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Application of Eexergy Analysis to Black Tea Production Process in Çamlı Tea Factory

Betül SARAÇ

[1]Department of Naval Architecture and Marine Engineering, Karadeniz Technical University, 61530 Trabzon, Turkey

Abstract: ***This study treats the production process at the Çamlı Tea Factory as a continuous flow open system and analyses it according to the second law of thermodynamics, using the values for the years 2014-2015. Thermodynamic models of the component processes are constructed and each step is examined in terms of exergetic parameters. Tables are presented of the values of exergy input and exergy destruction for each component in the thermodynamic model. The study reports numerical values for important exergy losses in the system and identifies the zones where energy saving should be made.***

Keywords: Exergy analysis, tea factory analysis, exergy destruction, industry analysis

1. Introduction

Current methods for evaluating the performance of thermal systems are related in the technical literature to the laws of thermodynamics. Energy equilibrium methods (involving only energy conservation) are based on the first law of thermodynamics. Exergy analysis methods, based on the second law (the law of exergy), are most widely used to analyze the performance of thermal systems by considering the mass and energy balance. The exergy of a system is defined as the maximum useful work that can be obtained as the system is brought to thermodynamic equilibrium with the environment. Similar to energy, exergy has physical, chemical, kinetic and potential components; however, unlike energy, it is not conserved but is destroyed in any actual process [1-3]. Exergy destruction, directly caused by the irreversibilities of the process, is related to entropy production. Exergy is always conserved in a reversible process, but is always consumed in an irreversible one, according to the law of exergy. Exergy analysis enables quantitative evaluation of energy degradation and identification of the location, cause and true magnitude of sources destroyed [4-7].

Much research has been carried out on exergy analysis methods, most of them based on steady-state assumptions. A method for analyzing the combined effects of space- and time-dependent exergy and irreversibility in processes is reviewed briefly by Lior et al [8]. Exergy analysis has been applied to many kinds of industrial processes, including drying, air conditioning and withering, all of which are integrated in black tea production.

Some researchers have presented sector-specific analyses of whole countries and environmental conditions for dead state reference data [9, 10, 11], while others have focused on specific systems [12, 13]. Exergy analysis has been applied to many kinds of industrial processes, including drying, air conditioning and withering, all of which are integrated in black tea production [14, 15].

There are many published work on the energy and exergy analysis of drying processes. Exergy analysis was used to study the distribution of exergy losses of two porous packed beds and to identify the exergy input of different drying operations [16]. The effects of operating parameters on the exergy losses of these processes are identified and calculated. In a recent work, exergy efficiencies are expressed as functions of heat and mass transfer parameters for a drying process, using exergy analysis [17].

A laboratory-scale plug flow fluidized bed dryer was used to perform an exergy analysis of a rough rice drying process. Experiments were conducted to assess the effects of drying air inlet temperature, feed mass flow rate and weir height on energy efficiency, exergy destruction, exergy efficiency, entropy generation, improvement potential rate and sustainability index [18]. The authors report a strong influence of the drying variables on the magnitude of exergetic parameter sand emphasise that exergy analysis can be applied to minimise exergy destruction in industrial fluidised bed drying systems and to enhance the sustainability of their operation.

Recently, many studies have used exergy analysis to investigate air conditioning cycles for building applications [19], for the power plant by using moist air in the cycle [20] and for the various psycometric processes [21].

In the field of water desalination, Alhazmy identified the minimum work requirement for dehumidification as a means of producing potable water from humid air. The analysis is based on the exergy method and the results are shown as contours on a psychometric chart, which is presented as a tool enabling designers to determine the minimum work requirement for any temperature and humidity [22].

In a recent study of an industrial chips drying process using energy and exergy analyses were studied by Coşkun et al [23]. The energy and exergy efficiencies were evaluated with the actual thermodynamic data available, as obtained from the factory, in Turkey. They found that energy and exergy efficiencies of the drum drying system were as 34.07% and 4.39%,

In the black tea production process, the majority of machines use high quality energy such as electricity, but boilers, driers and withering units consume both electricity and heat. This is why boiler efficiency and the efficiency of black tea production were studied separately. The exergy of the steam provided by the boiler is the main objective of the energy efficiency analysis for black tea production. A previous study of black tea production included an exergy analysis of the withering process [24]. It found that environmental conditions had very important effects on the withering process including energy saving and achieving the desired aroma of the tea.

In Turkey, tea production factories use fossil fuels, mostly coal, to minimise their energy costs. An inherent problem arising from this intensive coal consumption is the quantity of carbon dioxide emitted by the production process [25]. Therefore, to reduce energy requirements and to solve the problem of carbon dioxide emission, it is necessary to explore, identify and implement appropriate practices such as process optimization, reduction of heat losses and the use of alternative fuels. It would be beneficial to use the large quantity of hot (100°C) and humid (95%) air emitted to the environment as an energy source. Air leakage, heat loss and conveyor friction losses were identified as important sources of exergy destruction in withering units. Other aspects of electro-mechanical system efficiency were identified as important in improving the efficiency of black tea production.

The main purpose of the present study is to create a practical model for the exergy analysis of black tea production processes using measured operational data. By characterising the sub-systems involving control volumes of each machine and providing numerical data on exergy destruction and the exergy efficiency of the units involved in each process, an overall exergy map of tea production could be drawn up and evaluated for a general overview. The operating data used in the analysis were collected directly from the tea factory under study.

2. Process Description

The Çamlı tea factory is located in the north-east of Turkey. It produced 2885.732 tons of black tea in the 2014-2015 seasonsby a process consisting of five major stages. The first stage is withering, which serves to reduce the moisture content of the leaves to around 45%. Rotorvaning and rolling then reduce the moisture content further, to 25%. During the rolling process, the tea leaves are broken and structural liquid is expelled. After rolling, the green tea is transferred into troughs where the enzymes in the leaves come into contact with the air and the tea begins to oxidise. This oxidation or fermentation process is the most important stage, when the aroma, flavour, colour and strength of the tea are created and controlled. During this process the colour of the leaf changes from green, through light brown to deep brown. Oxidation takes place at about 26 °C and lasts from half an hour to two hours. It is monitored constantly by experts with years of experience. After oxidation, the tea leaves are transferred to drying units, where they are exposed to a flow of hot air. This causes oxidation to cease and reduces the moisture content to about 3%. Finally, the finished black tea is graded and packed for export. It is normally packed in large wooden boxes but may also be packaged in smaller quantities or as tea bags. Figure 1 shows a schematic representation of the production processes at the Çamlı Tea Factory.

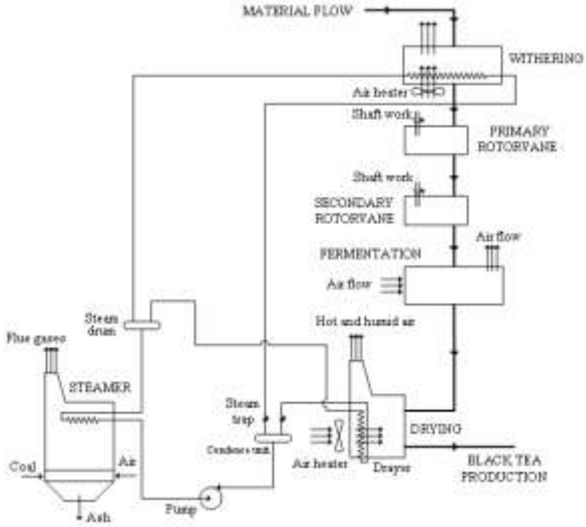

Figure 1: Schematic of production at the Çamlı Tea Factory

3. Analysis

This study develops a theoretical model of the Çamlı Tea Factory representing the six main units depicted in Figure 1: steamer, withering, rotorvane-I, rotorvane-II, oxidation and dryer. These account for the whole process except packing. Exergetic analysis of the tea processes is conducted using actual data obtained from each unit. Quantification of the input and output streams are allowed numerical specification for this analysis. The inputs (green tea and energy) and outputs (emissions) for the production of 2885.732 tons of processed tea (Çamlı Tea Factory, 2015) are very well illustrated by the flow diagram in Figure 2.

The steamer uses a coal-fired boiler to produce steam at a temperature of 300°C and pressure of 6 bars with a mass flow rate of 10.8 ton/h. Its thermal capacity is 11157kW and the thermal efficiency of the boiler is 90% as measured by the company. Chemical analysis of the Russian coal used to fuel the boiler is performed in Turkey by the Akabe Coal Company. The flue gas emissions and their mole fractions are measured using a stack gas emission analyser in the chimney. Enthalpy of intake air is calculated by using energy balance equation applying to the fan.

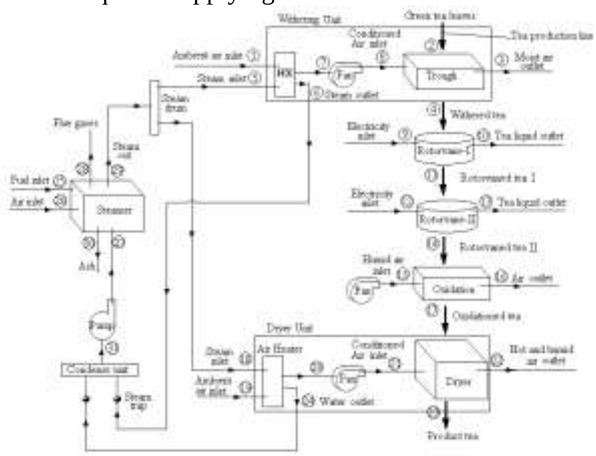

Figure 2: Life cycle inventory of the tea production system

The following assumptions are made during the analysis:

a) All processes are steady state and steady flow with negligible kinetic and potential effects.
b) Heat transfer to the system and work transfer are positive.
c) Ideal gas principles are applied to the air and exhaust gases.
d) The temperature, relative humidity and pressure of the dead state are taken as 20°C, 50% and 101.325 kPa.
e) Effects of fly ash and bottom ash in the steamer are ignored.
f) Oxidation is assumed to be an isothermal process which takes place at 26°C.
g) Water content of the processed tea leaves is reduced by 25% after rolling by rotorvane-I androtorvane-II.
h) Moisture content of the black tea is taken to be 3 % after drying.
i) The two heat exchangers in the system work adiabatically.
j) The water content of the fresh leaves is taken as 85%.
k) The exergy destruction rate of the oxidation process is very small due to the air flow and water flow friction. The oxidation process is there for ignored in the analysis.
l) The exergy of ash is ignored because the mass of ash is small.

Fig. 3 shows a schematic picture of the control volume for each component of the production process, with measured input and output data.

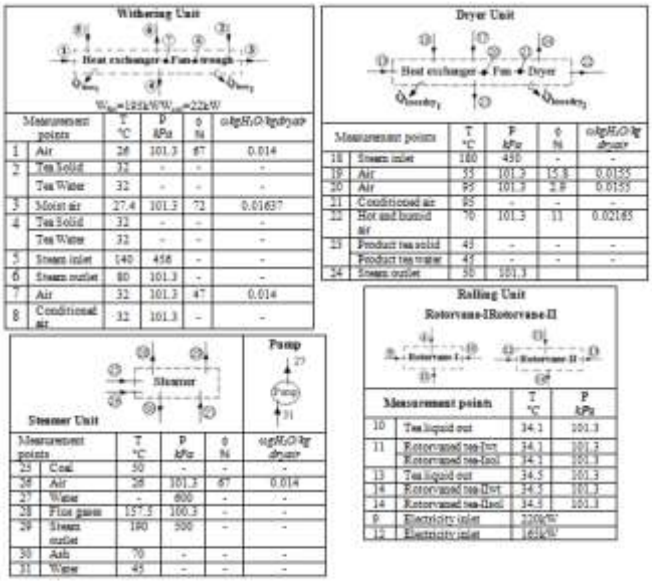

Figure 3: Withering unit, rolling unit, dryer unit, steamer unit and pump with measured data.

Mass, energy and exergy balances of each component of the black tea production process are given in Table 1.

Table 1: Mass, energy and exergy balances of each step in back tea production.

Unit	Component	Mass, energy and exergy balance relations	
Withering Unit	Heat Exchanger	$(\dot{m}_a)_1 = (\dot{m}_a)_7 = (\dot{m}_a)$	(1a)
		$(\dot{m}_g)_5 = (\dot{m}_g)_6 = (\dot{m}_g)$	
		$\dot{m}_a h_1 + \dot{m}_g h_{g_5} = \dot{m}_a h_7 + \dot{m}_g h_{g_6} + \dot{Q}_{lossw\,1}$	(1b)
		$\dot{m}_a e_1 + \dot{E}_{q_{5-6}} = \dot{m}_a e_7 + \dot{E}_{q_{loss\,1}} + \dot{E}_{d_{w1}}$	(1c)
	Fan	$(\dot{m}_a)_7 = (\dot{m}_a)_8 = (\dot{m}_a)$	(2a)
		$\dot{m}_a h_7 + \dot{W}_{Fan} = \dot{m}_a h_8 + \dot{W}_{kinetik}$	(2b)
		$\dot{m}_a e_7 + \dot{E}_{Fan} = \dot{m}_a e_8 + \dot{E}_{kinetik}$	(2c)
	Trough	$(\dot{m}_a)_8 = (\dot{m}_a)_3 = (\dot{m}_a)$	(3a)
		$(\dot{m}_s)_2 = (\dot{m}_s)_4 = (\dot{m}_s)$	(3a)
		$\omega_8 \dot{m}_a + (\dot{m}_w)_2 = \omega_3 \dot{m}_a + (\dot{m}_w)_4$	(3a)
		$\dot{m}_a h_8 + \dot{m}_s h_{s_2} + \dot{m}_{w\,2} h_{w\,2} + \dot{W}_{mot} = \dot{m}_a h_3 + \dot{m}_s h_{s_4} + \dot{m}_{w\,4} h_{w\,4} + Q_{lossw\,2}$	(3b)
		$\dot{m}_a e_8 + \dot{m}_s e_{s_2} + \dot{m}_{w\,2} e_{w\,2} + \dot{E}_{mot} = \dot{m}_a e_3 + \dot{m}_s e_{s_4} + \dot{m}_{w\,4} e_{w\,4} + \dot{E}_{q_{loss\,2}} + \dot{E}_{d_{w2}}$	(3c)
Rotorvane-I		$(\dot{m}_{gtea\ s})_4 = (\dot{m}_{gtea\ s})_{11}$	(4a)
		$(\dot{m}_{gtea\ w})_4 = (\dot{m}_{gtea\ w})_{11} + (\dot{m}_{gtea\ w})_{10}$	(4a)
		$\dot{m}_s h_{s_4} + \dot{m}_{w\,4} h_{w\,4} + \dot{W}_{r1} = \dot{m}_s h_{s_{11}} + \dot{m}_{w\,11} h_{w\,11} + \dot{m}_{w\,10} h_{w\,10} + Q_{lossrt\,1}$	(4b)
		$\dot{m}_s e_{s_4} + \dot{m}_{w\,4} e_{w\,4} + \dot{E}_{r1} = \dot{m}_s e_{s_{11}} + \dot{m}_{w\,11} e_{w\,11} + \dot{m}_{w\,10} e_{w\,10} + \dot{E}_{q_{lossrt\,1}} + \dot{E}_{d_{rt\,1}}$	(4c)
Rotorvane-II		$(\dot{m}_{gtea\ s})_{11} = (\dot{m}_{gtea\ s})_{14}$	(5a)
		$(\dot{m}_{gtea\ w})_{11} = (\dot{m}_{gtea\ w})_{14} + (\dot{m}_{gtea\ w})_{13}$	(5a)
		$\dot{m}_s h_{s_{11}} + \dot{m}_{w\,11} h_{w\,11} + \dot{W}_{r2} = \dot{m}_s h_{s_{14}} + \dot{m}_{w\,14} h_{w\,14} + \dot{m}_{w\,13} h_{w\,13} + Q_{lossrt\,2}$	(5b)
		$\dot{m}_s e_{s_{11}} + \dot{m}_{w\,11} e_{w\,11} + \dot{E}_{r2} = \dot{m}_s e_{s_{14}} + \dot{m}_{w\,14} e_{w\,14} + \dot{m}_{w\,13} e_{w\,13} + \dot{E}_{q_{lossrt\,2}} + \dot{E}_{d_{rt\,2}}$	(5c)
Oxidation Unit		$\dot{W}_{Fan} + \dot{W}_{electricity} = \dot{E}$	(6c)
		$(\dot{m}_s)_{14} = (\dot{m}_s)_{17} = (\dot{m}_s)$	
Dryer	Heat Exchanger	$(\dot{m}_a)_{19} = (\dot{m}_a)_{20} = (\dot{m}_a)$	(7a)
		$(\dot{m}_g)_{18} = (\dot{m}_g)_{24} = (\dot{m}_g)$	
		$\dot{m}_a h_{19} + \dot{m}_g h_{g_{18}} = \dot{m}_a h_{20} + \dot{m}_g h_{g_{24}} + Q_{lossdry\,1}$	(7b)
		$\dot{m}_a e_{19} + \dot{E}_{q_{18-24}} = \dot{m}_a e_{20} + \dot{E}_{q_{lossdry\ 1}} + \dot{E}_{d_{dry\,1}}$	(7c)

	Fan	$(\dot{m}_a)_{20} = (\dot{m}_a)_{21} = (\dot{m}_a)$ $\dot{m}_a h_{20} + \dot{W}_{Fan} = \dot{m}_a h_{21} + \dot{W}_{kinetik}$ $\dot{m}_a e_{20} + \dot{E}_{Fan} = \dot{m}_a e_{21} + \dot{E}_{kinetik}$	(8a) (8b) (8c)
	Dryer unit	$(\dot{m}_a)_{21} = (\dot{m}_a)_{22} = (\dot{m}_a)$ $(\dot{m}_s)_{17} = (\dot{m}_s)_{23} = (\dot{m}_s)$ $\omega_{21}\dot{m}_a + (\dot{m}_w)_{17} = \omega_{22}\dot{m}_a + (\dot{m}_w)_{23}$ $\dot{m}_a h_{21} + \dot{m}_{17} h_{s17} + \dot{m}_{w17} h_{w17} + \dot{W}_{mot} = \dot{m}_a h_{22} + \dot{m}_s h_{s23} + \dot{m}_{w23} h_{w23} + Q_{lossdry\ 2}$ $\dot{m}_a e_{21} + \dot{m}_s e_{s17} + \dot{m}_{w17} e_{w17} + \dot{E}_{mot} = \dot{m}_a e_{22} + \dot{m}_s e_{s23} + \dot{m}_{w23} e_{w23} + \dot{E}_{q_{lossdry\ 2}} + \dot{E}_{d_{dry\ 2}}$	(9a) (9a) (9a) (9b)(9c)
Steamer		$m_{25}h_{25} + m_{26}h_{26} + m_{27}h_{27} = Q_{losssteamer} + m_{28}h_{28} + m_{29}h_{29}$ $\dot{m}_{25}e_{25} + \dot{m}_{26}e_{26} + \dot{m}_{27}e_{27} = \dot{E}_{q\ steamer} + \dot{m}_{28}e_{28} + \dot{m}_{29}e_{29} + \dot{E}_{d\ steamer}$	(10b) (10c)
Pump		$W_p = \vartheta(P_{31} - P_{27})$ $e_{W_p} = \dot{m}_{27}(e_{31} - e_{27})/W_p$	(11a) (11b)

3.1 Measurement of molar flow rates of flue gas components in stack

The data for the flue gas emissions and their mole fractions are provided by the Çamlı Tea Factory; measurements are taken using a*stack* gas *emission* analyser in the chimney. The data show a flue gas temperature of 157.5 °C, pressure at 100.35 kPa and a volume flow rate of 10.58 m^3/s. The molar flow rate of the flue gases is calculated to be 0.296 kmol/s. Measured flue gas emissions and their molar fractions, together with calculated molar flow rates, are given in Table 2.

Table 2: Flue gas emissions, molar flow rates and molar factions

Flue gas components	Molar flow rate n_i (kmol/s)	Mole fraction y_i ($n_i/n_{flue\ gas}$)
O_2	0.03561	0.1203
CO_2	0.02368	0.08
CO	0.00128	0.0043
SO_2	0.00136	0.0046
NO	0.0044	0.01487
NO_2	0.00023	0.00078
H_2O	0.01095	0.037
N_2	0.21848	0.73815
Total	0.296	1.00003

The specific heat of the flue gases can be calculated by means of Eq. 12.

$$\bar{C}_p = y_{CO_2}.\bar{C}_{p_{CO_2}} + y_{O_2}.\bar{C}_{p_{O_2}} + y_{SO_2}.\bar{C}_{p_{SO_2}} + y_{NO_2}.\bar{C}_{p_{NO_2}} + y_{CO}.\bar{C}_{p_{CO}} + y_{H_2O}.\bar{C}_{p_{H_2O}} + y_{NO}.\bar{C}_{p_{NO}} \quad (12)$$

According to Eq.13, the enthalpy of the flue gases will be

$$(h - h_0) = \bar{C}_p.(T - T_0) \quad (13)$$

3.2 Specific exergy of flue gas

According to Eq. 14 and Eq. 15, the specific chemical and physical exergies of the flue gas can be calculated by using the data for the flue gas emissions.

$$\bar{e}x^{chem} = \bar{R}T_0 \sum_i y_i \bar{e}^{chem,i} + \bar{R}T_0 \sum_i y_i ln y_i \quad (14)$$

$$\bar{e}x^{phy} = \bar{C}_{p_{Flg}}.[(T - T_0) - T_0\, ln(T/T_0)] + \bar{R}T_0 ln(P/P_0) \quad (15)$$

where $\bar{C}_p$ can be calculated by Eq. 16 using data in Table 2.

$$\bar{C}_p = y_{CO_2}.\bar{C}_{p_{CO_2}} + y_{O_2}.\bar{C}_{p_{O_2}} + y_{SO_2}.\bar{C}_{p_{SO_2}} + y_{NO_2}.\bar{C}_{p_{NO_2}} + y_{CO}.\bar{C}_{p_{CO}} + y_{H_2O}.\bar{C}_{p_{H_2O}} + y_{NO}.\bar{C}_{p_{NO}} \quad (16)$$

The total specific exergy of the flue gas can be calculated as follows:

$$\bar{e}x^{total} = \bar{e}x^{phe} + \bar{e}x^{chem} \quad (17)$$

3.3 Properties of solid fuel

Properties of the coal obtained in season 2015 for use in the boiler are shown in Table 3. The heating value of the coal is 6800 kcal/kg. The mass flow rate of coal in the boiler is measured as 0.35kg/s and its supply temperature is 50 °C at the inlet of the boiler.

Table 3: Composition and volumetric fractions of coal used in Çamlı Tea Factory, 2015

Components of coal	Mole fractions (%)
Moisture	0.0354
Ash	0.0743
Sulphur	0.0027
Volatiles	0.2414
Carbon	0.5912
Hydrogen	0.02
Nitrogen	0.0188
Oxygen	0.0193

3.4 Chemical exergy of the solid fuel

The parameter β, used for calculating the chemical exergy of solid hydrocarbons depends on the oxygen/carbon ratio. Eq. 18 is applied to calculate the value of $\beta$when the O/C ratio is$\frac{o}{c} = 0.024 < 0.667$ [26].It is found to be 1.1226. The chemical exergy of the solid fuel is calculated using Eq. 19 with the calculated value of β [4].

$$\beta = 1.0437 + 0.1882\frac{h}{c} + 0.061\frac{o}{c} + 0.04\frac{n}{c} \quad (18)$$

$$e_x{}^{chem} = \beta(Hu.4.18 + h_{fg}.y_{H_2O}) + 9683y_{S_2} + 22000y_{ash} + 340y_{H_2O} \quad (19)$$

3.5 Specific exergy of intake air

Intake air is supplied by fan to the steamer at rate of38000 m^3/h. The air is considered to be an ideal gas mixture consisting of 21% oxygen and 79%nitrogen ata relative humidity of 60% and temperature of 25°C. According to Eq. 20, the exergy of intake air becomes

$$e_{26} = \left[C_{p_a} + \omega_{26} C_{p_w}\right](T_{26} - T_0) - T_0\left\{\left(C_{p_a} + \omega_{26} C_{p_w}\right) ln\frac{T_{26}}{T_0} - (R_a + \omega_{26} R_w)\right\} ln\frac{P_{26}}{P_0} + T_0\left\{(R_a + \omega_{26} R_w) ln\frac{1 + 1.6078\omega_0}{1 + 1.6078\omega_{26}}\right\} + 1.6078 R_a \omega_{26} ln\frac{\omega_{26}}{\omega_0} \qquad (20)$$

3.6 Exergy of feed water and steam

Feed water temperature is 51°C and the pressure is 300 kPa at the inlet of the boiler. The boiler produced saturated steam with mass flow rate of 3 kg/s at a temperature of 190 °C and pressure of 500kPa. The exergy of feed water supply and of the saturated steam produced can be calculated by Eq.21.

$$e_{w_{29}} = \left[h_{(T_3,P_3)} - h_{g(T_0)}\right] - T_0\left[s_{(T_3,P_3)} - s_{g(T_0)}\right] - T_0 R_v ln\frac{P_{g(T_0)}}{x_{v0(PT_0)}} \qquad (21)$$

The exergy efficiency for each unit is given

$$\eta_{ex_{unit}} = \frac{E_{Product\ \ unit}}{E_{input\ \ unit}} \qquad (22)$$

$$\eta_{ex_{dry}} = \frac{(Exergy\ \ used\ \ for\ \ evaporation\ \ of\ moisture\ \ in\ product\ )_{dry}}{Dryer\ \ input\ \ energy}$$

$$\eta_{ex_{dry}} = \frac{\dot{m}_{w23} e_{w23} + \dot{m}_{w17} e_{w17}}{E_{in\ dry}} \qquad (23)$$

The overall exergy efficiency of the tea factory can be calculated as follows:

$$\eta_{ex_{system}} = \frac{Exergy\ \ used\ \ for\ evaporation\ \ of\ moisture\ \ in\ product}{Exergy\ \ of\ \ steam}$$

$$\eta_{ex_{sys}} = \frac{\dot{m}_{w2} e_{w2} - \dot{m}_{w4} e_{w4} + \dot{m}_{w10} e_{w10} + \dot{m}_{w13} e_{w13} + \dot{m}_{w23} e_{w23} + \dot{m}_{a22} w_{17} e_{w17}}{\dot{m}_{29} \dot{e}_{29}} \qquad (24)$$

4. Findings and Discussion

Thermodynamic properties and their calculated values for the proposed system are given in Table 4. The value of exergy flow calculations for the each component of the system are presented in details. It is clear that the exergy use in the steamer (11869 kW) is higher than other units of the factory reported in Table 4.

Table 5 shows the exergy destruction rates and the exergy efficiency for each unit in the tea production process. The exergy destruction rate in the steamer unit, dryer unit, withering unit, rotorvane-I and rotorvane-II were found to be 7467 kW, 3626 kW, 258.26 kW, 208.26 kW and 156.35 kW respectively. Similar order can be observed for the exergy efficiency; 24.96%, 0.21%, 20.95% and 27.5%. It is shown that the highest exergy efficiency is calculated for the steamer; consequently withering unit, drying unit, rotorvane-II, rotorvane-I. The exergetic efficiency of the rotorvane-II for the rolling process is higher than rotorvane-I due to the content of the cell liquid lower than in rotorvane-I. All exergy input for rotorvane-I and rotorvane-II are destroyed because of the nature of the rolling process. Drying and withering processes are basically kinds of dehumidification from the green tea leaves. Thus the most of useful energies are wasted for these processes. The exergy destruction rate in the withering unit is smaller than for the steamer and drying units, as reported in Table 5. Exergy losses in the withering unit were due to air leakage, heat losses and conveyor band friction losses [24]. Other sources of exergy loss in the system were smaller than for the steamer, withering and drying units; hence, a future study should focus on the steamer, dryer and withering units to increase the efficiency of the tea factory.

Table 4: Thermodynamic properties and their calculated values on the state points

			h (kJ/kg)	$\dot{m}$ (kg/s)	e (kJ/kg)	m*e (kW)
Withering Unit	1	Air	62	115.75	0.389	45.04
	2	Solid	53.12	0.2778	11.25	3.12
		Water	134	1.574	91.74	144.42
	3	Moist air	69.31	115.75	0.656	76.025
	4	Solid	53.12	0.2778	11.25	3.125
		Water	134	1.296	91.74	118.97
	5	Steam inlet	2733	1	173.52	173.22
	6	Steam outlet	1720	1	113.22	113.51
	7	Air	67.94	115.75	0.573	66.35
	8	Conditioned air	69	115.75	2.258	261.35
		Fan and conveyor	217kW			
Rotorvane-I	9	Electricity	220 kW			
	10	Tea liquid out	142.8	0.324	92.134	29.87
	11	Rotorvaned tea-Iwater	142.8	0.972	92.134	89.61
	11	Rotorvaned tea-Isolid	56.6	0.2778	13.225	3.673
Rotorvane-II	12	Electricity	165 kW			
	13	Tea liquid out	144.5	0.243	92.215	22.42
	14	Rotorvaned tea-II water	144.5	0.729	92.215	67.26
		Rotorvaned tea-II solid	57.27	0.2778	13.602	3.77
Oxidation	15	Oxidation fan	3.5 kW			
	16	Conveyor belt	6 kW			
	17	Oxidised teawater	138.2	0.759	91.92	69.76
		Oxidised tea solid	54.78	0.2778	12.19	3.386
Dryer	18	Steam inlet	2760	2	2227	4453.72
	19	Air	95.606	53.818	2.472	133.07
	20	Air	136.95	53.818	8.968	482.64
	21	Conditioned air	139.3	53.818	11.08	
	22	Hot and humid air	127	53.8	5.241	282.09
	23	Product tea solid	74.7	0.2778	23.47	6.52
		Product tea water	188.41	0.0259	95.06	2.46
	24	Steam outlet	209	2	96.52	193.04
Steamer	25	Coal	26752 (kJ)	0.35	33912	11869
	26	Air	62	12.58	0.389	4.89
	27	Water	188	3	97.89	293.68
	28	Flue gases	4254 kJ/kmol	0.296 kmol/s	5398 kJ/kmol	1619
	29	Steam outlet	2785	3	1012.7	3038.19
	30	Ash	50	0.007	-	-
	31	Water	2756	3	96.42	289

Table 5: Exergy efficiency of the components for the tea factory

Unit	$\dot{Q}_{loss}$ kW	$\dot{E}_{in}$ kW	$\dot{E}_{d}$ kW	η_{exe} %
Withering	326	582.805	258.26	20.95
Rotorvane-I	215	342.10	208.46	27.26
Rotorvane-II	185	258.28	156.35	27.5
Drying	3991	4662	3626	2.1
Steamer	2363	12168	7467	24.96

The effect of intake air humidity ratio on the exergetic efficiency of the tea factory is shown in Figure 4. The data used for this study causes scattering pattern on this graph due to the ambient climatic condition of the ambient air in Trabzon for the time period of 2014-2015 season. The increase of moisture in the ambient air causes overall exergy efficiency of the factory decrease (Fig. 4). It can be attributed to exergy losses in steamer, withering and drying units as well as in rotorvane-I and rotorvane-II.

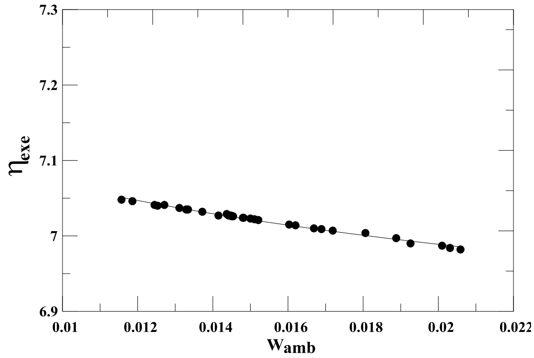

Figure 4: Variation of the exergy efficiency of the tea factory with humidity ratio of intake air.

5. Conclusions

This paper has investigated the exergetic performance of each component of black tea production at the Çamlı tea factory in Trabzon, Turkey. A comprehensive exergy analysis is developed for all components, allowing the following conclusions to be drawn:

- The total exergy use in the steamer is higher than for other components.
- The steamer has the highest exergy destruction rates. The optimization of the combustion process, reducing coal use, is of great importance for reducing irreversibility. The exergy efficiency of the steamer is calculated to be 24.96%.
- The measured and theoretically calculated first law efficiency of the boiler is 90% and 88% respectively.
- The exergy use and destruction rate in the withering process depend mainly on the physical water content of the green tea. The exergy efficiency of the withering process is calculated to be 20.9%.
- The exergy destruction rate in the drying process depends mainly on atmospheric conditions. The exergy efficiency of the dryer is calculated to be 2.1%.
- The exergy efficiency of the rotorvane-I and rotorvane-II processes are calculated to be 27.26% and 27.5% respectively.
- The intake air humidity ratio does not contribute significantly to the exergetic efficiency of the tea factory.
- This present work is also able to provide a thermodynamic analysis of the effect of uncontrolled green tea mass flow rates on the exergetic efficiency of the tea factory.
- The exergetic efficiency of the black tea production process for the Çamlı Tea Factory, as calculated by Equation 24, is 7.03%.System has low exergy efficiency when compared with the energy efficiency. Mean reason of low exergy efficiency is exergy destruction. Exergy destruction is 77% of input exergy of the drying process and exergy destruction is 61.2 % of input exergy of steam generation process.
- In order to achieve a significant improvement in energy efficiency, the steamer and drying units need to be altered, which will require further techno-economic research.

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References

[1] Bejan, A., Tsastsarroins, G. and Moran, M. (1996) *Thermal Design & Optimisation*. Wiley, New York.

[2] Çengel, Y.A. and Boles, M.A. (2008) *Thermodynamics: An engineering Approach*,7th Ed.McGraw-Hill, New York.

[3] Vosough, A., Noghrehabadi, A. Ghalambaz, M. and Vosough, S. (2011) Exergy concept and its characteristics, *International Journal of Multidisciplinary Sciences and Engineering*, Vol. 2, No. 4.

[4] Wall, G. (1998) Exergy flows in industrial processes, *International Journal of Energy*, Vol. 13, No. 2, pp.197-208.

[5] Cortes-Rodríguez, E.F., Nebra, S.A. and Sosa-Arnao, J.H. (2013) Efficiency analysis of sugarcane bagasse boilers through the first and second law of thermodynamics, *22nd International Congress of Mechanical Engineering*, Brazil, ISSN 2176-5480.

[6] Irandeganir, M.Y. (2013) Exergy analysis of a steam power plant, *Journal of American Science*, Vol.9, No.8,pp.402-408.

[7] Regulagadda, P., Dincer, I. and Naterer, G.F. (2010) Exergy analysis of a thermal power plant with measured boiler and turbine losses,*Applied Thermal Engineering*, Vol.30, pp.970-976.

[8] Lior,N., Sarmiento-Darkin,W. and Al-Sharqawi,H.(2006) The exergy fields in transport processes:their calculation and use, *Energy*,Vol.31,pp.553-578.

[9] Morris, D.R. and Szargut, J. (1986) 'Standard chemical exergy of some elements and compounds on the planet earth', Exergy, Vol. 11, No. 8, pp.733-755.

[10] Hammond, P.G. (2004) "Engineering sustainability, thermodynamics, energy system and the environment", International Journal of Energy, Vol.31,pp.553-578.

[11] Gong, M. and Goran, W. (1997) On exergetics, economics and optimization of technicalprocesses to meet environmental conditions, *Thermodynamic Analysis and Improvement of Energy Systems*, TAIES'97, Beijing, China.
[12] Gaggioli, R.A. (2012) The dead state, *International Journal of Thermodynamics*,Vol. 15, No. 4, pp.191-199.
[13] Simpson, A.P. and Edwards, C.F. (2011) An exergy-based framework for evaluating environmental impact, *Energy*, Vol.36, pp.1442-1459.
[14] Pons, M. (2009) On the reference state for exergy when ambient temperature fluctuates, *International Journal of Thermodynamics*, Vol. 12, No. 3, pp.113-121.
[15] Gogus, Y.A., Camdali,U. and Kavsaoglu,M.S. (2002) Exergy balance of a general system with variation of environmental conditions and some applications,*Energy*, Vol.27,No.7, pp.625-646.
[16] Prommas, R., Rattanadecho, P. and Jindarat, W. (2012) Energy and exergy analyses in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt system (CMCB), *International Communications in Heat and Mass Transfer*, Vol. 39, pp.242-250.
[17] Khanali,M., Aghashlo,M., Rafiee,S.and Jafari,A.(2013) Exergetic performance assessment of plug flow fluidised bed drying process of rough rice,*International Journal of Exergy*,Vol.13,No.3, pp.387-408.
[18] Dincer, I. and Sahin, A.Z. (2004) A new model for thermodynamic analysis of a drying process, *International Journal of Heat and Mass Transfer*, Vol. 47, pp.645-652.
[19] Feiza, M. and Sag, K.O. (2009) Exergy analysis methodology for all air systems,*Annals of the University of Petroşani, Mechanical Engineering*, Vol. 11, pp.141-146.
[20] Salazar-Pereyra, M., Toledo-Velázquez, M., Guilibaldo-Tolentino, E., Raúl Lugo, L. and Celerino Reséndiz, R. (2011) Energy and exergy analysis of moist air for application in power plants, *Energy and Power Engineering*, Vol. 3, pp.376-381.
[21] Qureshi, B.A. and Zubair, S.M. (2003) Application of exergy analysis to various psychrometric processes, *International Journal of Energy Research*, Vol. 27, pp.1079-1994.
[22] Alhazmy, M. (2007) Minimum work requirement of water production in humidification-dehumidification desalination cycle', *Desalination*, Vol.214,pp.102-111.
[23] Coskun, C., Bayraktar1, B., Oktay, Z., and Dincer, İ., Energy and exergy analyses of an industrial wood chips drying process, International Journal of Low-Carbon Technologies 2009, 4, 224–229.
[24] Sarac BA.Exergy analysis in the withering process for Turkish black tea production. *Int. J. of Exergy*.
[25] Cuhadaroglu, B. (2004) Cay işleme fabrikalarinda emisyonlarinin incelenmesi, *Muhendis ve Makina Dergisi*, Vol.43, No.508, pp.2-26 (Turkish).
[26] Cotas,T.J.(1985)*The Exergy Method of Thermal Plant Analysis*, Anchor Brendon, Great Britain.

Author Profile

Betul Saraç holds her PhD in Mechanical Engineering and works as an Assistant Professor in Naval Architecture and Marine Engineering Department, Karadeniz Technical University, Trabzon. She teaches undergraduate and master courses in Naval rchitecture and Marine Engineering. Her research areas of interest include heat-transfer, swirl flows and exergy analysis.

Nomenclature

C_p	specific heat (J/kgK)
e	specific exergy (J/kg)
$\dot{E}$	rate of exergy flow (W)
h	specific enthalpy (J/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
P_v	vapour pressure (Pa)
Q	rate of heat transfer (W)
R	gas constant (J/kgK)
s	specific entropy (J/kgK)
T	temperature (K)
v	specific volume (m^3/kg)
x_v	mole fraction of vapour
x_{v0}	mole fraction of vapour in air at dead state
Greek symbols	
η	efficiency
ϕ	percent relative humidity of air
ω	humidity ratio of air
ω_0	humidity ratio of air at dead state
Subscripts	
0	dead state
a	air
d	destruction
e_v	evaporation
l	loss
f	saturated liquid state
g	saturated vapour state
g_{tea}	green tea
q	heat transfer rate
v	vapour
w	water
s	solid
mot	conveyor motors
amb	ambient
rt	rotorvane
dry	drayer
Hu	lower thermal value
y	mole fraction