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Performance Assessment of a Potato Crisp Frying Process

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Performance Assessment of a Potato Crisp Frying Process

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Frying is a common and popular cooking method, which has been widely used in food manufacturing, though it is a very energyintensive process. Energy analysis has been commonly used to assess the performance of fryers. In this study, we attempted to exergetically assess the performance of a potato crisp frying system, which consists of three main components, a combustor, a heat exchanger, and a fryer. In the analysis, we utilized the actual operational data obtained from the literature. We determined exergy destruction in each system component and the whole system. We calculated universal and functional exergy efficiency values for the system components and compared them with each other. We also undertook a parametric study to investigate how the overall cycle performance was affected by changing the reference environment temperature and some operating conditions. We illustrated the exergy results through the Grassmann (exergy loss and flow) diagram. We calculated the universal exergetic efficiency values of 58, 82, and 77% for the combustor, heat exchanger, and fryer, respectively, with a universal exergetic efficiency value of 4% for the whole frying system. We found that the fryer had the highest functional exergetic efficiency value of 74%, followed by the heat exchanger with 47%and the combustor with 0.08%.

Keywords Energy analysis; Exergy; Exergy analysis; Performance assessment; Potato frying

INTRODUCTION

Potato (*Solanum tuberosum*) is among the world's major agricultural crops, consumed by millions of people from diverse cultural backgrounds even on an everyday basis. Potatoes are cultivated in approximately 80% of all countries and worldwide production stands in excess of 300 million tons per year.^[1,2]

Frying is among the oldest methods for food preparation, dating back to 1600 BC,^[3] though it is considered to be a very energy-intensive process because it involves the evaporation of significant quantities of oil.^[4] It is also essentially a dehydration process, where an effective medium of heat

transfer is provided by the oil. As a result, part of the frying oil is absorbed by the food, considerably contributing to the quality of the fried product. During frying, the oil is exposed continuously or repeatedly to elevated temperatures in the presence of air and moisture.^[3] In food manufacturing, fuel-fired boilers and direct heating systems use about 68% of the energy for process and space heating purposes. From the remainder, 16% is electrical energy used by electric motors, 8% is used by electric heating, 6% by refrigeration equipment, and the remaining 2% by air compressors.^[4,5]

The potato chip market in Turkey has only developed within the last 10 years. The annual per capita consumption of potato chips remains less than 1 kg in Turkey, although the size of the potato chip market has grown at a yearly rate of 115%, increasing from 15,225 tonnes in 2002 to 32,850 tonnes in 2004.^[6] The Turkish potato chips market also increased at a compound annual growth rate of 8.4% between 2004 and 2009.^[7]

Energy analysis is based on the first law of thermodynamics, which is expressed by the principle of the conservation of energy. It also provides no information about the irreversibility aspects of thermodynamic processes and does not distinguish the different qualities of energy such as heat quality, which depends on the heat source temperature. Due to these deficiencies and shortcomings of energy analysis, exergy analysis is considered a more powerful tool for assessing the performance of thermal systems. *Exergy* may be defined in various ways. According to one definition, it is the maximum amount of work obtainable from a stream of matter, heat, or work when some matter is brought to a state of thermodynamic equilibrium with the common components of natural surroundings by means of reversible processes.^[8,9]

As far as energetic assessment and modeling studies conducted on potato crisp frying processes are concerned, Wu et al.^[4] performed energy analysis of a potato crisp frying line based on operational data. Most of the energy used in the process was due to the evaporation of water contained in the potatoes and on the surface of the slices, which represented over 90% of the energy input to the fryer. The frying oil was heated by an industrial gas furnace

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and the efficiency of this process was calculated to be 84%. The overall efficiency of the frying system was determined to be on the order of 70%. Wu et al.^[10] developed a quasi-steady-state model to simulate the behavior of a continuous frying system using the MATLAB/Simulink environment. The model consisted of three major components, namely, a combustor, a heat exchanger, and a fryer. The impact of the design and control parameters on the energy consumption of the system was investigated. Wu et al.^[11] developed a 2D fryer model to investigate the effect of different control parameters on final product properties. They proposed some correlations for the determination of the moisture content and the oil content of crisps. The correlations were based on the important fryer control variables, namely, the supply oil temperature, potato mass throughput, fryer paddle velocity, and crisp takeout velocity. The correlations were also validated against data obtained from an industrial continuous fryer system. The three studies^[4,10,11] based on energetic approaches were performed by the same coinvestigators. Considering exergy analyses applied to various food processes by some investi-gators,^[12–16] Erbay and Hepbasli^[14] studied exergy analysis of a heat pump drying system and they reported that inefficiencies were mainly caused by internal operating conditions. In another study of Icier et al.,^[15] broccoli was dried in three different drying systems and they reported that increasing the drying air temperature resulted in an increase in the exergy destruction in both the tray and the heat pump dryer. On the other hand, the effect of ambient temperature on the performance of the dryer system was investigated by Gungor et al.^[16] and it was found that

the performance of the system reached its highest value at a low ambient temperature (0°C). No studies on comprehensive exergetic assessment of the production lines of fried potato products, such as potato chips and french fries, have appeared in the open literature to the best of the authors' knowledge. This was the main motivation behind performing this study.

SYSTEM DESCRIPTION

Figure 1 illustrates a schematic of the system of a potato crisp frying process. This process was adopted from a study conducted by Wu et al.^[4] In this regard, energy needed for the potato frying is produced by a combustor and the combustion products are transferred to a heat exchanger to heat up the oil circulating in the fryer. The system was designed to produce potato crisps on an industrial scale. In the study by Wu et al.,^[4] the model for evaluating the effect of the fat temperature on the heat energy consumption proposed by Rywotycki^[17] was used and the heat transfer coefficient of the casing of the fryer was assumed to be constant. Wu et al.^[4] also validated the model prediction and the real data with a maximum calculated error of around 13%.

As can be seen in Fig. 1, the system consists of three main parts, namely, (i) the combustor, which is used for production of the combustion products to yield energy; (ii) the heat exchanger containing the U-tube cross-counter flow type, which is responsible for transferring energy (heat) from the exhaust gases to the frying oil; and (iii) a fryer, which is used to produce the crisp product.



FIG. 1. Schematic of the system of the potato crisp frying process (adapted from Wu et al.^[4]).

MODELING

The main balance equations, namely, mass, energy, and exergy balance equations, are applied to the system considered under steady-state conditions to obtain the exergy destruction.

In general, the mass balance equation can be expressed in the rate form as

$$\sum \dot{m}_{\rm in} = \sum \dot{m}_{\rm out}.$$
 (1)

The general energy balance can be defined as the total energy input equal to the total energy output:

$$\sum \dot{E}_{\rm in} = \sum \dot{E}_{\rm out}.$$
 (2)

With all energy terms, it becomes

$$\dot{Q} + \sum \dot{m}h_{\rm in} = \dot{W} + \sum \dot{m}_{\rm out}h_{\rm out}.$$
(3)

The general exergy balance is written in the rate form as

$$\sum E\dot{x}_{\rm in} - \sum E\dot{x}_{\rm out} = \sum E\dot{x}_{\rm destruction} \tag{4}$$

or

$$\sum \dot{\boldsymbol{m}}_{\rm in} \boldsymbol{\psi} - \sum \dot{\boldsymbol{m}}_{\rm out} \boldsymbol{\psi} + \sum \left(1 - \frac{T_0}{T_k}\right) \dot{\boldsymbol{\mathcal{Q}}}_k - \dot{\boldsymbol{\mathcal{W}}} = \sum E \dot{\boldsymbol{x}}_{\rm destruction},$$
(5)

where

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

Exergy can be evaluated by its physical and chemical meanings. In this study, we have used physical and chemical exergies in all stages of the process.

The specific physical exergy of the components, such as the fuel, foul gas, air, exhaust gas, combustion products, oil, and raw potato, is calculated using

$$\psi^{ph} = (h - h_0) - T_0(s - s_0), \tag{7}$$

where the specific enthalpy of materials is computed by

$$h - h_0 = c_p (T - T_0), (8)$$

where subscript 0 denotes the reference (dead) state condition of the system ($T_0 = 25^{\circ}$ C and $P_0 = 1$ atm).

The specific entropy of the materials at the inlet temperature (T_{in}) is calculated as^[18]

$$s - s_0 = c_p \ln(T/T_0) - R \ln(P/P_0).$$
 (9)

In this study, unknown specific heat of a mixture is calculated as follows:

$$c_p = \sum c_{p,i} x_i, \tag{10}$$

where i is the number of pure species found in the component, and x is the weight fraction of the component.

The standard chemical exergies of the pure substances are taken from Bejan et al.^[19] and Szargut et al.^[20]

The reference substances are gaseous components of the atmosphere. The chemical exergy of a gas mixture^[18] is defined as

$$\psi^{ch} = \sum n_k e x^{ch} + RT_0 \sum n_k \ln n_k, \qquad (11)$$

where *n* is the mole fraction of the component, and ex^{ch} is the standard chemical exergy of the substance.^[20]

The general mass and energy balance equations of the frying system are given in the study by Wu et al.,^[4] and the following section covers mass, energy, and exergy balance equations on the basis of the system components, as illustrated in Fig. 1.

The mass and energy balances as well as the exergy destructions obtained from the exergy balances for each component of the frying system (Fig. 1) are derived as follows:

The combustor (I):

$$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 = \dot{m}_5$$
 (12a)

$$\dot{E}_1 + \dot{E}_2 + \dot{E}_3 + \dot{E}_4 = \dot{E}_5$$
 (12b)

$$\dot{E}_{\text{fuel}} = \dot{m}_1 (CV_1/\rho_1) \tag{12c}$$

$$\dot{E}_{\text{foulgas}} = c_{p,2} \dot{m}_2 T_2 \tag{12d}$$

$$\dot{E}_{\text{combustionair}} = c_{p,3}\dot{m}_3T_3$$
 (12e)

$$\dot{E}_{\text{recyclingexhaustgas}} = c_{p,4} \dot{m}_4 T_4$$
 (12f)

$$\dot{E}_{\text{combustion products}} = c_{p,5} \dot{m}_5 T_5.$$
 (12g)

The specific heat of the foul gas is calculated by

$$c_{p,2} = c_{p,w} x_w + c_{p,a} x_a + c_{p,o} x_o.$$
(13)

The enthalpy changes of the components at the inlet temperature are calculated by

$$h_1 - h_0 = c_{p,1}(T_1 - T_0) \tag{14a}$$

$$h_2 - h_0 = c_{p,2}(T_2 - T_0)$$
 (14b)

$$h_3 - h_0 = c_{p,3}(T_3 - T_0)$$
 (14c)

$$h_4 - h_0 = c_{p,4}(T_4 - T_0)$$
 (14d)

$$h_5 - h_0 = c_{p,5}(T_5 - T_0).$$
 (14e)

The specific entropies of the components at the inlet temperature (T_{in}) are obtained from^[18]

$$s_1 - s_0 = c_{p,1} \ln(T_1/T_0) \tag{15a}$$

$$s_2 - s_0 = c_{p,2} \ln(T_2/T_0)$$
 (15b)

$$s_3 - s_0 = c_{p,3} \ln(T_3/T_0) \tag{15c}$$

$$s_4 - s_0 = c_{p,4} \ln(T_4/T_0) \tag{15d}$$

$$s_5 - s_0 = c_{p,5} \ln(T_5/T_0),$$
 (15e)

where T_0 is the reference temperature, which is taken to be 25°C in this study.

The specific chemical exergy of the natural gas is calculated from^[21]

$$\psi_{\text{fuel}}^{ch} = 1.04 C V_1. \tag{16}$$

In this study, the fuel is considered as methane and the combustion products are assumed to contain N₂ (79.1%), O₂ (14.46%), CO₂ (3.31%), and H₂O_(g) (3.13%).^[18] The combustion relations are given in more detail elsewhere,^[19] and the following includes the corresponding chemical exergise.

$$\psi_{\text{combustionproducts}}^{ch} = x_{N_2} e x_{N_2}^{ch} + x_{O_2} e x_{O_2}^{ch} + x_{CO_2} e x_{CO_2}^{ch} + x_{H_2O(g)} e_{H_2O(g)}^{ch} + RT_0 (x_{N_2} \ln x_{N_2} + x_{O_2} \ln x_{O_2} + x_{CO_2} \ln x_{CO_2} + x_{H_2O(g)} \ln x_{H_2O(g)})$$
(17)

$$\psi_{\text{foulgas}}^{ch} = x_{\text{air}} e x_{\text{oil}}^{ch} + x_{\text{oil}} e x_{\text{oil}}^{ch} + x_{\text{H}_2\text{O}(g)} e_{\text{H}_2\text{O}(g)}^{ch} + RT_0(x_{\text{air}} \ln x_{\text{air}} + x_{\text{oil}} \ln x_{\text{oil}} + x_{\text{H}_2\text{O}(g)} \ln x_{\text{H}_2\text{O}(g)}).$$
(18)

The flow (specific) exergies of other components are calculated as follows:

$$\psi_{\text{foulgas}} = (h_2 - h_0) - T_0(s_2 - s_0) \tag{19a}$$

$$\psi_{\text{combustionair}} = (h_3 - h_0) - T_0(s_3 - s_0)$$
 (19b)

$$\psi_{\text{recyclingexhaustgas}} = (h_4 - h_0) - T_0(s_4 - s_0)$$
(19c)

$$\psi_{\text{combustion products}} = (h_5 - h_0) - T_0(s_5 - s_0). \tag{19d}$$

The exergy destroyed at the combustor is

$$E\dot{x}_{dest} = E\dot{x}_1 + E\dot{x}_2 + E\dot{x}_3 + E\dot{x}_4 - E\dot{x}_5,$$
 (19e)

where the heat interactions with the environment are neglected.

The heat exchanger (II):

$$\dot{m}_5 + \dot{m}_{14} = \dot{m}_4 + \dot{m}_6 + \dot{m}_7 \tag{20a}$$

$$\dot{E}_5 + \dot{E}_{14} = \dot{E}_4 + \dot{E}_6 + \dot{E}_7$$
 (20b)

$$\dot{E}_{\text{combustionproducts}} = c_{p5}\dot{m}_5 T_5$$
 (20c)

$$\dot{E}_{\text{oilinlet}} = c_{po} \dot{m}_{14} T_{14} \tag{20d}$$

$$E_{\text{recyclingexhaustgas}} = c_{p4} \dot{m}_4 T_4 \qquad (20e)$$

$$\dot{E}_{\text{exhaustgas}} = c_{p6} \dot{m}_6 T_6 \tag{20f}$$

$$\boldsymbol{E}_{\text{oiloutlet}} = c_{po} \dot{\boldsymbol{m}}_7 T_7. \tag{20g}$$

The specific enthalpies of the components at the inlet temperature (T_{in}) are calculated as

$$h_4 - h_0 = c_{p,4}(T_4 - T_0) \tag{21a}$$

$$h_5 - h_0 = c_{p,5}(T_5 - T_0)$$
 (21b)

$$h_6 - h_0 = c_{p,6}(T_6 - T_0) \tag{21c}$$

$$h_7 - h_0 = c_{p,7}(T_7 - T_0) \tag{21d}$$

$$h_{14} - h_0 = c_{p,14}(T_{14} - T_0).$$
 (21e)

The specific entropies of the components at the inlet temperature (T_{in}) are calculated as^[18]

$$s_4 - s_0 = c_{p,4} \ln(T_4/T_0) \tag{22a}$$

$$s_5 - s_0 = c_{p,5} \ln(T_5/T_0)$$
 (22b)

$$s_6 - s_0 = c_{p,6} \ln(T_6/T_0) \tag{22c}$$

$$s_7 - s_0 = c_{p,7} \ln(T_7/T_0)$$
 (22d)

$$s_{14} - s_0 = c_{p,14} \ln(T_{14}/T_0),$$
 (22e)

where T_0 is the reference temperature, which is taken to be 25°C in this study.

The flow (specific) exergies are calculated as follows:

$$\psi_{\text{combustionproducts}} = (h_5 - h_0) - T_0(s_5 - s_0) \tag{23a}$$

$$\psi_{\text{oil}} = (h_{14} - h_0) - T_0(s_{14} - s_0) \tag{23b}$$

$$\psi_{\text{recyclingexhaustgas}} = (h_4 - h_0) - T_0(s_4 - s_0)$$
(23c)

$$\psi_{\text{exhaustgas}} = (h_6 - h_0) - T_0(s_6 - s_0) \tag{23d}$$

$$\psi_{\text{oil}} = (h_7 - h_0) - T_0(s_7 - s_0).$$
 (23e)

The exergy destroyed at the heat exchanger is

$$E\dot{x}_{dest} = E\dot{x}_5 + E\dot{x}_{14} - (E\dot{x}_4 + E\dot{x}_6 + E\dot{x}_7),$$
 (24)

where the heat interactions with the environment are neglected.

The fryer (III):

$$\dot{m}_7 + \dot{m}_8 + \dot{m}_9 + \dot{m}_{10} = \dot{m}_2 + \dot{m}_{11} + \dot{m}_{12} + \dot{m}_{13}.$$
 (25a)

Frying oil

$$\dot{m}_7 = \dot{m}_{11} + \dot{m}_{12} + \dot{m}_{o,2} + \dot{m}_{o,13}$$
 (25b)

$$\dot{E}_{\text{oilevaporation}} = h_{fgo}(\dot{m}_7 - \dot{m}_{11} - \dot{m}_{12} - \dot{m}_{o,13}).$$
 (24c)

Potato solid

$$\dot{m}_{s,9} = \dot{m}_{s,13}$$
 (25d)

$$\dot{E}_{\text{potatosolid}} = c_{ps} \dot{m}_{s,9} (T_{13} - T_9).$$
 (25e)

Water

$$\dot{m}_{w,9} + \dot{m}_{10} = \dot{m}_{v,2} + \dot{m}_{w,13} \tag{25f}$$

$$\dot{E}_{\text{potatowater}} = [c_{pw}(T_b - T_9) + h_{fgw}](\dot{m}_{w,9} + \dot{m}_{10} - \dot{m}_{w,13}).$$
(25g)

Air

$$\dot{m}_8 = \dot{m}_{a,2} \tag{25h}$$

$$\dot{E}_{\text{air}} = c_{pa} \dot{m}_8 (T_2 - T_8). \tag{25i}$$

The heat flow from the wall of the fryer is obtained by

$$\dot{E}_{\text{transmittedwall}} = \dot{Q} = UA(T_{fo} - T_{\text{amb}}).$$
 (25j)

The specific enthalpies of the components at the inlet temperature (T_{in}) are calculated as

$$h_7 - h_0 = c_{p,7}(T_7 - T_0)$$
 (26a)

$$h_8 - h_0 = c_{p,8}(T_8 - T_0) \tag{26b}$$

$$h_9 - h_0 = c_{p,9}(T_9 - T_0) \tag{26c}$$

$$h_{10} - h_0 = c_{p,10}(T_{10} - T_0)$$
 (26d)

$$h_2 - h_0 = c_{p,2}(T_2 - T_0)$$
 (26e)

$$h_{11} - h_0 = c_{p,11}(T_{11} - T_0)$$
(26f)

$$h_{12} - h_0 = c_{p,12}(T_{12} - T_0)$$
 (26g)

$$h_{13} - h_0 = c_{p,13}(T_{13} - T_0).$$
 (26h)

The specific entropies of the components at the inlet temperature (T_{in}) are calculated as

$$s_7 - s_0 = c_{p,7} \ln(T_7/T_0)$$
 (27a)

$$s_8 - s_0 = c_{p,8} \ln(T_8/T_0)$$
 (27b)

$$s_9 - s_0 = c_{p,9} \ln(T_9/T_0) \tag{27c}$$

$$s_{10} - s_0 = c_{p,10} \ln(T_{10}/T_0)$$
 (27d)

$$s_2 - s_0 = c_{p,2} \ln(T_2/T_0)$$
 (27e)

$$s_{11} - s_0 = c_{p,11} \ln(T_{11}/T_0)$$
(27f)

$$s_{12} - s_0 = c_{p,12} \ln(T_{12}/T_0)$$
 (27g)

$$s_{13} - s_0 = c_{p,13} \ln(T_{13}/T_0).$$
 (27h)

The exergy destroyed at the fryer is

$$\begin{aligned} E\dot{\mathbf{x}}_{\text{dest}} &= E\dot{\mathbf{x}}_7 + E\dot{\mathbf{x}}_8 + E\dot{\mathbf{x}}_9 + E\dot{\mathbf{x}}_{10} - (E\dot{\mathbf{x}}_2 + E\dot{\mathbf{x}}_{11} + E\dot{\mathbf{x}}_{12} \\ &+ E\dot{\mathbf{x}}_{13}) + (1 - \frac{T_0}{T_f})Q. \end{aligned} \tag{28}$$

The universal exergy efficiency is defined as the ratio of the total exergy out to the total exergy in, where out refers to the net output or the exergetic product or the desired value and in stands for the net input of the exergetic fuel.

$$\varepsilon_u = \frac{Ex_{\text{out}}}{Ex_{\text{in}}}.$$
 (29)

The functional exergy efficiency is defined as

$$\varepsilon_f = \frac{Ex_{\text{product}}}{Ex_{\text{source}}}.$$
(30)

The exergy efficiencies of the frying system components along with the whole system are determined as follows:

- The combustor (I):
- The universal efficiency is given by

$$\varepsilon_{u,\text{combustor}} = \frac{E\dot{x}_5}{E\dot{x}_1 + E\dot{x}_2 + E\dot{x}_3 + E\dot{x}_4}.$$
 (31)

		LINIES AIIU	r vadigy allaly	entment ere	monede om to	nomne				
					Specific heat	Mass	Physical specific	Chemical specific		Exergy
i					capacity	flow	exergy	exergy	Energy	rate
Staté no.	e Description	Fluid	Temperature $T(\mathbf{K})$	Pressure P (kPa)	${c_p \over ({ m kJ/kg~K})}$	rate ṁ(kg/s)	ψ (kJ/kg)	ψ (kJ/ kg)	rate (kW)	$Ex = \dot{m}\psi$ (kW)
0		Air	298.15	101.33	1.006					
0^{I}		Water	298.15	101.33	4.18					
0^{II}		Oil	298.15	101.33	2.34					
0		Fuel (natural gas)	298.15	101.33	40,120 kJ/					
					m ³ (calorific					
					value)					
0^{IV}		Raw potato	298.15	101.33	1.3					
V		Exhaust gas	298.15	101.33	1.08					
0^{VI}		Combustion	298.15	101.33	1.54					
		products								
1	Combustor inlet	Fuel	298.15	1,200	2.00	0.061	383.95	52,156.00	3,059.15	3,204.94
0	Combustor inlet/fryer oulet	Foul gas	375.90		3.89	1.070	33.65	84.08	1,562.77	125.97
ε	Combuster inlet	Combustion air	298.15		1.01	1.21	0	0	362.93	0
4	Combustor inlet/heat	Recycling exhaust	473.00		1.08	1.56	40.23	3.98	796.91	68.97
	exchanger outlet	gas								
2	Combustor outlet/heat	Combustion	975.00		1.54	3.90	498.33	3.98	5,857.35	1,959.51
	exchanger inlet	priducts								
9	Heat exchanger outlet	Exhaust gas	473.00		1.08	2.34	40.23	3.98	1,195.88	103.51
٢	Heat exchanger	Oil	445.80		2.34	62.73	64.85	0	18.819.00	4,067.81
	outlet/fryer inlet									
8	Fryer inlet	Air	298.15		1.01	0.04	0.00	0	12.00	0.00
6	Fryer inlet	Raw potato	333.00		3.60	1.10	6.81	0.00	2,228.82	7.5
10	Fryer inlet	Surface water of	333.00		4.18	0.05	7.90	2.5	130.92	0.56
		potato								
11	Fryer outlet/heat	Oil	423.00		2.34	62.57	48.12	0	18,771	3,010.92
	exchanger inlet	i							,	
12	Fryer outlet	Fines	423.00		2.34	0.02	290.06	0	9	5.80
13	Fryer outlet	Crisp product	423.00		1.66	0.32	34.16	0	231.14	11.03
14	Fryer inlet	Oil	427.90		2.34	62.73	51.55	0	62,810.67	3,233.82

 TABLE 1

 Energy and exergy analysis results of the system studied

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• The functional efficiency is written as

$$\varepsilon_{f,\text{combustor}} = \frac{\dot{E}x_{\text{product}}}{\dot{E}x_{\text{source}}} = \frac{\dot{E}x_{\text{fluegas}}^{ph} - \dot{E}x_{\text{fuel}}^{ph} - \dot{E}x_{\text{air}}^{ph}}{\dot{E}x_{\text{foulgas}}^{ch} - \dot{E}x_{\text{reyexhaustgas}}^{ph} - \dot{E}x_{\text{fuelgas}}^{ch}} + \dot{E}x_{\text{foulgas}}^{ch} - \dot{E}x_{\text{fluegas}}^{ch}}$$

$$+ \dot{E}x_{\text{reyexhaustgas}}^{ch} - \dot{E}x_{\text{fluegas}}^{ch}} - \dot{E}x_{\text{fluegas}}^{ch}}$$

$$(32)$$

- The heat exchanger (II):
- The universal efficiency is defined as

$$\varepsilon_{u,\text{heatexchanger}} = \frac{E\dot{x}_7 + E\dot{x}_4 + E\dot{x}_6}{E\dot{x}_5 + E\dot{x}_{14}}.$$
 (33)

• The functional efficiency is calculated from

$$\varepsilon_{f,\text{heatexchanger}} = \frac{\dot{E}x_7 - \dot{E}x_{14}}{\dot{E}x_5 - (\dot{E}x_4 + \dot{E}x_6)}.$$
 (34)

• The fryer (III):

• The universal efficiency is given by

$$\varepsilon_{u,\text{fryer}} = \frac{E\dot{x}_2 + E\dot{x}_{11} + E\dot{x}_{12} + E\dot{x}_{13}}{E\dot{x}_7 + E\dot{x}_8 + E\dot{x}_9 + E\dot{x}_{10} - (1 - \frac{T_0}{T_k})\dot{Q}_k}.$$
(35)

• The functional efficiency is computed as

$$\varepsilon_{f,\text{fryer}} = \frac{\dot{E}x_{11} + \dot{E}x_{13}}{E\dot{x}_7 + E\dot{x}_9}.$$
 (36)

• For overall system:

The universal and functional efficiencies for the whole system are defined as follows, respectively.

$$\varepsilon_{u,\text{overall}} = \frac{E\dot{x}_6 + E\dot{x}_{12} + E\dot{x}_{13}}{E\dot{x}_1 + E\dot{x}_3 + E\dot{x}_8 + E\dot{x}_9 + E\dot{x}_{10} - (1 - \frac{T_0}{T_k})\dot{Q}_k}$$
(37)

$$\varepsilon_{f,\text{overall}} = \frac{E\dot{x}_{13}}{\dot{E}x_1}.$$
(38)

DATA USED AND ASSUMPTIONS MADE

The data utilized in this study were obtained from Wu et al.^[4] Using these data, Table 1 was formed for a representative case. The system described previously is evaluated from the exergetic point of view and the model presented previously is applied to this system.

The following several assumptions are made for the exergy analysis of the system given as an illustrative example:

- 1. All processes are steady state and steady flow with negligible potential and kinetic energy effects and no nuclear reactions.
- 2. Ideal gas mixture principles apply for the air and the combustion products.
- 3. The specific heats of the components are constant during the process.
- 4. The fuel used in the combustor is natural gas and the oil is the sunflower oil.
- 5. The combustion in the combustion chamber is complete and N_2 is assumed as an inert gas.
- 6. The directions of the heat transfer to the system and the work transfer from the system are positive.
- 7. The pressure losses in the pipelines connecting the components are ignored because their lengths are short.
- 8. The chemical exergies of the raw potato and the crisp product are assumed to be zero.
- 9. The data used in the calculations are taken from the study of Wu et al.^[4] and some calculations are also made using the values given in the reference in order to complete Table 1. Note that state 0 indicates the reference state for all components found in the system.
- 10. The overall heat transfer coefficient and the surface area of the fryer are $1.4 \times 10^{-3} \text{ kW/m}^2 \text{ K}$ and 45 m^2 , respectively.
- 11. The heat interaction with the environment of both the combustor and the heat exchanger is neglected.
- 12. The values for the dead (reference) state temperature and pressure are taken to be 25°C and 101.325 kPa, respectively.

RESULTS AND DISCUSSION

The temperature, specific heat capacity, mass flow rate, and specific physical and chemical exergy data for the fuel (natural gas), combustion air, recycling exhaust gas, combustion products, oil, raw potato, water, fines, and crisp products are shown in Table 1. They follow the state numbers specified in Fig. 1 and the exergy rates for each state are calculated and inserted into this table (Table 1).

Table 2 displays the exergetic product rate, exergetic fuel rate, exergetic destruction rate, universal exergetic efficiency, and functional exergetic efficiency data for each component of the frying system and the whole system at a reference state temperature of 25° C.

The greatest irreversibility (exergy destruction) on the whole system basis occurs in the combustor (1,440.38 kW), followed by the heat exchanger (953.04 kW) and the fryer (924.89 kW), as seen in Table 2.

Exergetic product rate, exergetic fuel rate, exergetic destruction rate, universal exergetic efficiency, and fu exergetic efficiency data for a representative unit in the whole system				and functional		
Component no.	Component	Exergetic product rate P (kW)	Exergetic fuel rate <i>F</i> (kW)	Exergetic destruction rate <i>Ex_{dest}</i> (kW)	Universal exergetic efficiency $\varepsilon_u(\%)$	Functional exergetic efficiency ε _f (%)
Ι	Combustor	1,959.51	3,399.88	1,440.38	58	0.08
II	Heat exchanger	4,240.29	5,193.33	953.04	82	47
III	Fryer	3,153.73	4,078.62	924.89	77	74
Overall	-	9,353.52	12,671.83	3,318.31	4	0.35

TABLE 2

The exergy efficiency values for the system components are calculated in two ways, namely, using Eqs. (29) and (30) based on the universal exergetic efficiency and functional exergetic efficiency, respectively, based on the values given in Table 1. The universal exergetic efficiency values are found to be 58% for the combustor, 82% for the heat exchanger, and 77% for the fryer and the universal exergetic efficiency for the whole frying system is 4% (Fig. 2). On the other hand, the functional exergetic values are computed using the values listed in Table 1. It is found that the fryer has the highest functional exergetic value at 74%, followed by the heat exchanger and the combustor with 47 and 0.08%, respectively (Fig. 3). For both cases (the universal and function exergetic efficiencies), the combustor has the lowest exergetic efficiency (58%, 0.08%), whereas its exergy destruction rate has the highest value with 1,440.38 kW among other components of the entire system. This means that the exergetic efficiency values differ from each other depending on the exergetic efficiency definition used in the calculation.

Figure 4 shows variations between the reference temperature (288.15–303.15 K) and the exergy destruction rate for the combustor, heat exchanger, and fryer. It is seen that the exergy consumption is a linear function of the reference temperature for both the combustor and the heat



FIG. 2. Comparison of the universal exergetic efficiencies for the combustor, the heat exchanger, and the fryer.

exchanger. On the other hand, the exergy destruction rate has a sharp decrease with increasing reference temperature for the fryer.



FIG. 3. Comparison of the functional exergetic efficiencies for the combustor, the heat exchanger, and the fryer.



FIG. 4. Effect of the reference temperature on the exergy destruction rate.



FIG. 5. Effect of the mass flow rate of the potato entering the fryer on the exergy destruction rate.



FIG. 6. Effect of the mass flow rate of the potato entering the combustor on the exergy destruction rate.

In the system of interest, the mass flow rate of the potato entering the fryer can be changed. To investigate the effect of the mass flow rate of the potato (m_9) entering the fryer on the exergy destruction rate, five different mass flow rates, 0.5, 0.8, 0.9, 1.1, and 2 kg/s, were considered. Figure 5 presents the variation in the exergy destruction rate of the fryer as a function of the mass flow rate of the potato entering the fryer. It is clear from the figure that increasing the mass flow rate of the potato scales up the exergy destruction rate of the fryer. The maximum exergy destruction rate of the fryer of 931 kW is obtained at a mass flow rate of the potato of 2 kg/s. The minimum value of the exergy destruction rate is 921 kW and the mass flow rate of the potato is 0.5 kg/s.

The effect of the mass flow rate of the fuel entering the combustor is shown in Fig. 6 for the mass flow rate of the fuel with the values between 0.05 and 0.1 kg/s. As expected, the exergy destruction rate of the combustor increases with an increase in the mass flow rate of the fuel. At a mass flow rate of 0.05 kg/s, the exergy destruction rate of the combustor is almost 800 kW. Increasing the mass flow rate to 0.1 kg/s stimulated the exergy destruction rate of the combustor to 3,500 kW.

The exergy destruction rate of the overall system is calculated as 3,318.31 kW. The combustor involves the highest portion (1,440.38 kW) of the exergy destruction rate of 43%, and the heat exchanger and the fryer have similar portions with values of 953.04 and 924.89 kW, representing 29 and 28% of the total exergy destruction rate, respectively. The exergy destructions in the overall system are quantified and illustrated in Fig. 7 using the exergy flow diagrams.

An exergetic efficiency assessment was conducted on the drying of various foodstuffs. Colak and Hepbasli^[22] studied drying of green olive in a tray dryer and the exergy efficiency values of the system were found to be in the range of 68.65–91.79% from 40 to 70°C with drying air mass flow rates of 0.01–0.015 kg/s. Another study on exergetic performance assessment of three different dryers, namely, a heat



FIG. 7. Grassman (exergy flow and loss) diagram of the potato crisp frying process studied.

pump (HP) dryer, a tray dryer, and fluid bed dryer, was performed by Hepbasli et al.^[23] The highest exergetic efficiency values were in the range of 72.72–75.66% for the HP dryer, followed by the tray and fluid bed dryers, varying between 37.94 and 39.46% and between 22.83 and 24.07%, respectively. Erbay and Hepbasli^[12] used conventional and advanced exergy analyses to evaluate the performance of a ground-source heat pump dryer and the conventional and modified (advanced) exergy efficiency values were calculated to be 77.05 and 93.5%, respectively.

CONCLUSIONS

In evaluating the performance of various food processes, the energy analysis method based on the first law of thermodynamics, which is a traditional approach, is widely used. In recent years, the exergy analysis method has been more popular and especially considered a more useful tool due to the deficiencies and shortcomings of energy analysis. In this regard, we have assessed the performance of a potato crisp frying process using the actual operational data from the literature.

We have drawn the following conclusions from the results of the present study:

- 1. The greatest irreversibility (exergy destruction) on the whole system basis was due to the combustor, followed by the heat exchanger and the fryer.
- 2. Two various exergy efficiencies were calculated and compared with each other. In this context, the universal exergetic efficiency values for the combustor, the heat exchanger and the fryer were determined to be 58, 82, and 77% while the functional exergetic values for those were computed to be 0.08, 46, and 74%, respectively,
- 3. The universal and functional exergetic efficiency values for the whole system were 4 and 0.35%, respectively.
- 4. As the mass flow rate of the potato increases, the exergy destruction rate of the fryer increases.
- 5. The rise in the reference state temperature led to an increase in the exergy destruction rate of both the combustor and the heat exchanger. Hovewer, the exergy destruction rate of the fryer decreased with increasing the reference temperature.

NOMENCLATURE

A	Surface area (m)	

- C Specific heat $(kJ/kg \cdot K)$
- CV Calorific value (kJ/m³)
- *E* Energy rate (kW)
- $\dot{E}x$ Exergy rate (kW)
- ex Standart exergy (kJ/mol)
- h Specific enthalpy (kJ/kg)
- \dot{m} Mass flow rate (kg/s)
- *n* Mole fraction of the component
- *P* Pressure (kPa)

Q	Heat transfer rate (kW)
R	Universal gas constant (8.314 J/mol.K)
5	Specific entropy (kJ/kg · K)
Т	Temperature (K or°C)
U	Overall heat transfer coefficient (kW/m^2K)
Ŵ	Rate of work or power (kW)

Weight fraction of the component

Greek Letters

e	Exergy (second law) efficiency (dimensionless)
ρ	Density (kg/m^3)
ψ	Specific exergy (kJ/kg)

Indices

x

0	Reference (dead) state
a	Air
amb	Ambient
ch	Chemical
dest	Destruction
ex	Exergetic
f	Fryer
i	Number of pure species
in	Input, inlet
int	Internal
k	Location
0	Oil
out	Output
р	Pressure
ph	Physical
sys	System
u	Universal
w	Water

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