry-bulb temperature and enthalpy from Eq. (6), the specific and relative humidity of drying air at the outlet of the fan were determined by using the Psychometric Chart (Midilli and Kucuk, 2003).

3.1.2 Determination of the inlet and the outlet conditions of the heater

In order to determine the outlet conditions of the heater, it is assumed that there is no heat loss throughout the connection pipe between the fan and the heater, and thus, the inlet conditions of the heater are approximately equal to the outlet conditions of the fan, as given in Eq. (7).

$$\begin{aligned} w_{hi} &= w_{fo} \\ T_{hi} &= T_{fo} \\ \phi_{hi} &= \phi_{fo} \\ h_{hi} &= h_{fo} \end{aligned} \tag{7}$$

Where, subscript h_i defines the heater inlet, f_o fan outlet. Using the values of the outlet and inlet tem- peratures of the heater, the energy transmitted to drying air from heater may be calculated by the following equation.

$$\dot{Q}_{gda} = \dot{m}_{da} c_{Pda} (T_{ho} - T_{hi}) \tag{8}$$

Where, $\dot{Q}_{gda}$ refers to the energy gained to drying air by heater, T_{hi} and T_{ho} drying air temperatures at the inlet and outlet of the heater, respectively.

The relative humidity (ϕ_{ho}) and enthalpy (h_{ho}) at the outlet of the heater are respectively calculated using Eqs. (4) and (5) (Midilli and Kucuk, 2003).

3.1.3 Determination of the inlet conditions of drying chamber

The inlet temperature and relative humidity of drying air at the inlet of dryer should be firstly taken into consideration in order to determine the inlet conditions of drying chamber. However, the temperature measurements showed that little heat losses was taken place between the heater outlet and dryer inlet. Because of the heat losses in this part of the system, it should be definitely emphasized that the outlet conditions of the heater would not be equal to the inlet conditions of drying chamber. On the other words, the values of inlet temperatures of drying chamber are approximately 7-10℃ less than outlet temperatures of the heater. Hence, the quantity of the heat losses throughout the connection pipe between the heater and drying chamber can be estimated by the following equation.

$$\dot{Q}_{Lcp} = \dot{m}_{da} c_{Pda} (T_{ho} - T_{dci}) \tag{9}$$

Where, $\dot{Q}_{Lcp}$ defines the heat loss throughout the connection pipe between heater and drying chamber, T_{dci} temperature of drying air at the inlet of drying chamber. Furthermore, the inlet conditions of drying chamber are determined depending on inlet temperatures and specific humidity of drying air by using the Psychometric Chart (Midilli and Kucuk, 2003).

3.1.4 Determination of the outlet conditions of the drying chamber

The inlet conditions of the drying chamber were determined depending on the inlet temperatures and specific humidity of drying air. The inlet conditions of tray were assumed as equal to the inlet conditions of the drying chamber. Meanwhile, it was considered that the mass flow rate of drying air was equally passed throughout the tray. Thus, the inlet conditions of the tray can be written,

$$\begin{aligned} w_{dci} &= w_{tri} \\ T_{dci} &= T_{tri} \\ \phi_{dci} &= \phi_{tri} \\ h_{dci} &= h_{tri} \\ \text{and } \dot{m}_{da} &= \dot{m}_{datri} \end{aligned} \tag{10}$$

Using Eqs. (1 and 2), the equation of the specific humidity at the outlet of the tray was derived,

$$w_{tro} = w_{tri} + \frac{\dot{m}_{weggplant}}{\dot{m}_{da}} \tag{11}$$

Where, wtri denotes the specific humidity at the inlet of the tray, $\dot{m}_{weggplant}$ the mass flow rate of the moisture removed from eggplant slices. The relative humidity and enthalpy of drying air at the outlet of the tray were respectively estimated using Eqs. (4) and (5) (Midilli and Kucuk, 2003). During the humidification process at the tray, the heat used was calculated by using the following equations:

$$\dot{Q}_{tr} = \dot{m}_{da}(h_{tri} - h_{tro}) \quad (12)$$

Where, h_{tri}, h_{tro} identify orderly the enthalpies at the inlet and outlet of the tray. This energy is used both vaporization of moisture and to heat the eggplant slices. Energy used to heat the eggplant slices has a small effect in calculating energy utilization. But, the vaporization of moisture is more important in calculating energy utilization in the drying process.

The inlet conditions of tray were assumed as equal to the inlet conditions of the drying chamber. And also, the outlet conditions of tray were assumed as equal to the outlet conditions of the drying chamber. So, during the humidification process at the drying chamber, the heat used was calculated by using Eq. (12). The values of the relative humidity and enthalpy at the outlet of the chamber were calculated applying Eqs. (4) and (5). During the drying process, the energy utilization ratios of drying chamber were obtained (Midilli and Kucuk, 2003),

$$EUR_{dc} = \frac{\dot{m}_{da}(h_{dci} - h_{dco})}{\dot{m}_{da} c_{Pda}(T_{dci} - T_{hi})} \quad (13)$$

3.2 The second law analysis: exergy analysis

In the scope of the second law analysis of thermodynamics, total exergy inflow, outflow and losses of the tray and the drying chamber were estimated. The basic procedure for exergy analysis of the chamber is to determine the exergy values at steady state points and the reason of exergy variation for the process (Bejan, 1988). The exergy values are calculated by using the characteristics of the working medium from a first-law energy balance (Szargut et al., 1988). For this purpose, the following equation was employed (Ahern, 1980; Midilli and Kucuk, 2003).

$$\begin{aligned} Esergy = &\underbrace{(h-h_\infty)}_{enthalpy} - \underbrace{T_\infty(s-s_\infty)}_{entropy} + \underbrace{\frac{V^2}{2gJ}}_{momentum} + \underbrace{(z-z_\infty)\frac{g}{g_cJ}}_{gravity} \\ &+ \underbrace{\sum_c(\mu_c-\mu_{\infty})N_c}_{chemical} + \underbrace{E_iA_iF_i(3T^4-T_\infty^4-4T_\infty T^3)}_{radiation\ emission} + \cdots \end{aligned} \quad (14)$$

Where, the subscript ∞ denotes the reference conditions.

There are variations of this general exergy equation. In the analyses of many systems, some, but not all, of the terms shown in Eq. (14) are used. Since exergy is energy available from any source, the terms can be developed using electrical current flow, magnetic fields, and diffusional flow of materials. One common simplification is to substitute enthalpy for the internal energy and Pv terms that are applicable for steady flow systems. Eq. (14) is often used under conditions where the gravitational and momentum terms are neglected. In addition to these, the pressure changes in the system are also neglected because of $v \cong v_\infty$. In this case, Eq. (14) is derived as:

$$Exergy = \bar{c}_p\left[(T - T_\infty) - T_\infty \ln\frac{T}{T_\infty}\right] \quad (15)$$

Applying Eq. (15), the inflow, and outflow of exergy can be found depending on the inlet and outlet temperatures of the drying chamber. Hence, the exergy loss is determined by Eq. (16).

$$\begin{aligned} &Exergy\ loss = Exergy\ inflow - Exergy\ outflow \\ &\sum Ex_L = \sum Ex_i - \sum Ex_o \end{aligned} \quad (16)$$

The equation of exergy inflow can be written for the chamber and the tray as below:

$$Ex_{dci} = Ex_{tri} = \bar{c}_{Pda}\left[(T_{dci} - T_\infty) - T_\infty \ln\frac{T_{dci}}{T_\infty}\right] \quad (17)$$

Where, $\bar{c}_{Pda}$ defines the average specific heat of drying air.

The equation of exergy outflow can be also written, For the drying chamber and tray:

$$Ex_{dco} = Ex_{tro} = \bar{c}_{Pda}\left[(T_{dco} - T_\infty) - T_\infty \ln\frac{T_{dco}}{T_\infty}\right] \quad (18)$$

Moreover, the quantity of the exergy losses is calculated by applying Eq. (16) to Eqs. (17)-(18). Using the exergy calculations of this process, the Exergy Band Diagram was drawn as shown in Fig. 3.

The exergetic efficiency can be defined as the ratio of exergy outflow to exergy inflow for the chamber. Thus, the general form of exergetic efficiency is written as (Verkhivker and Kosoy, 2001; Midilli and Kucuk, 2003):

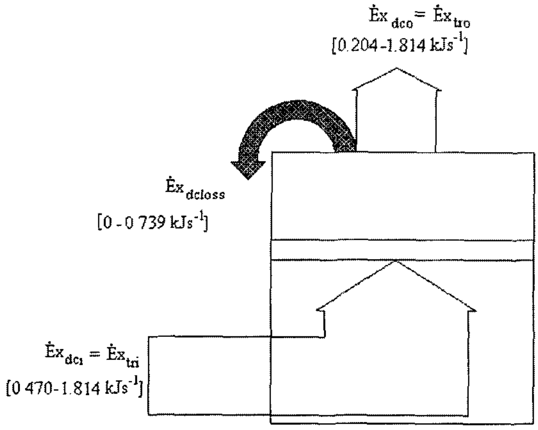


Fig. 3 Band diagram of exergy balance

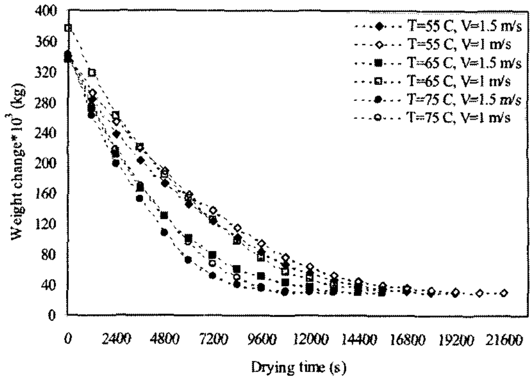


Fig. 4 Variation of weight change as a function of drying time

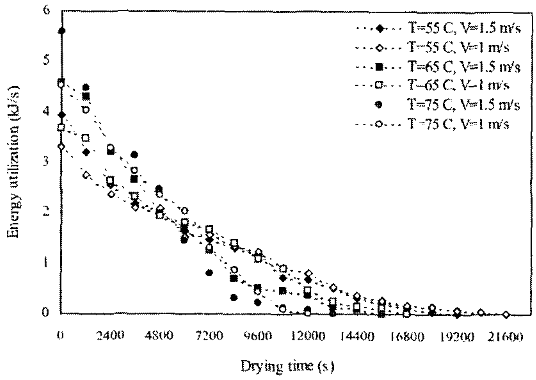


Fig. 5 Variation of energy utilization as a function of drying time

$$Exergetic\ Efficiency = \frac{Exergy\ outflow}{Exergy\ inf\ low}$$

$$\eta_{Ex} = \frac{Ex_o}{Ex_i} \tag{19}$$

4. Results And Discussion

The required data were obtained using the derived equations for the energy and exergy analyses, and presented in Figs. (4)-(10) and Tables 1 and 2.

Figure 4 presents the variations of weight change as a function of drying time at temperatures of 60, 70 and 80℃ based on the velocity of drying air. It was noticed from this figure that temperature and velocity of drying air affected on drying rates of eggplant slices. The velocity of drying air has little effect on the increase of drying rate. For example, drying rate of eggplant slices is 0.000181 (g-water/g-dry matter.s) at 75℃ and 1.5 ms^{-1} of drying air and 1200 s while drying rate of eggplant slices is 0.000164 (g-water/g-dry matter.s) at 75℃ and 1 ms^{-1} of drying air and 1200 s. However, drying rate of eggplant slices is 0.000132 (g-water/g-dry matter.s) at 55℃ and 1.5 ms^{-1} of drying air, 1200 s. It can be seen in the figure that the temperature of drying air significantly influences the drying time of eggplant slices. Increasing the temperature effectively reduces the moisture content of eggplant slices for the same period of drying time. Furthermore, increasing the temperature effectively increases the enthalpy of the drying air for the same period of time. A difference is found between the drying rates at different temperatures. These differences at the initial stage of drying are higher than at the final stage.

The amounts of the energy utilization in the drying chamber were calculated using Eq. (12), Table 1 presents the results of the energy analysis of this process. Figure 6 displays the variation of the energy utilization as a function of weight change while Figure 5 shows the variation of the energy utilization as a function of drying time at each of drying temperatures and velocities. The mass of eggplant slices decreased from approximately 340 g to 30 g in all experimental conditions. At drying air velocity of 1.5 ms^{-1}, the energy utilization varied in the ranges of 0-3.948 kJs^{-1} during 19200 s at drying air temperature of 55℃, in the ranges of 0-4.563 kJs^{-1} during 15600 s at drying air temperature of 65℃, and in the ranges of 0-5.590 kJs^{-1} during 13200 s at drying air temperature of 75℃. At drying air velocity of 1 ms^{-1}, the energy utilization varied in the ranges of 0-3.305 kJs^{-1} during 21600 s at drying air temperature of 55℃, in the ranges of 0-3.679 kJs^{-1} during 16800 s at drying air temperature of 65℃, and in the ranges of 0-4.521 kJs^{-1} during 12000 s at drying air temperature of 75℃. The energy utilization of drying chamber is higher at the beginning of the drying process than at the final stage. It was noticed that the energy utilization of drying chamber increased with the increase of drying air temperature and velocity and decreased with the increase of drying time.

Figure 7 exhibits the variation of the energy utilization ratio (EUR) as a function of drying

Table 1 The results of energy analysis

t	E	EUR	E	EUR	E	EUR	E	EUR	E	EUR	E	EUR
(s)	(kJs^{-1})	(%)	(kJs^{-1})	(%)	(kJs^{-1})	(%)	(kJs^{-1})	(%)	(kJs^{-1})	(%)	(kJs^{-1})	(%)
	T=55℃		T=65℃		T=75℃		T=55℃		T=65℃		T=75℃	
			V=1.5 ms^{-1}						V=1 ms^{-1}			
0	3.948	28.68	4.563	24.66	5.590	24.02	3.305	34.91	3.679	29.15	4.521	28.62
1200	3.226	23.43	4.314	23.31	4.481	19.25	2.752	29.07	3.490	27.64	4.033	25.53
2400	2.571	18.68	3.226	17.43	3.214	13.81	2.373	25.07	2.632	20.85	3.285	20.80
3600	2.165	15.73	2.665	14.40	3.137	13.48	2.112	22.31	2.331	18.47	2.839	17.97
4800	1.953	14.19	1.988	10.74	2.467	10.60	2.088	22.05	1.940	15.37	2.351	14.88
6000	1.633	11.86	1.685	9.10	1.448	6.22	1.526	16.12	1.814	14.37	2.022	12.80
7200	1.484	10.78	1.265	6.83	0.792	3.40	1.562	16.50	1.678	13.30	1.308	8.28
8400	1.308	9.50	0.700	3.78	0.316	1.36	1.358	14.34	1.408	11.15	0.859	5.43
9600	1.195	8.68	0.515	2.78	0.226	0.97	1.231	13.01	1.089	8.62	0.437	2.76
10800	0.721	5.24	0.469	2.53	0.113	0.48	0.931	9.83	0.887	7.03	0.090	0.57
12000	0.676	4.91	0.361	1.95	0.067	0.29	0.796	8.41	0.469	3.71	0.000	0.00
13200	0.518	3.76	0.149	0.80	0.000	0.00	0.525	5.55	0.246	1.95		
14400	0.324	2.36	0.090	0.48			0.360	3.80	0.144	1.14		
15600	0.225	1.63	0.000	0.00			0.264	2.79	0.117	0.93		
16800	0.112	0.81					0.165	1.74	0.000	0.00		
18000	0.058	0.42					0.156	1.65				
19200	0.000	0.00					0.075	0.79				
20400							0.060	0.63				
21600							0.000	0.00				

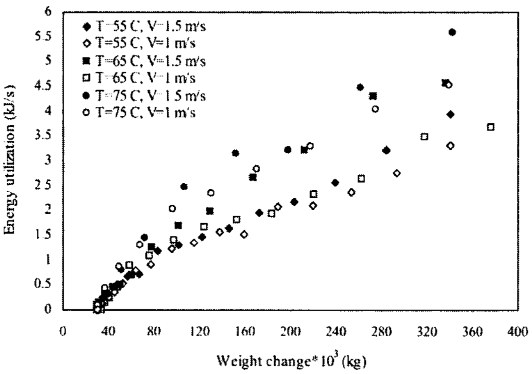


Fig. 6 Variation of energy utilization as a function of weight change

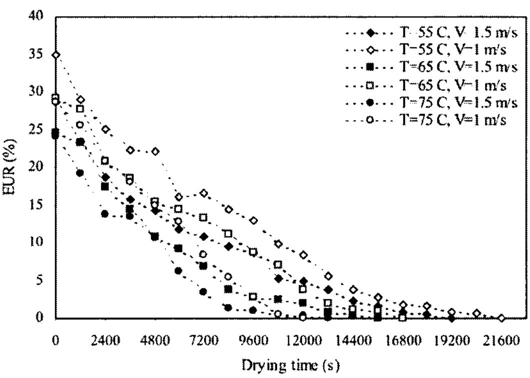


Fig. 7 Variation of energy utilization ratio as a function of drying time

time. The values of EUR are summarized in Table 1. It was determined that, using Eq. (13), EUR varied between 0-34.91 % depending on drying air temperature and velocity. It was noticed that EUR of drying chamber decreased with the increase of drying time. This is in fact by nature correct since the drying process itself is time dependent (i.e., transient). Moreover, EUR of drying chamber decreased with the increase of drying air temperature and velocity. Higher temperatures of drying air can be used which lead to the shorter drying times. The enthalpy

Table 2 The results of exergy analysis

t	Ex_{dl}	Ex_{do}	Ex_{dloss}	η_{ex}	Ex_{dl}	Ex_{do}	Ex_{dloss}	η_{ex}	Ex_{dl}	Ex_{do}	Ex_{dloss}	η_{ex}
(s)	(kJs^{-1})	(kJs^{-1})	kJs^{-1}	(%)	(kJs^{-1})	(kJs^{-1})	kJs^{-1}	(%)	(kJs^{-1})	(kJs^{-1})	kJs^{-1}	(%)
	T=55℃				T=65℃				T=75℃			
					V=1.5 ms^{-1}							
0	0.660	0.342	0.318	51.791	1.172	0.679	0.492	57.983	1.814	1.074	0.739	59.232
1200	0.660	0.393	0.268	59.490	1.172	0.703	0.469	59.997	1.814	1.207	0.607	66.547
2400	0.660	0.442	0.219	66.904	1.172	0.811	0.361	69.201	1.814	1.367	0.446	75.382
3600	0.660	0.474	0.187	71.713	1.172	0.869	0.303	74.173	1.814	1.377	0.436	75.935
4800	0.660	0.491	0.170	74.287	1.172	0.942	0.230	80.402	1.814	1.466	0.348	80.822
6000	0.660	0.517	0.144	78.257	1.172	0.976	0.196	83.259	1.814	1.605	0.208	88.516
7200	0.660	0.529	0.131	80.135	1.172	1.023	0.149	87.301	1.814	1.698	0.115	93.642
8400	0.660	0.544	0.116	82.381	1.172	1.088	0.084	92.872	1.814	1.767	0.047	97.434
9600	0.660	0.554	0.107	83.837	1.172	1.110	0.062	94.734	1.814	1.780	0.033	98.164
10800	0.660	0.595	0.066	90.081	1.172	1.116	0.056	95.191	1.814	1.797	0.017	99.080
12000	0.660	0.599	0.062	90.687	1.172	1.128	0.043	96.291	1.814	1.804	0.010	99.448
13200	0.660	0.613	0.047	92.822	1.172	1.154	0.018	98.462	1.814	1.814	0.000	100.000
14400	0.660	0.631	0.030	95.476	1.172	1.161	0.011	99.067				
15600	0.660	0.640	0.021	96.848	1.172	1.172	0.000	100.000				
16800	0.660	0.650	0.010	98.418								
18000	0.660	0.655	0.005	99.176								
19200	0.660	0.660	0.000	100.000								
	T=55℃				T=65℃				T=75℃			
	V=1 ms^{-1}											
0	0.470	0.204	0.266	43.341	0.820	0.422	0.398	51.515	1.256	0.660	0.596	52.577
1200	0.470	0.241	0.229	51.270	0.820	0.440	0.380	53.648	1.256	0.716	0.540	57.030
2400	0.470	0.268	0.202	57.064	0.820	0.523	0.297	63.801	1.256	0.806	0.450	64.166
3600	0.470	0.288	0.182	61.237	0.820	0.554	0.266	67.557	1.256	0.862	0.394	68.608
4800	0.470	0.289	0.180	61.628	0.820	0.595	0.225	72.589	1.256	0.925	0.331	73.625
6000	0.470	0.334	0.136	71.094	0.820	0.609	0.211	74.251	1.256	0.968	0.288	77.091
7200	0.470	0.331	0.139	70.467	0.820	0.623	0.196	76.050	1.256	1.067	0.190	84.876
8400	0.470	0.348	0.122	74.053	0.820	0.654	0.166	79.709	1.256	1.130	0.126	89.942
9600	0.470	0.358	0.111	76.310	0.820	0.690	0.130	84.119	1.256	1.192	0.065	94.823
10800	0.470	0.384	0.086	81.810	0.820	0.713	0.107	86.963	1.256	1.243	0.014	98.919
12000	0.470	0.396	0.074	84.345	0.820	0.762	0.057	93.002	1.256	1.256	0.000	100.000
13200	0.470	0.420	0.049	89.521	0.820	0.789	0.030	96.293				
14400	0.470	0.436	0.034	92.756	0.820	0.802	0.018	97.822				
15600	0.470	0.445	0.025	94.663	0.820	0.805	0.015	98.229				
16800	0.470	0.454	0.016	96.648	0.820	0.820	0.000	100.000				
18000	0.470	0.455	0.015	96.830								
19200	0.470	0.462	0.007	98.470								
20400	0.470	0.464	0.006	98.775								
21600	0.470	0.470	0.000	100.000								

of drying air also increases leading to higher EUR. It can be said that EUR is based on the structure and the moisture content of the dried products and could be assumed as an important parameter to analyze the energy utilization in drying process.

Table 2 presents the results of the exergy analysis. The exergy inflow rates were calculated using Eq. (17) depending on the ambient and inlet temperatures. The exergy inflow to the drying chamber varied between 0.470-1.814 kJs^{-1}. However, the exergy outflows were added up with Eq. (18). These values were obtained between 0.204-1.814 kJs^{-1}. It was observed that the exergy outflow from the drying chamber increased with the drying time. Additionally, at drying velocity of 1.5 ms^{-1}, the exergy losses were obtained as the ranges between 0-0.318 kJs^{-1} at drying air temperature of 55℃, 0-0.492 kJs^{-1} at drying air temperature of 65℃ and 0-0.739 kJs^{-1} at drying air temperature of 75℃ by using Eq. (16). At drying velocity of 1 ms^{-1}, the exergy losses were determined as the ranges between 0-0.0.266 kJs^{-1} at drying air temperature of 55℃, 0-0.398 kJs^{-1} at drying air temperature of 65℃ and of 0-0.596 kJs^{-1} at drying air temperature of 75℃. It was noticed that the exergy outflow and the exergy loss increased with the increase of drying air temperature and velocity. Figure 8 shows the variation of exergy loss with drying time for each of drying temperature and velocity. Also Figure 9 shows the variation exergy loss with weight change. These figures explanted that the exergy loss was high at the first periods of drying process and decreased towards the last periods of drying process. Thus, it can be inferred that it is necessary to show the variations of exergy with drying time in order to determine when and where the maximum values of the exergy losses took place during the drying process.

Figure 10 shows the variation of the exergetic efficiency as a function of drying time. The exergetic efficiency provides a true measure of the performance of a drying system from thermodynamic viewpoint. The exergetic efficiency was calculated by using Eq. (19) based on the inflow, outflow, and loss of exergy. The exergetic efficiency of the drying chamber increased with the increase of drying time. They varied at range of 43.341-100% on depending drying air tempera-

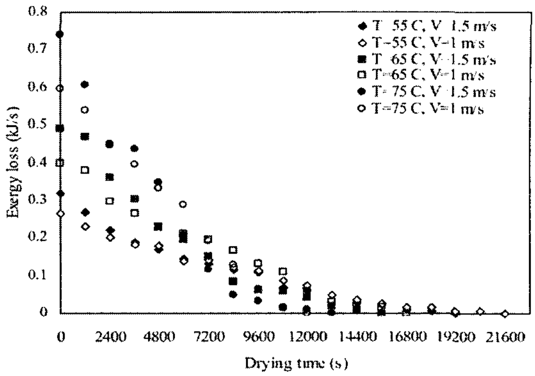


Fig. 8 Variation of exergy loss as a function of drying time

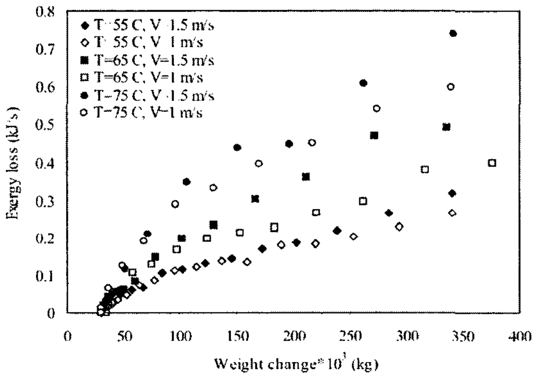


Fig. 9 Variation of exergy loss as a function of weight change

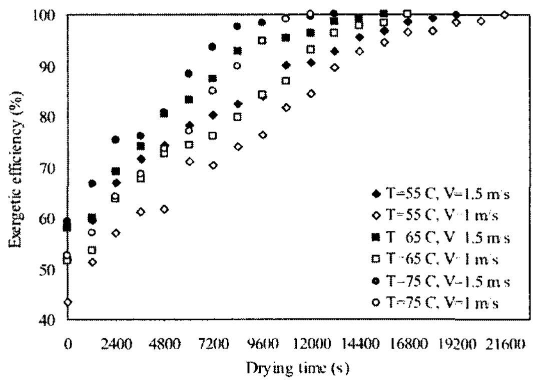


Fig. 10 Variations of exergetic efficiency with drying time

ture and velocity. It was realized that the exergy losses were equal to zero at the point where the exergetic efficiency was estimated as 100% due to discontinuity of drying process in the system. Moreover, it seems from Figs. 1 and 2 that exergy of outflow air goes to the environment and wasted. If the outflow exergy can be used in some other energy conversion equipment, the amount of the exergetic efficiency can be more increased.

5. Conclusions

Energy and exergy analyses of the drying process of the eggplant were accomplished in this study. The energy utilization of drying chamber increased with the increase of drying air temperature and velocity. It was noticed that the energy utilization and EUR of drying chamber decreased with the increase of drying time. Moreover, EUR of drying chamber decreased with the increase of drying air temperature and velocity. The inflow, the outflow, the loss of exergy varied depending on drying air temperature and velocity. It was observed that the exergetic efficiency values increased with the increase of drying time. And also, it was seen that the exergy inflow, exergy outflow, the exergy loss and the exergetic efficiency increased with the increase of drying air temperature and velocity.

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