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Performance assessment and optimization of industrial pasta drying

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SUMMARY

Drying is a high-energy-intensive operation and an important step in the pasta production. In this study, exergy analysis of a four-step drying system in a farfalle pasta production line using actual operational data obtained from a plant located in Izmir, Turkey, was performed. Exergy loss rates, evaporation rates, exergy efficiencies, and improvement in potential rates for each dryer section were determined in this drying system. The exergy efficiency values varied between 0.25% and 5.27% from the predrying to the final drying section. The exergy efficiency value for the entire drying system was calculated to be 2.96%, and the highest exergetic improvement in potential rate was 165.54 kW for the first dryer section. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS
drying; exergy analysis; pasta; improvement potential; performance analysis

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1. INTRODUCTION

Pasta is a fundamental element of the Mediterranean diet. It is extremely digestible because its carbohydrates suffer some fission processes that help digestion and its assimilation by our organism [1,2]. The process of drying is one of the oldest and common operations for the pasta production, and it is an important step in the industrial manufacture of pasta. The drying process plays a crucial role in assuring the final quality of product because the operational conditions may imply thermal and mechanical damage that affect final pasta texture [3]. For these reasons, much effort has been devoted to discovering optimum drying conditions [4,5]. This process is considerable not only for the final product quality but also for the cost of its manufacture.

Food drying is a high-energy-consuming process that should be adequately engineered and economically evaluated. It is reported that industrial dryers consume, on average, approximately 12% of the total energy used in manufacturing processes. In these processes, where drying is required, the cost of drying can approach to 60% to 70% of the total cost [6,7].

Exergy is based on the first and second laws of thermodynamics and combines the principles of conservation of energy and nonconservation of entropy. In other words, the first law of thermodynamics (energy analysis) is conventionally used to analyze energy consumption and plant/process performances, but unfortunately it is unable to account for the quality of energy. This is where exergy analysis becomes relevant. Exergy is a consequence of the second law of thermodynamics, and it measures the quality of energy in a plant or process. It is the available energy for conversion from a reservoir with reference to a specified datum, usually the ambient environmental conditions. The exergy method is useful for improving the efficiency of energy-resource use because it quantifies the locations, types, and magnitudes of wastes and losses [8,9]. The exergy method is related to the problem of defining how well an available work is used in actual process. During drying, a large portion of the exergy is used in the process, while the rest is lost or destroyed [10,11].

It has become apparent in recent years that energy resources are limited. Consequently, all industrial sectors in all parts of the world need to identify more efficient methods of energy utilization [12]. Thus, one of the most important challenges of the drying industry is to reduce the cost of energy sources for good quality dried products [7,13]. Therefore, the minimization of the exergy loss, independently of the primary source of energy, should be the main goal [14].

Although the energy analysis method has been widely used in evaluating the performance of food systems, studies on exergy analysis are relatively few in numbers compared with energetic assessments. Although some types of food processes in olive oil refining [15], sugar, [16,17] and orange juice productions [18] were investigated by exergy analyses, there are some more studies focused on drying food materials. In these studies, the drying process was thermodynamically modeled by Dincer and Sahin [19], whereas drying different products such as wheat kernel [7], pistachio [20], red pepper slices [21], potato [22], apple slices [23], pumpkin [24], laurel leaves [25,26], pasta [27], green olive [28], mint [29], potato [30], coroba [31], fish [32], carrot [33], plum [34], parsley [35], olive leaves [36], broccoli, [37] and different medicinal and aromatic plants (*Thymus vulgaris, Foeniculumvulgare, and Malvasylvestris*) [38] were evaluated in terms of energetic and exergetic aspects using various drying devices, such as fluidized bed, solar assisted, convective type, and heat pump dryers. Ozgener and Ozgener [39] and Ozgener [27] performed exergy analyses of final pasta-drying step of a three-step industrial pasta-drying system.

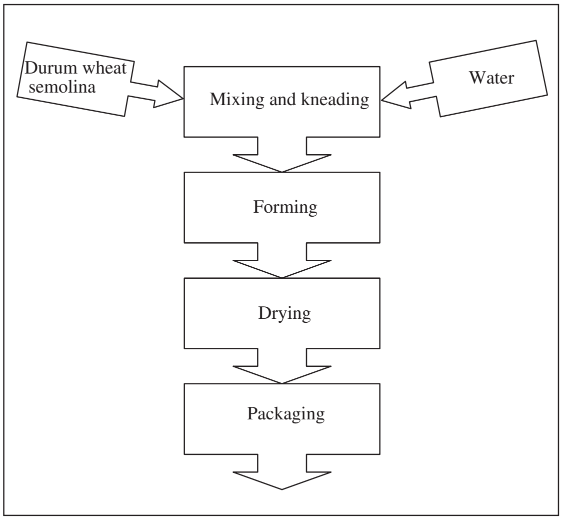

Figure 1. Flow diagram of pasta production.

Approximately 12.8 million tones of pasta are produced worldwide. Total pasta production of Turkey is estimated to be approximately 600,000 tons, and it ranks in the fifth order of the world production [40]. Hence, reducing the energy demand of pasta production is very important.

The main objective of this contribution is to perform exergy analysis of a four-step drying system in a farfalle pasta production line using actual operational data obtained from a plant located in Izmir, Turkey. In this regard, first, we will describe the pasta production line studied using a flow diagram. Then some energetic and exergetic relations were derived to analyze the system. Finally, the whole dryer and the individual components in terms of exergetic aspects were assessed while discussing the results obtained.

2. SYSTEM DESCRIPTION

Figure 1 represents schematically the dried pasta production process. Ingredients, basically water and durum wheat semolina, are mixed together under vacuum to give a dough with a water content percentage close to 29% (wet basis). The resulting dough is then sent into an extruder press and finally extruded through a head to obtain the desired pasta shape.

The drying process occurs in four steps. The extruded pasta dough come into a predrying section first, which includes shake trays. Moisture of entering pasta in this part is 28.64% and exiting 22.9%. The pasta dough comes then into a rotary drying section consisting of three rotary dryers. The moisture contents of the pasta exiting from the first, second, and rotary dryers are 15.24%, 14.30%, and 11.48%, respectively. Temperature and relative humidity values of the drying air in each dryer are given in Table I. These values have been measured at the plant. Figure 2 illustrates this system, where the drying air is heated with hot water at a temperature of 130 °C and a pressure of 2 bar.

Table I. Major property data for the four-step industrial pasta-drying system.

Unit		Temperature (°C)			Relative humidity (%)	Moisture content (%)	Mass flow rate (kgs^{-1})		
		Drying air	Pasta	Hot water	Drying air	Pasta	Drying air	Pasta[a]	Hot water
Predryer	Inlet	82.0	34.0	129.0	46.0	28.6	1.67	0.09	1.42
	Outlet	78.2	76.0	117.0	48.0	22.9	1.67	0.08	1.42
First Dryer	Inlet	53.0	70.0	129.0	47.0	22.9	6.27	0.08	1.42
	Outlet	49.0	47.4	117.0	48.0	15.2	6.27	0.07	1.42
Second dryer	Inlet	52.0	47.0	129.0	45.5	15.2	6.27	0.07	1.42
	Outlet	50.0	49.6	117.0	46.3	14.3	6.27	0.07	1.42
Third dryer	Inlet	50.6	49.0	129.0	42.0	14.3	5.35	0.07	1.42
	Outlet	49.7	48.8	117.0	43.6	11.5	5.35	0.07	1.42

[a]Mass flow rate of pasta included the dry material and moisture.

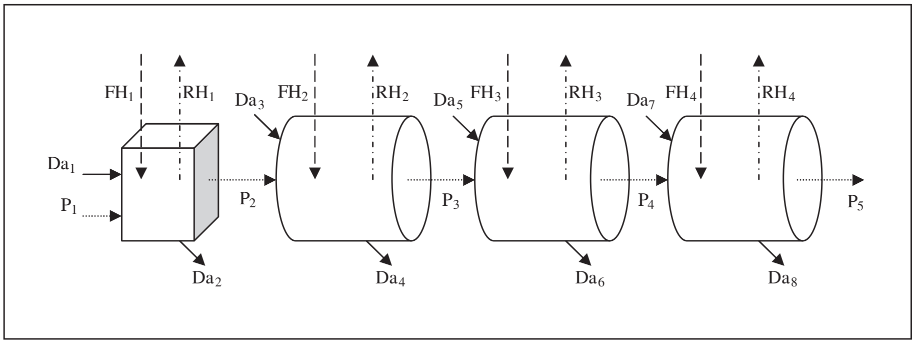

Figure 2. Schematic illustration of a four-step industrial farfalle pasta-drying system.

The boundary temperature of the drying chambers and the air velocity were also measured using a Fluke 61 infrared thermometer and a digital anemometer, respectively.

Moisture content of the pasta was determined by AOAC method at 70 °C and 400 mmHg in a vacuum oven. The composition of the pasta dough was determined using semolina composition, which was taken from the plant and is presented in Table II.

3. ANALYSES

3.1. Uncertainty analysis

Uncertainty analysis is needed to prove the accuracy of the experiments. An uncertainty analysis was performed using the method described by Holman [41]:

$$U_{\mathrm{F}} = \left[\left(\frac{\partial F}{\partial z_1} u_1 \right)^2 + \left(\frac{\partial F}{\partial z_2} u_2 \right)^2 + \ldots + \left(\frac{\partial F}{\partial z_n} u_n \right)^2 \right]^{1/2} \tag{1}$$

In the present study, the temperatures, pressures, relative humidities, and flow rates were measured with appropriate instruments clarified before. The total uncertainties of these parameters calculated are given in Table III.

3.2. Exergy analysis of the drying process

For a general steady-state, steady-flow process, the three balance equations, namely, mass, energy, and exergy balance equations, are used to find the heat input, the rate of exergy destruction, energy, and exergy efficiencies.

Table II. The composition of pasta dough.

Components	Mass fraction (%)
Water	28.64
Protein	8.63
Fat	0.25
Carbohydrate	62.48

Table III. Total uncertainties of the measured parameters and experimental results.

Description	Unit	Total Uncertainty (%)
Temperature of drying air	°C	1.59
Temperature of product	°C	1.59
Boundary temperature of drying chamber	°C	1.59
Mass flow rate of air	kg s^{-1}	3.00
Mass flow rate of product	kg s^{-1}	1.00
Relative humidity of drying air	%	0.1
Water content of product	%	1.0
Enthalpy of drying air	kJ kg^{-1}	0.1
Entropy of drying air	kJ kg^{-1} K^{-1}	0.1
Specific heat of product	kJ kg^{-1} K^{-1}	0.1
Entropy of product	kJ kg^{-1} K^{-1}	0.1

The mass balance equation can be expressed in the rate form as

$$\sum \dot{m}_{\mathrm{in}} \sum \dot{m}_{\mathrm{out}} \tag{2}$$

The general energy balance is written as

$$\sum \dot{E}_{\mathrm{in}} = \sum \dot{E}_{\mathrm{out}} \quad \text{or} \quad \dot{Q} + \sum \dot{m}_{\mathrm{in}} \dot{h}_{\mathrm{in}} = \dot{W} + \sum \dot{m}_{\mathrm{out}} \dot{h}_{\mathrm{out}} \tag{3}$$

The general exergy balance is expressed in the rate form as

$$\sum \dot{E}x_{\mathrm{in}} - \sum \dot{E}x_{\mathrm{out}} = \sum \dot{E}x_{\mathrm{dest}} \quad \text{or} \quad \sum \dot{m}_{\mathrm{in}} \psi - \sum \dot{m}_{\mathrm{out}} \psi - \sum \left(1 - \frac{T_0}{T_{\mathrm{s}}} \right) \dot{Q}_{\mathrm{loss}} - \dot{W} = \dot{E}x_{\mathrm{dest}} \tag{4}$$

$$\psi = (h - h_0) - T_0 (s - s_0) \tag{5}$$

$$\dot{E}x = \dot{m} \psi \tag{6}$$

The exergy destroyed or the irreversibility is expressed as follows

$$\dot{I} = \dot{E}x_{\mathrm{dest}} = T_0\dot{S}_{\mathrm{gen}} \tag{7}$$

To evaluate the entropy of moist air, the contribution of each component in the mixture is determined at the mixture temperature and the partial pressure of the component [42]:

$$s_{\mathrm{da}} = s_{\mathrm{a}} - R_{\mathrm{a}}\ln\frac{P_{\mathrm{a}}}{P_0} + w\left(s_{\mathrm{v}} - R_{\mathrm{v}}\ln\frac{P_{\mathrm{v}}}{P_0}\right) \tag{8}$$

The specific exergies at the inlet (ψ_{m1}) of the material and with a stream of drying air entering the dryer (ψ_{da1}) are calculated as follows, respectively [42]:

$$\psi_{\mathrm{m1}} = (h_{\mathrm{m1}} - h_{\mathrm{m0}}) - T_0(s_{\mathrm{m1}} - s_{\mathrm{m0}}) \tag{9}$$

$$\psi_{\mathrm{da1}} = (h_1 - h_0) - T_0(s_1 - s_0) \tag{10}$$

The exergy of an incompressible substance may be written as follows [43]:

$$\psi_{\mathrm{is}} = C\left(T - T_0 - T_0\left(\ln^{T}/_{T_0}\right)\right) \tag{11}$$

The heat transfer rate due to phase change ($\dot{Q}_{\mathrm{evap}}$), the rate of exergy transfer due to evaporation of the dryer ($E\dot{x}_{\mathrm{evap}}$), the heat transfer rate to the environment ($\dot{Q}_{\mathrm{loss}}$), and the rate of exergy loss to the surrounding ($E\dot{x}_{\mathrm{L}}$) are determined as follows, respectively [42]:

$$\dot{Q}_{\mathrm{evap}} = \dot{m}_{\mathrm{w}}h_{\mathrm{fg}} \tag{12}$$

$$\dot{E}x_{\mathrm{evap}} = \left(1 - \frac{T_0}{T_{\mathrm{m2}}}\right)\dot{Q}_{\mathrm{evap}} \tag{13}$$

$$\dot{E}x_{\mathrm{L}} = \left(1 - \frac{T_0}{T_{\mathrm{b}}}\right)\dot{Q}_{\mathrm{loss}} \tag{14}$$

The exergy balance equations for the predryer, first, second, and final rotary dryers may be written as follows:

(a) Predryer

$$\dot{E}x_{\mathrm{dest}} = \left(\dot{E}x_{\mathrm{FH1}} - \dot{E}x_{\mathrm{RH1}}\right) + \left(\dot{E}x_{\mathrm{Da1}} - \dot{E}x_{\mathrm{Da2}}\right) + \left(\dot{E}x_{\mathrm{P1}} - \dot{E}x_{\mathrm{P2}}\right) - \dot{E}x_{1,\mathrm{loss}} \tag{15}$$

(b) First rotary dryer

$$\dot{E}x_{\mathrm{dest}} = \left(\dot{E}x_{\mathrm{FH2}} - \dot{E}x_{\mathrm{RH2}}\right) + \left(\dot{E}x_{\mathrm{Da3}} - \dot{E}x_{\mathrm{Da4}}\right) + \left(\dot{E}x_{\mathrm{P2}} - \dot{E}x_{\mathrm{P3}}\right) - \dot{E}x_{2,\mathrm{loss}} \tag{16}$$

(c) Second rotary dryer

$$\dot{E}x_{\mathrm{dest}} = \left(\dot{E}x_{\mathrm{FH3}} - \dot{E}x_{\mathrm{RH3}}\right) + \left(\dot{E}x_{\mathrm{Da5}} - \dot{E}x_{\mathrm{Da6}}\right) + \left(\dot{E}x_{\mathrm{P3}} - \dot{E}x_{\mathrm{P4}}\right) - \dot{E}x_{3,\mathrm{loss}} \tag{17}$$

(d) Final rotary dryer

$$\dot{E}x_{\mathrm{dest}} = \left(\dot{E}x_{\mathrm{FH4}} - \dot{E}x_{\mathrm{RH4}}\right) + \left(\dot{E}x_{\mathrm{Da7}} - \dot{E}x_{\mathrm{Da8}}\right) + \left(\dot{E}x_{\mathrm{P4}} - \dot{E}x_{\mathrm{P5}}\right) - \dot{E}x_{4,\mathrm{loss}} \tag{18}$$

3.3. Determination of thermal properties of pasta

In this study, the specific heat for foods is determined using the relations proposed by Choi and Okos [44]:

$$C = \sum C_iX_i \tag{19}$$

with the specific heat of pure components given as [45]

$$C = C_{\mathrm{w}}X_{\mathrm{w}} + C_{\mathrm{p}}X_{\mathrm{p}} + C_{\mathrm{f}}X_{\mathrm{f}} + C_{\mathrm{c}}X_{\mathrm{c}} + C_{\mathrm{fi}}X_{\mathrm{fi}} + C_{\mathrm{ash}}X_{\mathrm{ash}} \tag{20}$$

The enthalpy of pasta is written in terms of specific heat [45]. Assuming a constant C over the temperature range, Equation (19) is reduced to

$$h = \sum C_iX_i(T_{\mathrm{m}} - T_0) \tag{21}$$

where T_0 is the reference temperature, which is taken to be 0 °C in this study, and T_{m} is the temperature of food item in degrees Celsius.

The specific entropy of pasta at the inlet temperature ($T_{\mathrm{m,in}}$) is calculated as [42]

$$s_{\mathrm{m}} - s_{\mathrm{mo}} = C_{\mathrm{m}}\ln(T_{\mathrm{m}}/T_0) \tag{22}$$

where T_0 is the reference temperature, which is taken to be 30 °C in this study.

3.4. Exergetic performance parameters

Exergy efficiency is defined as the ratio of total exergy out to total exergy in where "out" refers to "net output" or "product" or "desired value" and "in" refers to "given" or "used" or "fuel." Hence, the exergy efficiency of the each dryer and entire drying system can be defined as the ratio of the evaporation exergy to exergy inflow. Exergy efficiency is calculated in this study as

$$\eta_{\mathrm{ex}} = \frac{\dot{E}x_{\mathrm{evap}}}{\dot{E}x_{\mathrm{in}}} \tag{23}$$

Van Gool [46] had also proposed that maximum improvement in the exergy efficiency for a process or system was obviously achieved when the exergy loss or irreversibility ($\dot{E}x_{\mathrm{in}} - \dot{E}x_{\mathrm{out}}$) was minimized. Consequently, he suggested that it was useful to use the concept of an exergetic "improvement potential" when analyzing different processes or sectors of the economy. This improvement in potential in the rate form, denoted $\dot{\mathrm{IP}}$, is given by Hammond and Stapleton [47], was calculated in this study:

$$I\dot{P} = (1 - \eta)\left(\dot{E}x_{in} - \dot{E}x_{out}\right) \tag{24}$$

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4. RESULTS AND DISCUSSION

The thermodynamic properties are based on the actual operational data taken from a farfalle pasta-drying section, installed in a factory, located in Izmir, Turkey. The major property data for the drying system illustrated in Figure 2 are summarized in Table I. In this study, the restricted dead state was taken to be the state of environment at which the temperature and the atmospheric pressure are 30 °C and 101 kPa, respectively, which were the values measured at the time when the drying section data were obtained.

It is well known that errors and uncertainties in any experiments can arise from instrument selection, instrument condition, instrument calibration, environmental conditions, observation and reading, and test planning. Uncertainty analysis is needed to prove the accuracy of the experiments. Uncertainties of the experimental measurements and total uncertainties for some predicted values are listed in Tables III and IV. The maximum uncertainty values obtained from the uncertainty analysis were under 5%, which is reasonable for an experimental study [48–50].

The polynomial relations for the variations of specific heat and enthalpy of pasta with temperature and composition are obtained with the help of a regression program using the numerical values of specific heats and enthalpies at some temperatures from Mannaperuma and Singh [51]. The entropy of the pasta at the inlet and outlet is calculated from Equation (23). With thermodynamic date obtained from the system, exergy loss rates, evaporation rates, exergy destruction rates, exergy efficiencies, and improvement in potential rates for all system components and the entire system were calculated and summarized in Table V.

Table IV. Total uncertainties associated with the calculated values.

		Total uncertainty (%)			
Description	Unit	Predryer	First dryer	Second dryer	Third dryer
$\dot{E}x_{loss}$	kJ s^{-1}	1.92	1.36	0.42	0.20
$\dot{E}x_{evap}$	kJ s^{-1}	3.69	2.69	1.26	0.09
$\dot{E}x_{dest}$	kJ s^{-1}	4.25	3.14	2.56	0.92
η_{ex}	(%)	0.03	0.02	0.01	0.01
$\dot{IP}$	kJ s^{-1}	0.13	0.06	0.03	0.01

Table V. Values of exergy loss rates, evaporation rates, exergy destruction rates, exergy efficiencies, and improvement in potential rates for each dryer and entire system.

	$\dot{E}x_{loss}$	$\dot{E}x_{evap}$	$\dot{E}x_{dest}$	η_{ex}	$\dot{IP}$
Unit	(kJ s^{-1})	(kJ s^{-1})	(kJ s^{-1})	(%)	(kJ s^{-1})
Predryer	42.57	62.70	117.74	5.27	111.54
First dryer	27.38	42.07	171.93	3.72	165.54
Second dryer	7.26	19.22	110.75	1.81	108.75
Third dryer	0.94	2.15	62.83	0.25	62.68
Entire system	78.15	126.14	463.25	2.96	525.37

The highest exergy efficiency was obtained from the predryer, followed by the first and second dryers. The third dryer had the lowest exergy efficiency. The results showed that evaporation exergy was the main parameter that affects the exergy efficiency. Although the evaporation exergy values of the predryer were 1.49, 3.26, and 29.14 times bigger, exergy efficiency values were 1.42, 2.92, and 21.28 times bigger than the first, second, and third dryers, respectively.

Although the predryer's drying air temperature was higher than the first dryer, the first dryer had the highest exergy destruction value (Table V). The reason of this was the drying air mass flow rates. The drying air mass flow rate of the first dryer was 3.75 times bigger than the predryer. If the drying air mass flow rates were equalized, the predryer's exergy destruction rate would approximately be two times higher than the first dryer's. There was a similar circumstance about the remarks of the variation of IP rates, and the highest IP rate was obtained from the first dryer (Table V). Apart from these, Grassmann diagrams, which give the quantitative information related to the share of the exergy input to the pasta-drying system for all dryers, were presented and shown in Figure 3. Because of the Grassmann diagram, it is obvious that reusing of hot water would cause significant improvements in the system performance as more than 80% of the stream was unused.

The mass flow rates of streams, the surface temperatures of dryers, and the ambient temperature values were changed to evaluate the effects and weights of these parameters on process performance (Figures 4–9). The hot water stream was used to heat the drying air temperature, and it caused an important entropy generation because its temperature degree was high. The decrease in the mass flow rate of hot water stream caused an increase in the process performance (Figure 4). The rise in mass flow rate of dried product caused an increase in the process efficiencies. The reason lied behind this fact was the capacity increase in drying process that caused an increase in evaporation rates (Figure 5). Similar observations were seen in different studies in the literature [19,28,33]. As mentioned earlier, the increase in the mass flow rates of drying air resulted in the increase in exergy destructions and also in the decrease in exergy efficiencies (Figure 6). This situation could be clearly seen on the performance variation of the predryer. The rising of the mass flow rates of drying air streams from 1 to 7 kg/s caused a decrease of 4.66, 2.64, 2.57, and 2.40 times in the exergy efficiencies of the predryer, first dryer, second dryer, and third dryer, respectively. Dincer and Sahin [19] calculated that the rise in the mass flow rate of drying air caused a decrease in exergy efficiency as in this study.

The effect of the variation of surface temperature of dryers on the exergy losses for each dryer is illustrated in Figure 7. The exergy losses were associated with the transfer of exergy through material and energy streams to the surroundings [52]. The exergy losses for all dryers increased as the boundary temperature increased. Similar results were obtained in the literature [28,29]. The highest exergy losses were obtained from the first dryer, followed by the predryer. Figure 8 showed the variation of the IP rates of the drying processes with boundary temperatures. The highest IP rates were calculated for the predryer,

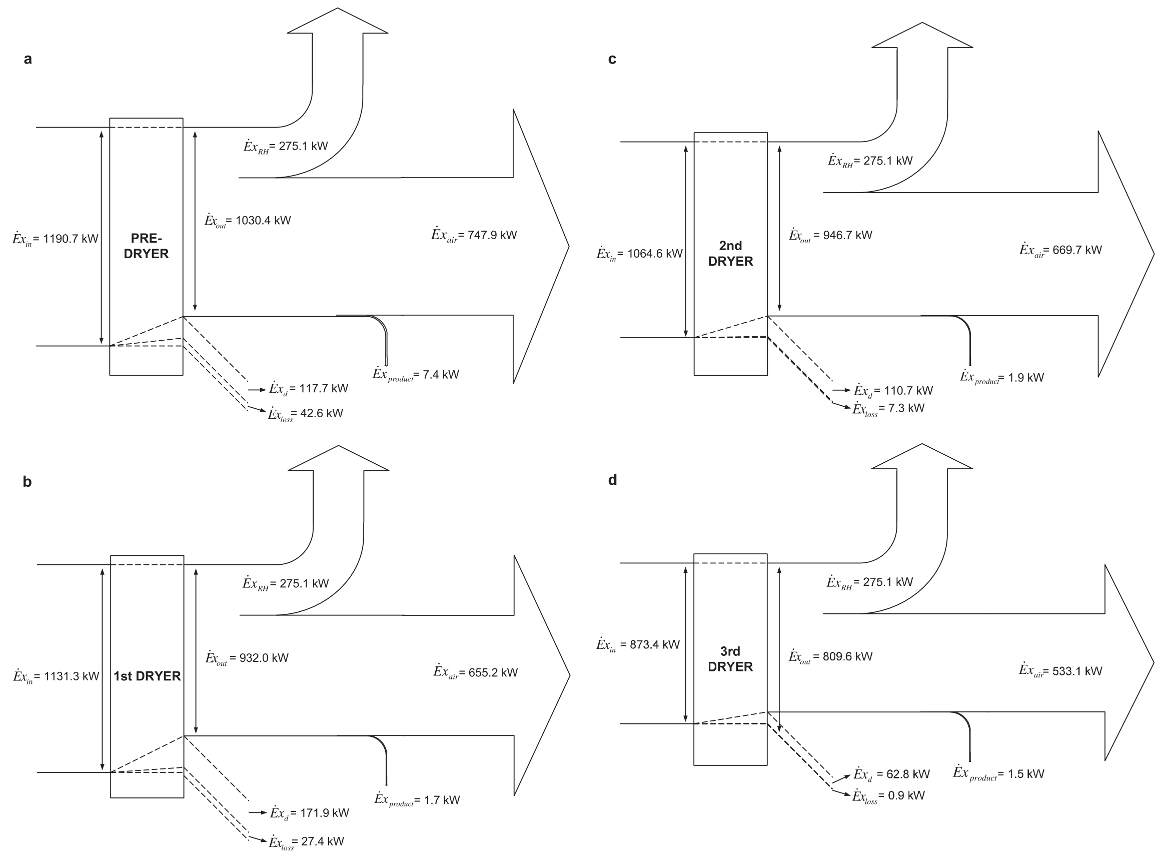

Figure 3. Exergy loss, destruction, and flow diagram (Grassmann diagram) for the pasta-drying system for each dryer; (a) predryer, (b) first dryer, (c) second dryer, and (d) third dryer.

followed by the first dryer. For interpreting Figures 7 and 8, it is important to calculate the amounts of exergy that was handled by each dryer. They can be calculated as the ratio of the sum of the inlet exergy streams for each dryer and total fuel exergy. It is calculated that 29.35%, 27.13%, 24.99%, and 18.49% of the total exergy was handled in the predryer, first dryer, second dryer, and third dryer, respectively. It is obvious that the rise in the ratio of the amount of exergy handled in the dryer would cause an increase in the exergy loss. Although the higher amount of exergy was handled by the predryer, the exergy loss of exergy in the predryer was lower than the first dryer. The only reason that lies behind this case was the effective isolation of the predryer. In other words, the results showed that the isolation of the first dryer should be checked and improved.

For evaluating the effects of ambient temperature during the drying process on the drying process performance was examined in this study by performing the exergy analysis with different dead state temperatures (Figure 9). The exergy efficiencies of all dryers increased as the dead state temperatures decreased. The decreases in the ambient temperature caused increases in the exergy losses, and this increase affected the first dryer more than the predryer because of the improper isolation of the first dryer. On the other hand, the evaporation rates were increased at the low dead state temperatures, and this increase was higher than the increase in exergy losses, so the rise in the dead state temperatures caused decreases in exergy efficiencies (Figure 9). Gungor *et al.* [38] dried three different medicinal and aromatic plants and showed the effect of ambient temperature on exergy efficiencies. They found a positive correlation between the ambient temperature and the exergy efficiency [38].

The entire system's IP rate and exergy efficiency value were calculated as 525.37 kW and 2.96%, respectively. Although there were other two studies focused on the exergetic performance of pasta-drying process, their exergy efficiency values were not similar to the values obtained in the present study. The exergy efficiency values varied between 65.4% and 82.2% [27,39]. However, this confusion is not specific for just pasta drying. There are diverse and inconsistent results about the drying process efficiency in the literature. In various studies, different exergy efficiency equations were used. Kuzgunkaya and Hepbasli [25] performed the exergy analysis of drying laurel leaves, and they used two different equations, which were used in the literature. One of them was Dincer and Sahin's [19] approach, as used in this study, and the other one was the ratio of the exergy difference (inlet exergy–outlet exergy) to exergy inflow. The authors calculated the exergy efficiencies in the

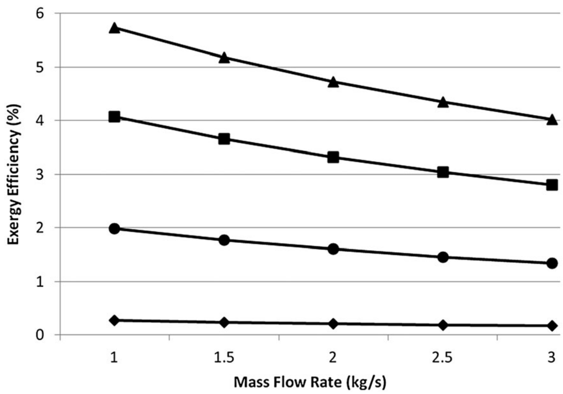

Figure 4. Variation of exergy efficiencies with mass flow rates of hot water for each dryer; predryer, first dryer, second dryer, and third dryer.

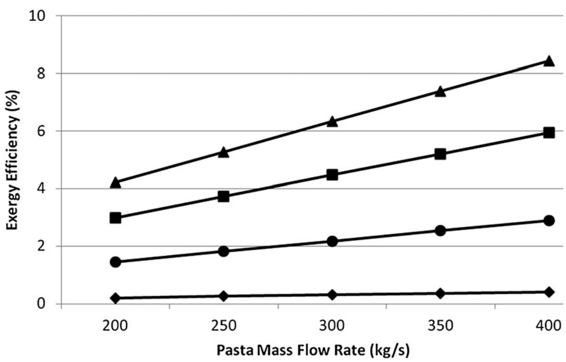

Figure 5. Variation of exergy efficiencies with mass flow rates of pasta for each dryer; predryer, first dryer, second dryer, and third dryer.

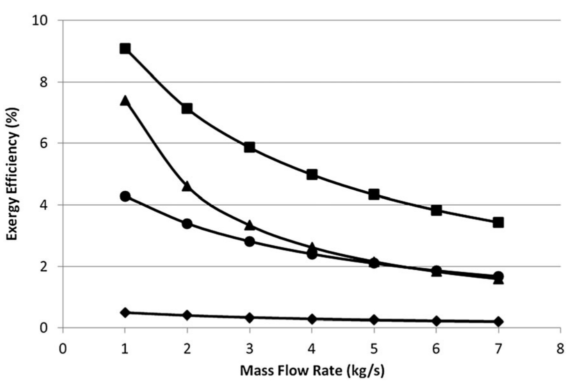

Figure 6. Variation of exergy efficiencies with mass flow rates of drying air for each dryer; predryer, first dryer, second dryer, and third dryer.

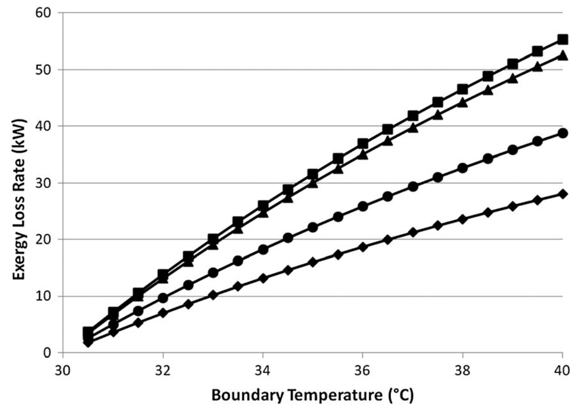

Figure 7. Variation of exergy loss rates with different boundary temperatures for each dryer; predryer, first dryer, second dryer, and third dryer.

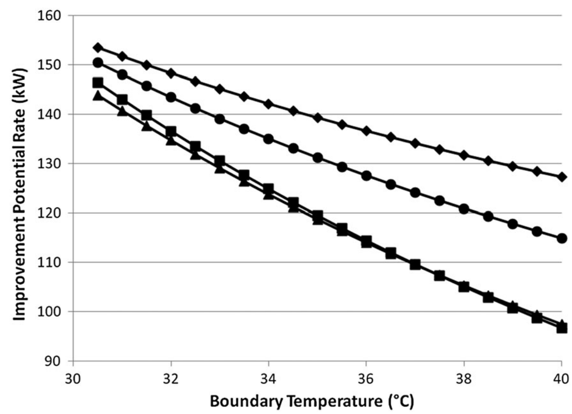

Figure 8. Variation of improvement in potential rates with different boundary temperatures for each dryer; predryer, first dryer, second dryer, and third dryer.

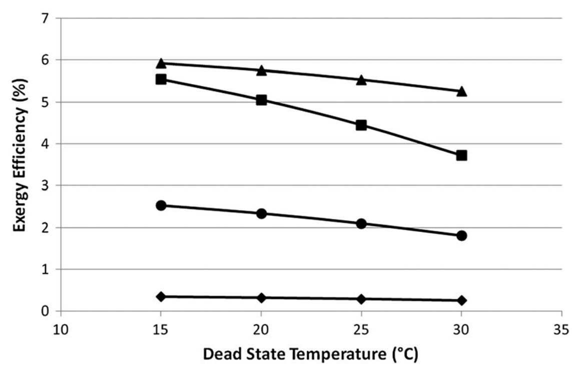

Figure 9. Variation of exergy efficiencies with dead state temperature for each dryer; predryer, first dryer, second dryer, and third dryer.

range of 9.1% to 15.5% with the first equation (close to the results of the present study) and 81.4% to 87.5% using the second equation under the same conditions. Hence, the discussion of the present study's results included only the studies that used the method described by Dincer and Sahin [19]. Dincer and Sahin [19] presented the exergetic model for drying processes and calculated the exergetic efficiency values in the range of 12% to 15% in an illustrative example. Gungor *et al*. [38] studied with three different medicinal and aromatic plants and obtained that the exergetic efficiencies varied between 0.6% and 1.8%, between 1.1% and 3.1%, and between 1.4% and 3.9% with *T. vulgaris*, *F. vulgare*, and *M. sylvestris*, respectively. All these results were similar with the present study.

5. CONCLUSION

The performance of a four-step industrial farfalle pasta-drying system along with every stage using exergy analysis method was evaluated in this study. The actual operational data obtained from the measurements in the farfalle drying unit of a factory, located in Izmir, Turkey, was used to analyze the system along with its main components. Although Grassmann diagrams were presented for each dryer, the effects of the mass flow rates of streams, the boundary temperatures of the dryers, and the ambient temperatures on the performance of the dryers were investigated.

The main conclusions drawn from the results of the present study are as follows:

(a) Although the exergy efficiency values of the four step drying system were determined tobe between 0.25% and 5.27%, the main parameter affecting the exergy efficiency was the evaporation exergy.
(b) In contradistinction to the variation of mass flow rate of dried product, the decrease in the mass flow rates of hot water and drying air temperature caused increases in the exergy efficiencies of the drying processes.
(c) Although exergy losses decreased as the boundary temperature decrease, the weight of exergy destructions on the overall system performance increased, hence the IP rates increased.
(d) It is obvious that the isolation of the dryers affects the performance of the process significantly.
(e) Instead of having separate hot water entry in each dryer, reusing return hot water flows in the following drying sections for heating of drying air would cause substantial improvement in the system performance.
(f) Performing an exergoeconomic analysis, which is a combination of exergy and economics, is recommended for a future work.

NOMENCLATURE

C = specific heat, kJ kg^{-1} K^{-1}
$\dot{E}$ = net energy transfer rate, kJ s^{-1} or kW
$\dot{E}x$ = exergy rate, kJ s^{-1} or kW
h = specific enthalpy, kJ kg^{-1}
$\dot{I}$ = rate of irreversibility (exergy destroyed), kJ s^{-1} or kW
$I\dot{P}$ = rate of improvement potential, kJ s^{-1} or kW
$\dot{m}$ = mass flow rate, kg s^{-1}
P = pressure, kPa
$\dot{Q}$ = heat transfer rate, kJ s^{-1} or kW
R = gas constant, J kg^{-1} K^{-1}
$\dot{S}$ = rate of entropy, kJ s^{-1} K^{-1}
s = specific entropy, kJ kg^{-1} K^{-1}
T = temperature, °C or K
t = time, s
$\dot{W}$ = work rate, kJ s^{-1} or kW
X = weight fraction of dry matter, dimensionless

Greek symbols

η = exergy efficiency, dimensionless
ψ = flow exergy, kJ kg^{-1}
w = specific humidity, g g^{-1}

Subscripts

a = air
b = boundary
c = carbohydrate
da = drying air
dest = destroyed, destruction
e = energy
evap = evaporation
ex = exergetic, exergy
f = fat
fi = fiber
FH = flow hot water
gen = generation
in = inlet
is = incompressible substance
k = location
L = loss
m = material
out = outlet
p = protein
P = Product
RH = return hot water
v = vapor
w = water
0 = restricted dead state

Superscripts

Over dot quantity per unit time (rate)

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