EXERGY AND EXERGOECONOMIC ANALYSIS OF A STEAM BOILER

by

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Relying on coal as primary fuel in thermal power plants represents an unsustainable concept due to limited coal reserves and a negative environmental impact. Efficient utilization of coal reserves and a request for minimization of irreversibilities are imperative for thermal power plants operation. Numerous studies have shown that a steam boiler is a thermal power plant component with the highest irreversibility. The idea of this paper is to quantify the amounts and sources of irreversibilities within a steam boiler and its components, serving a 348.5MWe thermal power plant. Having this in mind, exergy and exergoeconomic analysis of a steam boiler is presented in this paper. Exergy destruction and exergy efficiency of all boiler components and of the boiler as a whole were calculated. Based on exergy flows and economic parameters (cost of the boiler, annual operation hours of the unit, maintenance factor, interest rate, operating period of the boiler), exergy analysis resulted in the cost of produced steam. The obtained results show that the boiler exergy efficiency is at 47.4%, with the largest exergy destruction occurring in the combustion chamber with a value of 288.07 MW (60.04%), and the smallest in the air heater with a value of 4.57 MW (0.95%). The cost of produced steam is calculated at 49,356.7 $/h by applying exergoeconomic analysis.

Key words: *exergy destruction, efficiency, exergoeconomic analysis, steam boiler*

Introduction

Traditional analysis and calculation methods for complex thermal plants are based on the First law of thermodynamics. These methods use system the energy balance approach. By using the energy balance approach, one can obtain the energy demand in the form of heat flows, energy and mechanical work, but without precise information on whether or not this energy is efficiently utilized in the system. Energy balance does not provide information on internal losses. The only inefficiencies detected by the energy balance approach are related to energy transfer outside the observed system. On the other hand, the Second law of thermodynamics introduces exergy, which is far more suitable for analysis of thermal plants. This complements and improves energy balance by allowing the determination of the thermodynamic value of the energy carrier and real thermodynamic inefficiencies in processes or systems. Real thermodynamic inefficiencies of the system are exergy destruction within the system boundaries and exergy losses (exergy transfer outside the system boundaries).

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Exergy is used for determining energy quality and enables finding the location, cause and real values of generated losses as well as determining residues in a thermal process. When two systems with different states interact, they tend to reach equilibrium, thus performing work. If one of the systems represents surroundings and the other the thermodynamic system of interest, then the maximal possible work obtained by the interaction between these systems and reaching equilibrium is exergy, assuming only heat is being exchanged. Every system not in equilibrium with its surroundings has the potential to perform work. Every system which is in equilibrium with its surrounding, by definition, does not have the potential to perform work. Exergy can be treated as the distance of the state of a certain system from the state of its surroundings. Exergy can be destroyed but cannot be conserved (preserved). Exergy is completely destroyed if a system reaches equilibrium spontaneously with its surroundings without performing work.

Exergy analysis is a method that combines heat and mass balance with the Second law of thermodynamics. Exergy analysis enables determining the location, causes and sources of losses. This information can be used for constructing new energy-efficient systems, but also for improving the performance of the existing systems. Furthermore, exergy analysis provides an insight into and allows finding causes for thermodynamic inefficiency of systems.

In Serbia, 74% of electricity is produced in coal-fired thermal power plants with steam turbines (Energy Balance of the Republic of Serbia in 2014). Since steam boilers are used for transforming chemical energy of fuel into heat energy of water steam, significant primary energy savings can be achieved by improving the efficiency of the steam boiler in operation. For this reason it is very important to maximize heat transfer to water/steam and to reduce heat losses in the boiler, by identifying and quantifying these losses.

Many authors have applied exergy analysis to steam boilers in industrial facilities or thermal power plants. Talatappeh and Gazikhani [1] performed a boiler exergy analysis of an experimental thermal power plant. In the research they divided the boiler into three regions (combustion, heat transfer to water or steam, and exhaust) and calculated irreversibility in every region. The results showed the maximum irreversibility of 54.8% in the second region, 39% in the first region, and 6% in the third region, for the maximum boiler pressure of 8 bar. In their research, Gulhane and Thakur [2] analyzed a co-generation system in order to quantify and identify the sources of irreversibilities generated in the boiler. Exergy analysis revealed that for the load of 1.1 MW, exergy destruction in the boiler was approximately 83.35% compared to the whole system. Hada and Shah [3] showed the irreversibilities generated in a 30 MW boiler. The results showed that the maximum exergy destruction was in the boiler, and the boiler exergy efficiency was determined to be 33.73%. Pattanayak and Ayyagari [4] presented energy and exergy analysis of a 500 MW coal-fired boiler. The locations and magnitude of exergy destruction for the boiler were determined. The authors reported that the highest exergy destruction was in the combustor, followed by the heat exchanger. For design conditions, the energy efficiency of the boiler was 85.54% while the exergy efficiency of the boiler was 41.81%.

Exergoeconomics is a new analysis technique that combines thermodynamics (exergy) and economics using the concept of cost-to-exergy. It involves the calculation of the Second law (exergetic) efficiency and relates the economic loss to the technical and thermodynamic parameters of the system. Exergoeconomic analysis has become a powerful tool for assessing the performance of energy conservation systems. Variables such as exergy efficiency, the rates of exergy destruction, capital investment, operation, and maintenance cost provide a holistic view of the operation of the boiler. Several thermodynamic relations between the energy and exergy losses and capital cost for thermal systems in a modern coal-fired power plant have been developed and used extensively in research. From these relations concerning the power plant as a whole, the boiler is treated only as a component of a larger system without in-depth analysis of boiler components, contrary to the approach presented in this paper. This study presents the exergy and exergoeconomic analysis of lignite-fired steam boiler components (installed in a thermal power plant). The decomposition of the boiler is done by determining control volumes corresponding to the functional units-components of the boiler. The analysis presents: exergy efficiency of every component of the steam boiler, destruction of exergy and percentage of exergy destruction in the boiler components, as well as, the cost of generated steam. The boiler system comprises a feed water system, a steam system and a fuel system. The feed water system provides water to the boiler. The steam system collects and controls the steam production in the boiler. The fuel system includes all the equipment used to provide fuel to generate the necessary heat for steam production. The obtained results were used to evaluate and suggest improvements in the equipment. Furthermore, exergoeconomic analysis was applied based on exergy losses in the boiler. Application of exergy and exergoeconomic analysis to the boiler components leads to the detection of the component with the largest exergy destruction, which can further lead to operation optimization of the boiler or its components.

Exergy evaluation and mathematical model

The framework for the methodology of this study is shown in fig. 1. The methodology is based on having input and output operational parameters from every component of the boiler known. Using tables, diagrams or by applying necessary equations, variables needed for exergy and exergoeconomical analysis can be calculated.

Exergy analysis is based on the Second law of thermodynamics. The results of this analysis can be used to reduce irreversibilities in the steam boiler and thus increase its efficiency. In this research, exergy destruction and exergy efficiency were calculated for the steam boiler as a whole and for its components separately.

Total exergy consists of the potential, kinetic, physical, and chemical components [5]:

$$E_x = E_x^{\mathrm{PH}} + E_x^{\mathrm{KN}} + E_x^{\mathrm{PT}} + E_x^{\mathrm{CH}} \quad (1)$$

In this research, the kinetic and potential components were neglected, so only the physical and chemical components were determined. The physical exergy is defined as the maximum possible (theoretical) useful work obtained when a system interacts with its surroundings (equilibrium state), while the chemical exergy is associated with the chemical composition of a system departing from its chemical

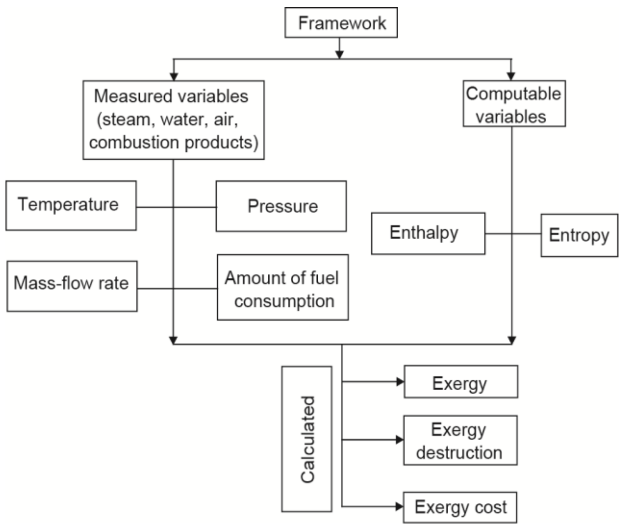

Figure 1. Methodological framework

equilibrium. The chemical exergy is an important part of exergy for combustion processes. In order to perform exergy analysis, mass and energy balance of a system are prerequisite. Combining the First and Second law, for a given control volume under steady-state conditions, the exergy destruction equation derived from exergy balance can be given [5, 6]:

$$\dot{E}_{x\mathrm{D}} = \sum (\dot{E}_x)_{\mathrm{in}} - \sum (\dot{E}_x)_{\mathrm{out}} + \left[\sum \dot{Q} \left(1 - \frac{T_0}{T}\right)_{\mathrm{in}} - \sum \dot{Q} \left(1 - \frac{T_0}{T}\right)_{\mathrm{out}} \right] \pm \dot{W} \tag{2}$$

where $\Sigma(\dot{E}_x)_{\mathrm{in}}$ are the exergy of streams entering and leaving the control volume, $\Sigma(Q)(1 - T_0/T)$ – the exergy transfer at temperature T, T_0 – the environment temperature of the system's surroundings, while the subscripts in and out represent inlets and outlets, respectively, and $\dot{W}$ is the work rate excluding the flow work.

In this research, only the physical exergy by mass-flows crossing the control volume is taken into account and given in the form:

$$\dot{E}_x = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{3}$$

where h represents the specific enthalpy, and s – the specific entropy, while the subscript 0 denotes the restricted dead state.

Fuel exergy

For the chemical exergy of the fuel, a semi-empiric formula is used as a function of fuel composition. This formula has the form [7]:

$$e_x^{\mathrm{CH}} = LHV \left(1.0438 + 0.0013 \frac{x_{\mathrm{H}}}{x_{\mathrm{C}}} + 0.1083 \frac{x_{\mathrm{O}}}{x_{\mathrm{C}}} + 0.0549 \frac{x_{\mathrm{N}}}{x_{\mathrm{C}}} \right) + 6740 x_{\mathrm{S}} \tag{4}$$

In literature, the chemical exergy of the fuel is often given as a function of a *LHV* of the fuel only, *i. e.* the ratio of chemical exergy and the *LHV*, $\varphi = e_{x\ \mathrm{f}}^{\mathrm{CH}} / LHV_{\mathrm{f}}$ and it is applied in this work as well. In [8, 9], the value of this ratio for lignite is 1.04, while the *LHV* is 6845 kJ/kg (lignite chemical composition: C = 20.62%, H_2 = 2.14%, S = 0.23%, O_2 = 9.65%, N = 1%, W = 51.95%, A = 14.41%).

Exergy of flue gases and air

For the mixture of ideal gases (flue gases can be treated as such), chemical exergy can be given in the following form [10]:

$$\bar{e}_x^{\mathrm{CH}} = \sum_{i=1}^{n} x_i e_{xi}^{\mathrm{CH}} + \bar{\mathrm{R}} T_0 \sum_{i=1}^{n} x_i \ln x_i \tag{5}$$

Specific exergy of flue gases and air can be calculated by the formula from [11] as well:

$$e_x = c_p \left[(T - T_0) - T_0 \ln \frac{T}{T_0} \right] \tag{6}$$

This was applied in this research. The specific heat capacity was calculated by the Rosario-Messina method [12]:

$$c_p(T) = \sum_{i=0}^{5} a_i (\ln T^*)^i \quad [\mathrm{Jmol^{-1}K^{-1}}] \tag{7}$$

where $T^* = T/T_0$ and a_i are coefficients from [12].

Parameters of the surroundings

For exergy analysis it is very important to select proper parameters of the surroundings (state of surroundings). These parameters refer to reference pressure and reference temperature, but also to the composition of air. Several models can be found in literature, but most common is to use 293.15 K for reference temperature and 1013 mbar for reference pressure. Reference air composition is given in tab. 1.

Table 1. Mole fractions and chemical exergy of the reference components in atmospheric air, [5]

Component	N_2	O_2	CO_2	$H_2O_{(g)}$
Mole fraction, [%]	77.48	20.59	0.03	1.9
Chemical exergy, [$\mathrm{Jmol^{-1}}$]	720.00	3970.00	19480.00	9500.00

Exergy efficiency

There are numerous ways to formulate exergy efficiency for different facilities and components, and they can be found in [13].

In this paper, the ratio of total exergy at the system outlet and total exergy at the system inlet is treated by exergy efficiency. Exergy efficiency is defined [14]:

$$\eta_{\mathrm{Ex}} = \frac{\text{exergy in products}}{\text{total exergy input}} = \frac{\dot{E}_{x,\mathrm{out}}}{\dot{E}_{x,\mathrm{in}}} \tag{8}$$

Cost-balance equations – exergoeconomic model

The Second law of thermodynamics, in combination with economic theory represents a powerful tool for exploring problems related to energy systems. This particular combination of disciplines is a relatively new field (technique) of science and engineering, called thermoeconomics (exergoeconomics). Exergoeconomics has the following characteristics:

- it combines exergy with economic theory to obtain relevant results and
- it recognizes exergy, not energy, as a fundamental variable for energy system analysis.

By applying exergoeconomics, the cost of a particular product (in our case live steam) of an energy system is calculated by taking into account all the costs associated with the system operation, as well as the cost of the investment.

The cost balance equation applied to the k^{th} component shows that the sum of cost rates related to all leaving exergy streams is equal to the sum of cost rates of all entering exergy streams and the cost rate of capital investment and operation and maintenance costs (denoted as $\dot{Z}_{\mathrm{B}}$).

For a boiler operating in the steady-state, the cost balance equation has the form:

$$\dot{C}_{\mathrm{s}} + \dot{C}_{\mathrm{g}} = \dot{C}_{\mathrm{f}} + \dot{C}_{\mathrm{a}} + \dot{C}_{\mathrm{feedwater}} + \dot{Z}_{\mathrm{B}} \quad [US\$/\mathrm{s}] \tag{9}$$

where $\dot{C}$ [US$/s] is the exergy cost flow rate, $\dot{C} = c\dot{E}_x$, c [US$/kJ] – the specific exergy cost, $\dot{E}$ [kW] – the exergy flow rate.

In order to express the investment cost of equipment in terms of design parameters in eq. (9), several methods have been proposed. For this research, cost functions suggested by Ameri *et al.* [15] are adopted. For converting capital investment to cost per time unit, the following equation is used:

$$\dot{Z}_{\mathrm{B}} = Z_{\mathrm{B}} CRF \frac{\varphi}{N3600} \quad [\mathrm{US\$/s}] \tag{10}$$

where Z_{B} [\$] is the cost of the boiler (purchase cost), N is the annual operation hours of the unit, φ (1.06) is the maintenance factor, and CRF is the capital recovery factor. The Z_{B} was determined using the following relation [15]:

$$Z_{\mathrm{B}} = c_1 (\dot{m}_{\mathrm{b}})^{c_2} \Phi_p \Phi_T \Phi_\eta \Phi_{\mathrm{SH/RH}} \tag{11}$$

where

$$\Phi_p = \exp\frac{p_{\mathrm{s}} - \bar{p}_e}{c_3}, \quad \Phi_T = 1 + c_4 \exp\frac{T_2 - \bar{T}_e}{c_5}, \quad \Phi_\eta = 1 + \left(\frac{1-\bar{\eta}_{\mathrm{B}}}{1-\eta_{\mathrm{B}}}\right)^{c_6}$$

$$\Phi_{\mathrm{SH/RH}} = 1 + \frac{T_{\mathrm{s}} - T_{i\mathrm{SH}}}{T_{\mathrm{s}}} + \frac{\dot{m}_{\mathrm{RH}}}{\dot{m}_{\mathrm{b}}} \cdot \frac{T_{e\mathrm{RH}} - T_{i\mathrm{RH}}}{T_{e\mathrm{RH}}}, \quad c_1 = 208582\ \$/(\mathrm{kg/s}), \quad c_2 = 0.8, \quad \bar{p}_e = 28\ \mathrm{bar},$$

$$c_3 = 150\ \mathrm{bar}, \quad c_4 = 5, \quad \bar{T}_e = 866\ \mathrm{K},$$
$$c_5 = 10.42\ \mathrm{K}, \quad \bar{\eta}_{\mathrm{B}} = 0.9, \quad c_6 = 7$$

The *CRF* depends on the interest rate and the expected equipment lifetime. The *CRF* was determined using the equation:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{12}$$

where i (7%) is the interest rate, and n (20 years) is the total expected operating period of the system in years.

Description of the steam boiler

In this research, a one-chamber, membrane-welded (SULZER) boiler with forced circulation is studied. Boiler construction enables operation with both constant and variable pressure. The boiler is mono-draught with two reheaters. The boiler can be divided into two parts heightwise. The lower part consists of the combustor (combustion chamber), a part of the evaporator and the wall superheater. The upper part which sits on the combustor has following heat exchange surfaces: the outlet superheater (superheater III), reheater II, superheater II,

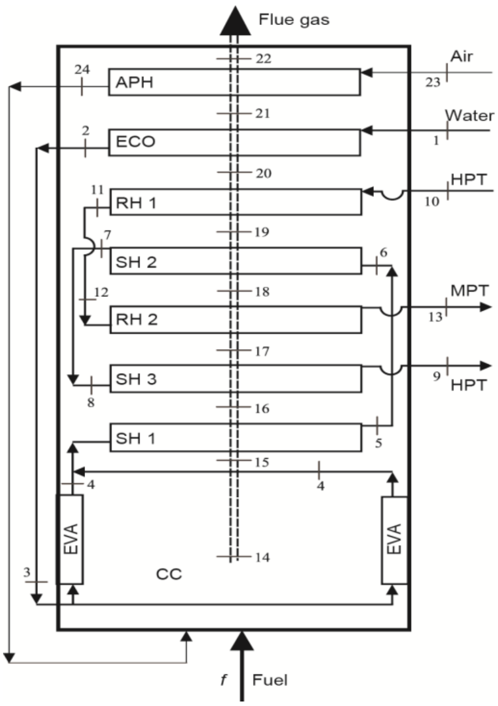

Figure 2. Schematic of the steam boiler; *APH – air heater, ECO – economizer, RH – reheater, SH – superheater, CC – combustion chamber, EVA – evaporator, HPT – high-pressure steam turbine, MPT – medium-pressure steam turbine*

reheater I and the economizer (water heater). From the top of the boiler, flue gases are passed through a Lungstrom type air heater. The boiler schematic is shown in fig. 2.

Fresh steam at the pressure of 186 bar and temperature of 540 °C leaves the boiler and enters the high-pressure turbine through the steam line. From the high-pressure turbine, steam enters the boiler reheater through its cold line. From the reheater, steam at the pressure of 43.7 bar and 540 °C enters the middle-pressure turbine through the reheaters warm line and afterwards enters the low-pressure turbine. After condensation, the condensate passes through several low-pressure reheaters, the deaerator and finally

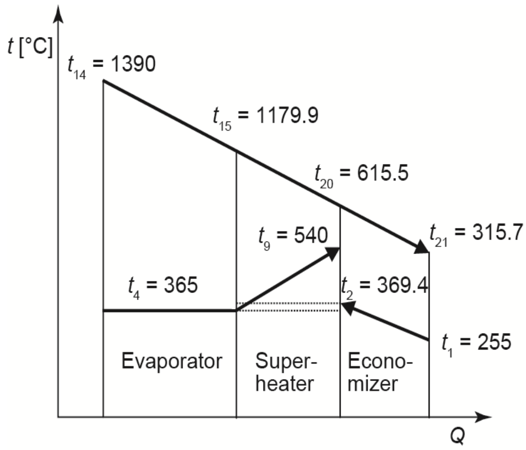

Figure 3. Boiler temperature profile

Table 2. The operational data at various state points with reference to the control volume

Components		Water/steam/air			Flue gases	
		t [°C]	*P* [bar]	$\dot{m}$ [kgs^{-1}]	*t* [°C]	$\dot{m}$ [kgs^{-1}]
Evaporator	In	365.0	209.0	277.8	1390.0	550.0
	Out	365.0	198.2	277.8	1179.9	550.0
Superheater 1	In	365.0	198.2	277.8	1179.9	550.0
	Out	374.0	194.0	277.8	1109.5	550.0
Superheater 3	In	464.0	190.2	277.8	1109.5	550.0
	Out	540.0	186.0	277.8	1015.6	550.0
Reheater 2	In	474.0	44.9	277.8	1015.6	550.0
	Out	540.0	43.7	277.8	960.0	550.0
Superheater 2	In	369.0	194.0	277.8	960.0	550.0
	Out	474.0	190.2	277.8	735.0	550.0
Reheater 1	In	334.0	46.1	258.9	735.0	550.0
	Out	469.0	44.9	258.9	615.5	550.0
Economizer	In	255.0	249.6	277.8	615.5	550.0
	Out	369.4	209.0	277.8	315.7	550.0
Air heater	In	20.0	–	422.0	315.7	550.0
	Out	291.0	–	422.0	169.7	550.0
Fuel	–	–	–	128.1	–	–

enters the feedwater tank (reservoir). Water from the feedwater tank is circulated by feed pumps through the high-pressure heater, first entering the economizer and afterwards the mixer, where it is mixed with water from the steam separator. From the mixer, water is circulated towards the evaporator by circulating pumps. Table 2 summarizes the boiler operation parameters (state variables for all streams in the boiler). The temperature profile of the boiler is given in fig. 3.

The boiler generates 1000.00 tons per hour of live steam, using lignite as primary fuel.

Results and discussion

The goal of this paper is to apply and conduct exergy analysis for a steam boiler and its components installed in a 348.5 MWe thermal power plant. The operational data at various state points with reference to the control volume shown in fig. 1 is given in tab. 2. The operational thermodynamic properties for the various boiler points are given in tab. 3 (for 100% of full load).

Table 3. The operational thermodynamic properties for the various boiler points

Components		Water/steam/air				Flue gases	
		h [kJkg^{-1}]	s [kJkg^{-1}K^{-1}]	e_x [kJkg^{-1}]	$\dot{E}_x$ [MW]	e_x [kJkg^{-1}]	$\dot{E}_x$ [MW]
Evaporator	In	1882.2	4.098	683.68	189.93	1203.65	662.01
	Out	2422.0	4.948	974.39	270.69	957.42	526.58
Superheater 1	In	2422.5	4.948	974.89	270.83	957.42	526.58
	Out	2633.9	5.283	1088.09	302.27	874.49	480.97
Superheater 3	In	3133.5	6.020	1371.64	381.04	874.49	480.97
	Out	3382.7	6.352	1523.51	423.23	760.64	418.35
Reheater 2	In	3380.1	6.954	1344.43	348.07	760.64	418.35
	Out	3533.7	7.163	1436.77	371.98	706.85	388.77
Superheater 2	In	2569.5	5.183	1053.00	292.52	706.85	388.77
	Out	3168.8	6.068	1392.87	386.94	467.30	257.02
Reheater 1	In	3036.6	6.432	1153.96	298.76	467.30	257.02
	Out	3368.5	6.938	1337.52	346.29	347.81	191.29
Economizer	In	1110.6	2.791	295.32	82.04	347.81	191.29
	Out	188.1	4.097	682.86	189.70	109.86	60.42
Air heater	In	–	–	0	0	109.86	60.42
	Out	–	–	89.93	37.95	32.55	17.90
Fuel	*LHV*	6845.0	–	7118.8	912.13	–	–

The exergy destruction rate and the exergy efficiency for each component and for the whole boiler, fig. 2, are presented in tab. 4.

Table 4. The exergy destruction rate and exergy efficiency equations for the boiler and its components

Components		Stream	Exergy destruction	Exergy efficiency
Boiler	In	23, f, 1, 10	$\dot{E}_{xD,B} = \dot{E}_{xf} + \sum \dot{E}_{xin,B} - \sum \dot{E}_{xout,B}$	$\eta_{Ex} = (\dot{E}_{xf} - \dot{E}_{xD,B})/\dot{E}_{xf}$
	Out	9, 13 ,22		
CC	In	24, f	$\dot{E}_{xD,CC} = \sum \dot{E}_{xin,CC} - \sum \dot{E}_{xout,CC}$	$\eta_{Ex,CC} = \dot{E}_{xout,CC}/\dot{E}_{xin,CC}$
	Out	14		
EVA	In	14, 3	$\dot{E}_{xD,EVA} = \sum \dot{E}_{xin,EVA} - \sum \dot{E}_{xout,EVA}$	$\eta_{Ex,EVA} = \dot{E}_{xproduct}/\dot{E}_{xinput}$
	Out	15, 4		
SH 1	In	15, 4	$\dot{E}_{xD,SH1} = \sum \dot{E}_{xin,SH1} - \sum \dot{E}_{xout,SH1}$	$\eta_{Ex,SH1} = \dot{E}_{xproduct}/\dot{E}_{xinput}$
	Out	16, 5		
SH 3	In	16, 8	$\dot{E}_{xD,SH3} = \sum \dot{E}_{xin,SH3} - \sum \dot{E}_{xout,SH3}$	$\eta_{Ex,SH3} = \dot{E}_{xproduct}/\dot{E}_{xinput}$
	Out	17, 9		
RH 2	In	17, 12	$\dot{E}_{xD,RH2} = \sum \dot{E}_{xin,RH2} - \sum \dot{E}_{xout,RH2}$	$\eta_{Ex,RH2} = \dot{E}_{xproduct}/\dot{E}_{xinput}$
	Out	18, 13		
SH 2	In	18, 6	$\dot{E}_{xD,SH2} = \sum \dot{E}_{xin,SH2} - \sum \dot{E}_{xout,SH2}$	$\eta_{Ex,SH2} = \dot{E}_{xproduct}/\dot{E}_{xinput}$
	Out	19, 7		
RH 1	In	19, 10	$\dot{E}_{xD,RH1} = \sum \dot{E}_{xin,RH1} - \sum \dot{E}_{xout,RH1}$	$\eta_{Ex,RH1} = \dot{E}_{xproduct}/\dot{E}_{xinput}$
	Out	20, 11		
ECO	In	20, 1	$\dot{E}_{xD,ECO} = \sum \dot{E}_{xin,ECO} - \sum \dot{E}_{xout,ECO}$	$\eta_{Ex,ECO} = \dot{E}_{xproduct}/\dot{E}_{xinput}$
	Out	21, 2		
APH	In	21, 23	$\dot{E}_{xD,APH} = \sum \dot{E}_{xin,APH} - \sum \dot{E}_{xout,APH}$	$\eta_{Ex,APH} = \dot{E}_{xproduct}/\dot{E}_{xinput}$
	Out	22, 24		

Exergy, percent of exergy destruction and exergy efficiencies are summarized in tab. 5.

The results show that the investigated boiler has exergy destruction of 479.82 MW, fig. 4, out of which 60.04% falls on the combustor (288.07 MW). Exergy efficiencies for the boiler and the combustor are 47.40% and 69.68%, respectively, tab. 5, fig. 5, for 100% of full load. All other heat exchangers, observed individually, have a significantly lower contribution to exergy destruction (up to 11%). The exergy destruction rate of all the heaters is 39.96%, while the corresponding exergy efficiencies were found to be 70.23%.

In this paper, exergoeconomics is applied following exergy analysis, in order to calculate the exergy cost of live steam by solving the exergoeconomic balance equation, eq. (9), assuming the specific exergy cost of feed water and air to be zero. The investment cost of the boiler, eq. (10) is $\dot{Z}_B = 0.1934$ \$/s $= 696.33$ \$/s.

Table 5. Exergy destruction and exergy efficiency of the boiler and its components

Components	Exergy destruction, [MW]	Percent exergy destruction, [%]	Exergy efficiency, [%]
Boiler	479.82	100.00	47.40
CC	288.07	60.04	69.68
Evaporator	54.67	11.39	59.63
Superheater 1	14.17	2.95	68.94
Superheater 3	20.43	4.26	67.38
Reheater 2	5.68	1.18	80.80
Superheater 2	37.34	7.78	71.66
Reheater 1	18.20	3.79	72.31
Economizer	23.21	4.84	82.27
Air heater	4.57	0.95	89.25
All heaters	191.75	39.96	70.23

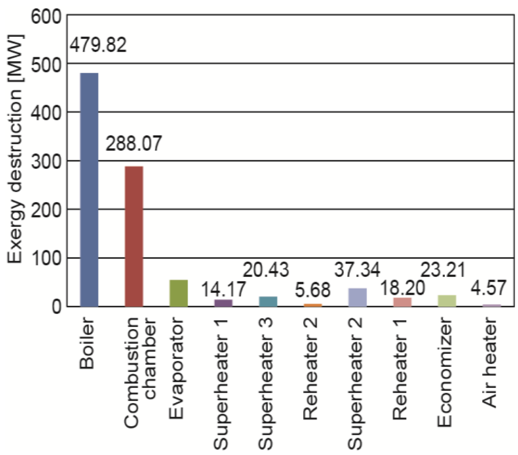

Figure 4. Exergy destruction for the boiler and every boiler component

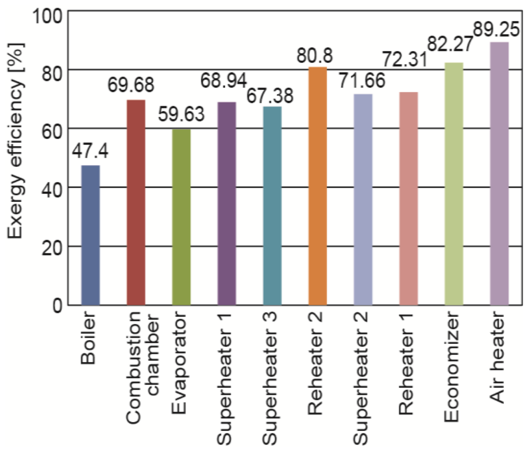

Figure 5. Exergy efficiency for the boiler and every boiler component

The values for exergy, cost rates associated with flows, and unit costs of flows for the boiler are given in tab. 6.

Table 6. Exergy, cost rates associated with flows and unit costs of flows for the boiler

Stream no.	$\dot{E}_x$ [kW]	c [\$kJ^{-1}]	C [\$$^{-1}$]
Fuel	912130.0	$9.5\cdot10^{-6}$	31194.8
Flue gases	17900.0	$9.5\cdot10^{-6}$	612.0
Steam – 9 and 13	799210.0	$1.72\cdot10^{-5}$	49356.7

Conclusion

The results of exergy analysis conducted on a coal-fired, steam boiler serving a 348.5 MWe thermal power plant were presented in this paper. Exergy analysis implies calculating exergy destruction and exergy efficiency for both the boiler and its heat exchanging components.

The results show that the exergy destruction in the boiler is 479.82 MW, out of which the combustion chamber is responsible for 288.07 MW (60.04%) of exergy destruction. This may be due to the irreversibility inherent in the combustion processes, heat loss, and incomplete combustion. The exergy destruction in the boiler components ranges from 4.5 MW to 55 MW, *i. e*. from 1% to 11%, which represents a small loss, individually. It is the result of the irreversibility during heat transfer and can be used for pre-heating air used in the combustion. However, it has to be noted that part of this irreversibility cannot be avoided due to the physical, technological, and economic constraints of this study. The boiler performance can be significantly improved by implementing the combustion process optimization. The obtained research results comply with the results from other authors [4, 16-18]: the boiler exergy efficiency is around 40%, the combustor exergy efficiency around 65%, and the heat exchangers exergy efficiency around 70%.

By applying the exergoeconomic analysis of the boiler, the exergy cost of live steam is calculated at the value of $1.72 \cdot 10^{-5}$ \$/kJ. The results obtained in this research comply with the results from other authors [19, 20]. The cost of produced steam dominantly depends on fuel cost (nearly 90%), and in smaller amount on cost of capital investment. This shows that the cost of produced steam can be reduced either by lowering fuel cost or, more likely, by reducing fuel consumption with increasing boiler efficiency through optimization of combustion process. The later statement is viable due to large exergy loss in combustion chamber.

Nomenclature

CRF – capital recovery factor
c_p – specific heat, [kJkg^{-1}K^{-1}]
$\dot{E}_x$ – exergy flow rate, [kW]
e_x – specific exergy, [kJkg^{-1}]
h – specific enthalpy, [kJkg^{-1}]
LHV – lower heating value, [kJ kg^{-1}]
M – molar mass, [kgkmol^{-1}]
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
$\bar{R}$ – the universal gas constant, [kJkmol^{-1}K^{-1}]
s – specific entropy, [kJkg^{-1}K^{-1}]
T – temperature, [K]
$\dot{W}$ – power
x – mass fraction
x_i' – volume percent of the component gas *k*

Greek symbol

η_{Ex} – exergy efficiency

Subscripts

a – air
B – boiler
D – destruction
f – fuel
g – flue gas
in – inlet
out – outlet
s – steam
0 – reference state

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