

EXERGEOECONOMIC EVALUATION OF REAL PROCESSES FOR COFFEE ROASTING

by

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Exergoeconomic methods provide an effective approach for identifying, evaluating and reducing thermodynamic inefficiencies and costs in an energy system. The aim of this paper is to show the potential for cost reduction on the demand side, using the exergoeconomic method in the example of real processes for coffee roasting. More than $6.5 \cdot 10^9$ kg of coffee beans is roasted worldwide annually, mostly in batch roasters. Near the end of the roast, roasting coffee emits volatile organic compounds, carbon monoxide and other pollutants, which in many industrialized countries have to be oxidized in afterburners. Afterburners release exhaust gases with a temperature of 250-450 °C, depending on the roasting process and the method of exhaust gas cleaning. The aim of this paper is to use exergy analysis and exergoeconomic performance evaluation to determine the energy use for coffee roasting and the afterburning process, and evaluate the way to utilize waste heat and reduce costs in the factory. For roasters with the capacity of up to 4 tons of green coffee beans per hour, the potential of heat recovery is 1.1 MW and the possibility to save money is around 60,000 € per year. This case study is similar to many others worldwide, and the results of this analysis could lead to more general conclusions.

Key words: exergy, exergoeconomics, coffee roasting, afterburner, costs

Introduction and background

In order to make coffee, several steps are necessary. The most energy-intensive of these steps are located in the countries that are coffee importers, not producers. Countries in the equatorial belt typically grow and harvest coffee, and although these are labor-intensive phases, they are not so energy-intensive, since most of the work is done manually or with simple machinery. Approximately 60% of the energy used to make a cup of coffee can be attributed to the transport phase, roasting phase, and brewing of coffee. Since green coffee is transported worldwide, a large part of energy is used during the transport. The roasting process occurs in countries which are coffee importers. After the delivery, green coffee is roasted. This is a very energy-intensive phase in coffee production, since roasting machines operate at high temperatures, around 288 °C, and can consume up to 293 kWh per kg of green coffee. After the roasting phase, coffee is once more transported to places where it will be brewed. Brewing is the last step of the coffee production process and, according to some life cycle analyses, it is the most energy-

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intensive. A large amount of energy, in the form of both heat and electricity, is needed to prepare the coffee and power the machinery used to do so. In the end, the aggregate total of all energy used to make a 100 ml cup of coffee is 1.94 MJ, or about 0.5 kWh [1].

The crucial stage in coffee production is roasting [2]. This is the phase in which the coffee industry has been consuming high amounts of energy for many years. To produce one ton of roasted coffee products (from green beans to roasted coffee beans), a commercial batch coffee roaster with an afterburner consumes about 1.67 GJ of fuel energy.

The main aim of roasting is to markedly change the chemical, physical, structural and sensory properties of green beans by heat induced reactions. Roasting represents a very intensive thermal treatment during which coffee beans are heated at high temperatures (160–240 °C) for times ranging between 8 and 20 minutes depending on the desired characteristics of the final product [2]. Roasting is a complex process involving both energy (from the roaster to the bean) and mass (water vapor and volatile organic compounds-VOC, from the bean to the environment) transfer implied in the main changes in coffee beans in terms of weight, density, moisture, color, and flavor [3, 4]. Heat is transferred from the hot gas to the bean by convective mechanisms and, depending on the technique, also by radiation and/or direct contact with the walls of the roaster. Process efficiency and quality of roasted coffee depend on several factors including: gas composition and temperature, pressure, time, relative velocity of beans, and gas flow rate [2].

Near the end of each roast, roasted coffee emits VOC and CO, which has to be additionally oxidized in afterburners. Roasting and afterburning use roughly $11.2 \cdot 10^{12}$ kJ fuel energy per year and cause the emission of roughly $7.0 \cdot 10^8$ kg CO₂ per year [5]. The VOC are a mixture of nearly 700 different volatile organic compounds, like ketones, aldehydes, pyrroles, furans, pyridines, nitrogen, sulphur compounds, *etc.* To prevent toxic smoke from entering the atmosphere, responsible roasting companies pass it through afterburners, using additional energy. Conventional roasters use afterburners to eliminate the smoke produced during roasting. Afterburners can consume up to 400 percent more fuel than the roaster itself. In particular, as far as the VOC are concerned, the insertion of an afterburner at about 500-600 °C for the roasting exhaust gases is foreseen as a possible solution [6]. The irreversible effect of heat transfer cannot be defined by material properties such as: mass, volume, temperature, pressure, or internal energy. In this sense, the second law of thermodynamics introduces a new term called entropy, whose changes are directly influenced by the irreversibility of heat transfer. This is the reason why the second law of thermodynamics is often called the entropy law [7]. So, the heat transfer in real systems is always characterized with the generation of entropy, and the direct consequence is the destruction of exergy (irreversible) which is on the other side of crucial importance in the analysis of real energy systems. For this reason, the terms exergy and exergy destruction have an important place in thermodynamic analysis of energy systems.

Exergy is a combination property of a system and its environment because it depends on both the state of the system and the environment. The ratio of energy to exergy in a substance can be considered as a measure of energy quality [8]. Exergy analysis is a very powerful tool for energy systems, particularly when it is combined with exergoeconomics.

Exergetic and exergoeconomic analyses are often used to evaluate the performance of energy systems from the thermodynamic and economic point of view [9]. Erbay and Hepbasli [10] applied conventional and advanced exergy analyses of a ground-source heat pump dryer in the case of a system for food drying. In [11] the authors demonstrated how the contribution of chemical reactions, heat transfers, and to a lesser extent friction and mixing, to the exergy destruction within combustion system could be approximately estimated. Vučković *et al.* [12] in-

investigated the performance of critical components and the potential for efficiency improvement of a complex industrial energy supply plant using an advanced exergy analysis. In [13] the exergoeconomic analysis was used for a comparison of the former and new perlite expansion furnaces. The effect of some parameters on the product cost, such as exergy destruction and losses, can be better understood through the exergoeconomic analysis. The results obtained are discussed from the different perspectives. In [14] the authors performed an exergoeconomic analysis to a proton exchange membrane vehicular fuel cell system used in the new generation of environmentally friendly cars. The results show that an end of a life-sized system with an expander is the most cost effective system, while the compression and humidification of air are very expensive processes. The stack is by far the most important component from the economic point of view, and the thermodynamic efficiency of almost all components must be improved to increase the cost effectiveness of the overall system. In [15] a comprehensive thermodynamic and exergoeconomic methodology was presented to assess the energy consumption and cost allocation of a real plant with all associated main components. Mass, energy, and exergy balances were applied to each system component considering various work and heat terms and exergy destructions. Paper [16] presented and evaluated the results of a detailed exergoeconomic analysis of a plant capturing CO₂ with chemical looping combustion, as compared to the performance of a conventional plant. In [17] the authors implemented a comprehensive exergoeconomic analysis in a 6.5 MW fluidized-bed coal combustor steam power plant using the data obtained from running system. The role and impact of each system component on the first and second law efficiencies were analyzed to understand the individual performance of sub-components.

There are many examples of exergoeconomic approaches in the open access literature, however, none focus on the coffee industry. The aim of this paper is to show the potential for the energy and cost reduction on the demand side, using the exergoeconomic evaluation in the example of a real process for coffee roasting. The inputs to the mathematical model are partly data obtained from the onsite measurements such as operation-related thermodynamic and flow parameters. The mathematical model consists of a set of non-linear/linear equations, including the ones required to determine the properties of working fluids. This problem is solved numerically using the engineering equation solver [18].

Roasting process and system description

Figure 1 depicts the basic components, material streams and energy flows for a gas-fired batch roaster with an afterburner. Natural gas, which is used as primary fuel for the

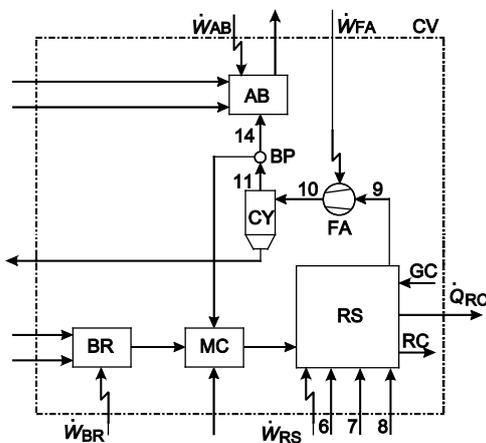


Figure 1. Flow diagram of the representative coffee roasting system; AB – afterburner, BP – branching point, BR – burner, CV – control volume, CY – cyclone, FA – fan, GC – green coffee, MC – mixing chamber, RC – roasting coffee, RS – roaster, 1,15 – natural gas, 2,16 – ambient air, 3,5 – combustion gasses, 4 – ambient air, 6 – coffee chaff with coffee beans, 7 – water from coffee beans, 8 – additional water, 9, 10 – combustion gasses, 11, 14 – combustion gasses, 12 – coffee chaff, 13 – combustion gasses, 17 – combustion gasses, GC – green coffee, RC – roasting coffee, W – electricity supply, Q_{RC} – heat for coffee roasting

roasting process, is supplied from a compressed natural gas (CNG) station to the burners of the batch coffee roasters. Table 1 shows the technical data for the roaster (component RS in fig. 1), its burner (BR) and afterburner (AB).

Table 1. Technical data for the roaster, its burner and afterburner

Roaster	Nominal power	580 kW
	Capacity	300 kg of fresh coffee
	Fuel	Compressed natural gas
Roaster burner	Power range	100-1000 kW
	Pressure range	15-500 mbar
	Inlet electrical power	1.9 kW
Afterburner	Power range	65-630 kW
	Pressure range	15-500 mbar
	Inlet electrical power	1.6 kW

Combustion gases enter the chamber located just before the drum where they are mixed with the ambient air entering through the diffusers (slots) of the roaster. The formed mixture of air and exhaust gases enters the drum where coffee roasting is performed. The temperature of the mixture inside the chamber is in the range of 400-450 °C. At the beginning, the mixture heats up the empty drum to the temperature of 200 °C and the duration of this stage of the process is 16-30 seconds. When the temperature of 200 °C is reached, the drum is filled with 300 kg of green coffee, which lasts for approximately 20 seconds.

Green coffee entering the roaster has the temperature of approximately 20 °C and the humidity of 9-11%. Roasted coffee leaving the roaster has the humidity of 3%, and this value is controlled by spraying the water at the end of the whole roasting process. One batch containing 300 kg of green coffee yields approximately 255-260 kg of roasted coffee.

Green coffee within the spinning drum interacts with the mixture of air and exhaust gases. The coffee roasting process has several phases and each one has a set-point temperature that needs to be reached at the end of the phase. Coffee roasting is performed until coffee beans reach the temperature of 200-220 °C.

The main part of the roasting process lasts around 13 minutes (740-900 seconds), depending on the recipe, but the total time when one batch is in the drum (time before the next batch enters the drum) lasts longer and is around 15 minutes (850-990 seconds). The time difference of around two minutes include controlling the humidity of the coffee (spraying water), additional roasting, transferring the coffee from the drum to the coffee cooling unit, and heating the drum to 200 °C for receiving the next batch.

When the main phase of coffee roasting is finished, coffee beans are sprayed with water in order to control the bean humidity. Water is added twice due to the technological requests, with a short delay of 8-12 seconds. The quantity of added water depends on the bean humidity and is controlled in order to reach 3% before leaving the drum. The spraying time is between 38-59 seconds.

After adding water, the beans are roasted for additional five seconds. This completes the coffee roasting process, the door of the roaster opens and roasted coffee is moved to the cooling unit. This phase lasts 40 seconds. The cooling unit is an open tank with the diameter

of 2.5 m, equipped with mixers in order to speed-up coffee cooling and prepares it for pneumatic transport. Coffee is cooled with the ambient air, so it reaches the ambient temperature before the pneumatic transport. The duration of coffee cooling is approximately 400 seconds. During next 270-280 seconds, coffee is transported to the silos, from which it is forwarded to grinding and packing.

After leaving the drum, combustion gases enter the cyclone separator where dust particles and coffee bean chaff are removed. After the cyclone separator, gases are incinerated in the afterburner together with VOC, and the particles not removed in the cyclone separator. The incinerator is equipped with the compressed natural gas burner. The exhaust gases leaving the afterburner have the temperatures in the range 350-420 °C which conform to the technology for the effective incineration of VOC and particles. The exhaust gases are emitted to the environment.

In this paper, the representative system of the coffee factory considered was mathematically modeled with six elements, 17 material streams, one stream of green coffee, one stream of roasting coffee and five energy flows.

Methodology and modeling

The entropy balance equation for a component k for steady-state conditions has the form:

$$0 = \sum_j \left(\frac{\dot{Q}_j}{T_j} \right)_k + \sum_i (\dot{m}_i s_i)_k - \sum_e (\dot{m}_e s_e)_k + \dot{S}_{\text{gen},k} \quad (1)$$

The first term on the right-hand side of eq. (1) represents the entropy transferred with energy flows due to heat transfer on the component k control volume boundary; the second and third terms represent the entropy transferred with streams entering and leaving the component k control volume boundary, while the last term represents the entropy generated due to heat transfer process irreversibility.

Conforming to the basic definition of the term exergy, Szargut *et al.* [19] found that the coefficient of proportionality between the generated entropy and the exergy destruction is the temperature of reference surroundings, so the exergy destruction originating from an internal irreversibility in the component k can be represented as a product of the reference surroundings temperature and the entropy generated within the component [15]:

$$\dot{E}_{D,k} = T_0 \dot{S}_{\text{gen},k} \quad (2)$$

Having in mind that it is rational to analyze energy systems in the steady-state, the quantity of destroyed work, *i. e.* the value of exergy destruction, can be determined from the exergy balance equation for the component k [20]:

$$0 = \sum_j \left(1 - \frac{T_0}{T_j} \right) \dot{Q}_{j,k} - \dot{W}_{\text{cv},k} + \sum_i (\dot{m}_i e_i)_k - \sum_e (\dot{m}_e e_e)_k + \dot{E}_{D,k} \quad (3)$$

The total exergy of a material stream is calculated as the sum of four major terms of exergy: physical, chemical, kinetic, and potential, but the physical and chemical exergy are more interesting for this paper. For this reason, the specific exergy per mass basis of a stream is:

$$e_j = e_j^{\text{PH}} + e_j^{\text{CH}} \quad (4)$$

The physical exergy of a stream of matter can be defined as the maximum work (useful energy) that can be obtained from it when taking it to the physical equilibrium (of temperature and pressure) with the environment [14] and the specific physical exergy transfer associated with a stream of matter:

$$e_j^{\text{PH}} = (h_j - h_0) - T_0(s_j - s_0) \quad (5)$$

The chemical exergy of a stream of matter can be defined as the maximum work (useful energy) that can be obtained from it when taking it to the chemical equilibrium (of composition) with the environment [21]. For many identified substances, the standard chemical exergy (*i. e.* at T_0 and p_0), can be found in the literature. The specific chemical exergy per mole of the gas component k is given simply by a logarithmic term of the form [22]:

$$\bar{e}_k^{\text{CH}} = -\bar{R}T_0 \ln y_k^e \quad (6)$$

The chemical exergy of a stream that represents a mixture of ideal gases is a sum of the contributions of all its components. If all the components are present in the environment as gases and the stream is at temperature T_0 and pressure p_0 , the chemical exergy of that stream, per mole of ideal gas mixture, is [22]:

$$\bar{e}_k^{\text{CH}} = -\bar{R}T_0 \sum_k \left(y_k \ln \frac{y_k}{y_k^e} \right) \quad (7)$$

Having in mind eq. (6), eq. (7) can also be written [14, 20]:

$$\bar{e}_j^{\text{CH}} = \sum_k (y_k \bar{e}_k^{\text{CH}}) + \bar{R}T_0 \sum_k (y_k \ln y_k) \quad (8)$$

The equation which expresses the ratio of standard chemical exergy and lower heating value of combustible gaseous hydrocarbons is [19]:

$$\beta = \frac{e_j^{\text{CH}}}{\text{LHV}} = 1.0334 + 0.0183 \frac{\text{H}}{\text{C}} - 0.0694 \frac{1}{N_{\text{C}}} \quad (9)$$

In this paper, the chemical exergy will be determined for the primary fuel – compressed natural gas. If the value of exergy destruction of a certain system component is being compared with the exergy of the fuel (a resource that is supplied to the whole system), according to the fuel-product form, the coefficient of exergy destruction for the component k can be expressed in the form [16]:

$$y_{\text{D},k} = \frac{\dot{E}_{\text{D},k}}{\dot{E}_{\text{F,tot}}} \quad (10)$$

When the coefficient of exergy destruction is expressed as a percentage, the percent of exergy efficiency decreases for the whole system is obtained from the exergy destruction in the component k . If we identify both fuel and product for the system, in the fuel-product concept, the exergy efficiency at the component level is the ratio between the product and the fuel [14, 16]:

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \quad (11)$$

Exergy efficiency shows what percent of exergy from fuel is found in the exergy of product of an observed system, plant or a component. The difference between 100% and the actual value of exergy efficiency represents the percent of the exergy of fuel lost in the system in the form of exergy destruction [7].

Exergy efficiency can make sense from both thermodynamic and economic point of view. The scientific community agrees that exergy is an adequate thermodynamic property to which costs can be attached. Costs are primarily related to economics, but exergy characterizes the quality of energy. Having this in mind, the term exergoeconomics is introduced. It allows the direct representation of interactions between thermodynamics and economics.

Exergoeconomic costs basically represent money costs of energy and material flows. The cost balance of the overall system operating at steady-state can be written [20]:

$$\dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} \quad (12)$$

The same form of eq. (12) applies to the component level of an energy system.

The balance of costs, *i. e.* cost rates, represents the equality between: (1) the cost rate associated with the product of the system, and (2) the sum of the fuel cost rate, the cost rate related to the levelized capital investment (CI), and the operating and maintenance (O&M) cost rate. The rates of CI and O&M are obtained by dividing the annual contribution of CI and annual O&M costs, respectively, with annual time units count of system operation. In eq. (12) the variable \dot{C} denotes a cost rate associated with an exergy stream – stream of matter, power, or heat transfer – while the variable \dot{Z} represents all the remaining costs [20].

The evaluation of exergoeconomic costs assumes formulating exergoeconomic balances for all the components of the system separately. The exergoeconomic balance for the component k of an energy system shows that the sum of the exergoeconomic costs of energy and material flows entering the component is equal to the sum of the exergoeconomic costs of energy and material flows leaving the component and non-exergy-related costs represented with CI and O&M costs [20]:

$$\sum_e (c_e \dot{E}_e)_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}_{q,k} + \sum_i (c_e \dot{E}_e)_k + \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \quad (13)$$

The exergy rates in eq. (13) exiting and entering the k^{th} component are calculated in an exergy analysis. In this paper, a real industrial facility for roasting coffee is analyzed, while the capital costs for equipment and facility production could not have been influenced and taken into account, leaving only O&M costs for every component of the system to be taken into account.

For this reason, CI equals zero and O&M costs associated with the k^{th} component are determined as the levelized values per unit of time (year, hour, or second) of the system operation. The variables in eq. (13) are levelized costs per unit of exergy for the exergy streams associated with the k^{th} component [20].

Having in mind that, in some cases, the separation of the total stream exergy to chemical and physical components is justified, as well as the detachment of the related costs, eq. (13) might take the form:

$$\sum_e (c_e^{\text{PH}} \dot{E}_e^{\text{PH}} + c_e^{\text{CH}} \dot{E}_e^{\text{EH}})_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}_{q,k} + \sum_i (c_e^{\text{PH}} \dot{E}_e^{\text{PH}} + c_e^{\text{CH}} \dot{E}_e^{\text{EH}})_k + \dot{Z}_k^{\text{CI}} + \dot{Z}_k^{\text{OM}} \quad (14)$$

Assuming that the exergy of a product is constant and that the unit exergoeconomic cost of the fuel for an analyzed component is independent of exergy destruction, the exergoeconomic cost for exergy destruction can be defined [14]:

$$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} (\dot{E}_{P,k} = \text{const.}) \quad (15)$$

The exergy destruction cost in eq. (15) is the cost for fuel additionally required by the component of interest (this fuel should be provided to the component), in order to compensate for the disturbance in the component caused by exergy destruction.

Results and discussion

The main purpose of the energy system considered in this paper is generating the heat required for coffee roasting. This heat is produced in the roaster. The roasters have a capacity of up to 4 tons of green coffee beans per hour. The system is composed of a large number of components. It is observed as a control volume including all components and streams, as shown in fig. 1. The input data for the calculation consisted of pressures and temperatures in different points of the flows of streams obtained from the existing process of the referent plant. The official data on the lower heating values for the fuel were used. The cost of air provided was considered to be zero. The rate Z_k was calculated as the levelized annual cost for a period of 20 years with the annual escalation rate of 6% and the rate of return of 12% using the real present operating and maintenance cost for 4,000 working hours per year.

The basic objective is to determine the exergy efficiency of the system and the cost of coffee roasting using exergy and exergoeconomic analyses. Another important aspect of this research is the examination of the possibilities to correct this cost by exploiting the energy content of streams 12 and 17. Table 2 shows the overview of the equations used for the determination of the exergy of fuels and products for all the components and the additional equations for the exergoeconomic analysis.

Table 2. Summary of equations for exergy and exergoeconomic analysis

Exergy of fuel	$\dot{E}_F = \dot{E}_1 + \dot{E}_2 + \dot{E}_4 + \dot{E}_6 + \dot{E}_7 + \dot{E}_8 + \dot{E}_{15} + \dot{E}_{16} + \dot{W}_{\text{BR}} + \dot{W}_{\text{RS}} + \dot{W}_{\text{FA}} + \dot{W}_{\text{AB}}$
Exergy of product	$\dot{E}_P = \dot{E}_{\text{RS}}$
Auxiliary exergoeconomic relations	$c_1^{\text{PH}} = c_{15}^{\text{PH}} = c_{12}^{\text{PH}} = c_{17}^{\text{PH}} = c_2 = c_4 = c_6 = c_7 = c_{16} = 0$

Table 3 presents the results of thermodynamic, exergy and exergoeconomic analyses for the inlet and the outlet streams of the regarded control volume. For the sake of simplicity, the properties of the dead state are taken as environmental conditions, such as 1.013 bar and 25 °C. Table 4 lists energy flows at the system boundary, as well as corresponding exergies and costs. Finally, tab. 5 gives the performance of the entire system, including its exergy efficiency. The results indicate that the largest contribution to the exergy on the inlet to the system control volume originates from the chemical exergy of fuel (natural gas). The exergy of natural gas is 99.93% of the total inlet exergy.

The total fuel exergy of the system is 920.76 kW. Stream 1 has 55.99% of this value (515.60 kW), while stream 15 contains 38.02% (360.90 kW). It can be seen that coffee chaff

Table 3. Results of thermodynamic, exergy, and exergoeconomic analyses at streams level

Stream		Thermodynamic analysis					Conventional exergy analysis				Exergoeconomic evaluation		
		m_j [kgs ⁻¹]	t_j [°C]	p_j [bar]	h_j [kJkg ⁻¹]	s_j [kJkg ⁻¹ K ⁻¹]	e_j^{PH} [kJkg ⁻¹]	e_j^{CH} [kJkg ⁻¹]	E_j [kW]	E_j [MJ]	c_j^{CH} [€/per GJ]	\dot{C}_j [€/per hour]	c_j [€/per GJ]
j	Name												
1	Natural gas	0.010	25.00	1.250	-4649.7	11.495	34.07	51525.8	515.6	443.4	23.33	43.30	23.33
2	Ambient air	0.181	25.00	1.013	298.60	6.884	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Ambient air	1.507	25.00	1.013	298.60	6.884	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Coffee chaff	0.003	25.00	1.013	31.40	0.000	31.40	11500.0	34.59	29.75	0.00	0.00	0.00
7	Water from cof.	0.055	25.00	1.013	104.84	0.367	4.59	2.50	0.39	0.34	0.00	0.00	0.00
8	Add. water	0.042	12.00	3.500	50.70	0.180	1.53	2.50	0.17	0.15		0.004	6.15
12	Coffee chaff	0.003	130.0	1.013	214.24	0.642	38.87	11500.0	34.62	29.77	0.00		
15	Natural gas	0.007	25.00	1.250	-4649.7	11.495	34.07	51525.8	360.9	301.1	23.33	29.40	23.33
16	Ambient air	0.123	25.00	1.013	298.60	6.884	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	Combust. gas	1.925	292.0	1.013	-2575.7	7.944	87.60	32.48	231.2	198.8	0.00		

(stream 6) possesses a significant specific potential of the chemical exergy (11,500.00 kJ/kg), but because of a relatively small mass flow (0.003 kg/s), the absolute contribution to the fuel exergy of the entire system is small – 3.76% or 34.59 kW.

A smaller part of the exergy of the system (2.23%) is provided by electricity input for running the fans and other electrically powered components.

The exergy of the product for the entire system (306.25 kW) is determined having in mind the heat required for the coffee roasting process (490 kW). The results show that the exergy destruction and loss of the entire system of 614.51 kW significantly reduce the overall exergy efficiency, which has the value of 33.26%. It is important to notice that the exhaust gases (stream 17) leave the control volume with a relatively high temperature (292 °C) and consequently high physical exergy. The physical exergy of exhaust

Table 4. Energy flows at the system boundary and corresponding exergies and costs

Component	Energy flow	Power	E_i	E_i	\dot{C}_i	c_i
–	–	[kW]	[kW]	[MJ]	[€/per hour]	[€/per GJ]
Burner	Electricity, W_{BR}	1.86	1.86	1.60	0.186	27.80
Fan	Electricity, W_{FA}	11.00	11.00	9.46	1.100	27.80
Afterburner	Electricity, W_{AB}	1.56	1.56	1.34	0.156	27.80
Roaster	Electricity, W_{RS}	5.50	5.50	4.73	0.550	27.80
Roaster	Heat RC, Q_{RC}	490.00	306.30	263.40	279.010	253.03

Table 5. Overall system performance data

Total fuel exergy	$E_{F,tot}$	920.76 kW
Total product exergy	$E_{P,tot}$	306.25 kW
Total destruction and loss of exergy	$E_{D,tot} + E_{L,tot}$	614.51 kW
Total exergy efficiency	ε_{tot}	33.26%

gases is 231.20 kW or 37.62% of the total exergy destruction and loss of the system. Obviously, the exploitation of the exhaust gases has a large potential for the improvement of the overall exergy efficiency.

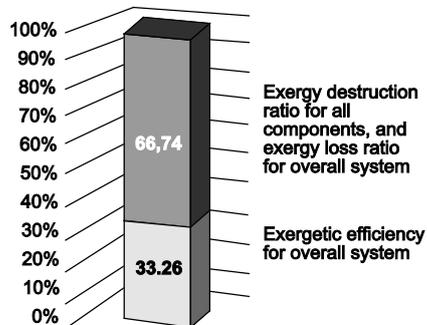


Figure 2. Exergy efficiency of the overall system and the influence of the exergy destruction ratio and the exergy loss ratio on its value

As already mentioned, the exergy efficiency of the system is low (33.26%), as can be seen from tab. 2. Since one of the goals of this study is its improvement (increase), it is important to identify the reasons for such a low value. Two indicators might be used for this purpose: (1) exergy destruction coefficient, and (2) exergy loss coefficient. Figure 2 illustrates the overall exergy efficiency and the sum of these two coefficients. The overall exergy efficiency reduction of 66.74% is related to exergy destruction and losses related to all the components. The analysis of the possibilities for reducing the exergy destruction of the components is beyond the scope of this paper.

Figure 3 shows the dependence of the coffee roasting cost expressed per unit of exergy on the costs of exhaust gases physical exergy and waste coffee chaff chemical exergy. The cost of exhaust gases (stream 17) physical exergy is varied in the range from 0 €/per GJ (the current state), to 23 €/per GJ, while the cost of coffee chaff (stream 12) chemical exergy is changed from 0 €/per GJ (also the current state) to 14 €/per GJ, with the step of 2 €/per GJ.

The cost of coffee roasting would linearly decrease with the exploitation of the exhaust gases potential, *i. e.* with the increase in the cost-value of their physical exergy. This cost additionally drops when coffee chaff, *i. e.* its chemical exergy, is made useful. In the worst case ($c_{17}^{PH} = c_{12}^{CH} = 0$ €/per GJ), the cost of coffee roasting is 253.03 €/per GJ. However, if one could exploit the potential of exhaust gases, *i. e.* if their monetary value is 23 €/per GJ, the cost

would drop by 16.28%, to 211.83 € per GJ. With the increase in the waste coffee chaff cost, the cost of roasting also decreases. If the cost of the exhaust gases is zero and the cost of coffee chaff is 14 €/per GJ, the cost of roasting is 247.90 € per GJ, *i. e.* it drops by 2.02%. As can be seen from fig. 3, the same percentage is kept for other costs of exhaust gases.

The best case is when both streams 12 and 17 have maximal associated costs – 14 and 17 €/per GJ, respectively. Then, the cost of coffee roasting is 206.70 € per GJ, which represents the reduction of 46.33 € per GJ or 18.31% compared to the worst-case scenario.

Figure 4 illustrates the dependence of coffee-roasting exergoeconomic cost (expressed in €/per hour) on the costs of exhaust gases physical exergy and waste coffee chaff chemical exergy. The trend of the decrease in costs is similar as in fig. 3, but with a more obvious quantification of financial savings. In the worst case ($c_{17}^{PH} = c_{12}^{CH} = 0$ €/per GJ), the exergoeconomic cost of coffee roasting is 86.09 €/per hour. In the case when the cost of exhaust gases is 23 €/per GJ and the cost of coffee chaff is zero, the cost of roasting is 72.07 € per hour, *i. e.* the savings compared to the worst-case scenario are 14.02 €/per hour or 16.28%. If the cost of coffee chaff is 14 €/per GJ, the savings are 1.75 €/per hour or 2.02%.

In the best case ($c_{17}^{PH} = 23$ €/per GJ, $c_{12}^{CH} = 14$ €/per GJ), the exergoeconomic cost of roasting is 70.33 €/per hour, and the savings comparing with the baseline (current, worst-case) scenario are 15.76 €/per hour or 18.31%. Under the assumption that the factory works 4,000 hours per year, the realistic absolute annual savings of 60,040 € are calculated.

Conclusions

This paper presents the results of exergy and exergoeconomic analyses of a real plant for coffee roasting, conducted with the goal to determine the exergy efficiency of the system and the cost of coffee roasting, as well as to estimate the potential of coffee roasting cost corrections due to the exploitation of the energy content of streams 12 and 17. The value of the overall exergy efficiency of 33.26% indicates that there is a potential for energy improvements and costs reduction. The dominant impact on the exergy input to the system is exerted by methane, *i. e.* streams 1 and 15 with 94.01%. The exploitation of exhaust gases (stream 17) has a significant potential for the increase in the overall exergy efficiency and cost savings because the gases leave the system with a high temperature (292 °C) and the exergy

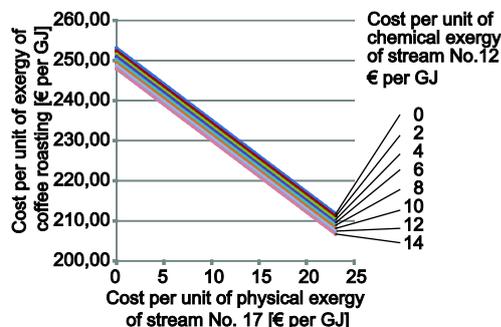


Figure 3. Dependence of the coffee roasting cost expressed per unit of exergy on the costs of exhaust gases physical exergy and waste coffee chaff chemical exergy

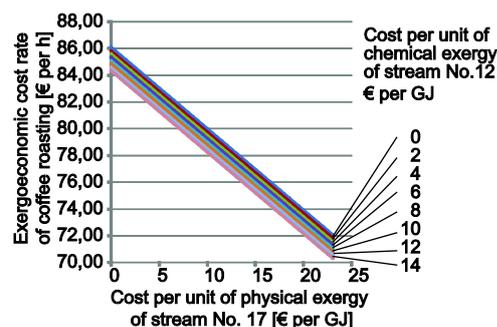


Figure 4. Dependence of the coffee-roasting exergoeconomic cost on the costs of exhaust gases physical exergy and waste coffee chaff chemical exergy

of 231.20 kW, which is 37.62% of the total exergy destruction and loss. By far smaller, but certainly not negligible potential for the reduction of the roasting cost is in the use of waste coffee chaff (stream 12), which has a high value of the specific chemical exergy (11,500 kJ/kg).

The analyses of the dependencies of the coffee roasting cost on the exhaust gases and waste coffee chaff costs indicate that the reduction of the roasting cost of 18.31% (15.76 €/per hour) is feasible when the cost of exhaust gases is 23 €/per GJ and waste coffee chaff costs 14 €/per GJ. In this case, annual cost savings of 60,040 € are realistic.

This paper presents the first publication of the application of exergoeconomic analysis on a real coffee roasting plant, to the best of the authors' knowledge. Possible directions for further research are mainly related to a deeper analysis – exergy and exergoeconomic, both conventional and advanced – of the roasting process, on the level of components. In addition to that, the quality of mathematical models for such a non-stationary process as coffee roasting could be significantly improved by conducting dynamic analysis, *i. e.* solving balance equations for smaller intervals and observing different parts of the process separately.

Nomenclature

\dot{C}	– exergoeconomic cost rate, [€/per hour]
c	– cost per unit exergy, [€/per GJ]
E	– exergy, [kJ]
\dot{E}	– exergy flow rate, [kW]
e	– specific exergy, [kJkg ⁻¹]
\bar{e}	– specific exergy per mole, [kJkmol ⁻¹]
h	– specific enthalpy, [kJkg ⁻¹]
H/C	– atomic ratio of the elements
LHV	– lower heating value, [kJN ⁻¹ m ⁻³]
\dot{m}	– mass flow rate, [kgs ⁻¹]
N_C	– main number of carbon atoms in molecule
p	– pressure, [bar]
\underline{Q}	– heat transfer rate, [kW]
\bar{R}	– universal gas constant, [kJkmol ⁻¹ K ⁻¹]
S	– entropy, [kWk ⁻¹]
s	– specific entropy, [kJkg ⁻¹ K ⁻¹]
T	– temperature, [K]
\dot{W}	– work rate, [kW]
y	– mole fraction (kmol/kmol); exergy destruction ratio
\dot{Z}	– cost rate associated non-exergy cost, [€/per year]

Greek symbols

β	– ratio of standard chemical exergy and LHV
ε	– exergy efficiency

Subscripts

cv	– control volume
D	– destruction
e	– outlet stream
F	– fuel
gen	– generated
i	– inlet stream
j	– stream
k	– system component
P	– product
q	– heat transfer
tot	– overall system
w	– generating power
0	– environment

Superscripts

CH	– chemical
CI	– capital investment
e	– environment
OM	– operating and maintenance
PH	– physical

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