

MILENA N. TODOROVIĆ
DRAGOLJUB S. ŽIVKOVIĆ
MARKO V. MANČIĆ
GRADIMIR S. ILIĆ

Faculty of Mechanical Engineering,
University of Niš, Serbia

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APPLICATION OF ENERGY AND EXERGY ANALYSIS TO INCREASE EFFICIENCY OF A HOT WATER GAS FIRED BOILER

Article Highlights

- Applied method - Energy and exergy analysis
- Paper goal - Application of energy and exergy analysis of hot water boiler
- The obtained results: largest energy loss - flame pipe, largest exergy - leaving flue gasses
- Investigation of possibilities of design modification to increase reliability and availability
- Proposing and analyzing more reliable solution

Abstract

In engineering practice, exergy can be used for technical and economic optimization of energy conversion processes. The problem of increasing energy consumption suggests that heating plants, i.e., hot water boilers, as energy suppliers for household heating should be subjected to exergy and energy analysis. Heating plants are typically designed to meet energy demands, without the distinguished difference between quality and quantity of the produced heat. In this paper, the energy and exergy analysis of a gas fired hot water boiler is conducted. Energy analysis gives only quantitative results, while exergy analysis provides an insight into the actually available useful energy with respect to the system environment. The hot water boiler was decomposed into control volumes with respect to its functional components. Energy and exergy of the created physical model of the hot water boiler is performed and destruction of exergy and energy loss in each of the components is calculated. The paper describes the current state of energy and exergy efficiency of the hot water boiler. The obtained results are analyzed and used to investigate possibilities for improvement of availability and reliability of the boiler. A comparison between the actual and the proposed more reliable solution is made.

Keywords: hot water boiler, exergy, energy, availability, reliability.

Improving energy efficiency as well as energy saving represents one of the major problems of modern developed countries worldwide. Hot water boilers, common in district heating systems, should be subjected to reliability, safety and efficiency research [1]. The efficiency of a hot water boiler has a large impact on thermal performance in district heating systems. In order to improve efficiency, heat transfer from flue gases to water is increased to reduce energy losses

of hot water boilers. In order to optimize the processes in hot water boilers, it is necessary to pinpoint areas with the greatest losses [2]. Since hot water boilers operate in conditions of high temperature and pressure, in addition to their efficiency, it is necessary to consider safety and reliability issues as well, so as to avoid the major disruption and downtime in operation [3].

The first law of thermodynamics is mainly used for the analysis of energy utilization, but it possesses the inability to analyze qualitative aspects of used or consumed energy. In these cases the exergy analysis becomes relevant. Exergy represents the consequence of the second law of thermodynamics. The concept of exergy defines the maximum available

Correspondence: M.N. Todorović, Faculty of Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia.

E-mail: milenatod1@yahoo.com

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work of a body or system, with clearly defined control volumes. Exergy can also be seen as a measure of deviation between the current state of a system and its equilibrium with the environment. Exergy analysis appears in modern thermodynamics as a very important tool, especially for technical thermodynamics [4]. The complete analysis of thermodynamic characteristics of the process usually requires using both energy and exergy analysis, since they provide different information about the characteristics of the process. Such comprehensive analysis represents a suitable approach to determining the performance of the system and finding ways to improve the process [5]. A substantial number of papers can be found in the literature dealing with energy and exergy analysis of power plants, *i.e.*, steam boilers using solid fuel. A study that presented a comparative analysis of steam boilers in Turkey [6] has used this comparison of energy and exergy analysis. The performance of a power plant in Jordan has been determined by modelling certain parts of the plant and a detailed analysis of energy and exergy losses considering the functionality of the power plant [7]. A detailed exergy analysis of steam blocks has been performed, decomposing the plant into several areas, considered independently [8]. The analysis of these steam boilers also included the measurement of boiler losses, as well as the turbine plant [9]. The power plants are affected by environmental conditions, such as ambient temperature, atmospheric pressure and humidity of air. In the analysis of the thermal plants in Mexico that use air as the working fluid, the energy and exergy method have been applied to humid air considering the ambient variables [10].

This kind of analysis may be also applied in different heating technologies as well as in systems with renewable energy sources, such as desiccant cooling systems [11,12]. A specific impact of exergy calculation on moist air in each system component is taken into consideration in order to identify and quantify the places where the exergy destruction occurs [11]. Specific attention is paid to the exergy method of air quality and comfort as one of the most demanding air conditioning processes [12]. In this study, an appropriate decomposition of the system to its subcomponents is done in order to determine the locations of exergy destruction.

Energy and exergy studies of systems with renewable energy sources are essential when it comes to the effective utilization of energy. Detailed exergy analysis of solar thermal power system, as well as wind and geothermal power systems is presented in [13]. This work also includes a comparison

of renewable and non-renewable energy sources. In addition to this renewable energy sources, the exergy method can be applied to systems with a photovoltaic solar collector as well in system that use biomass as fuel. Exergetic aspects of these systems are comprehensively presented in [14] as well as the comparison of the obtained results.

Cogeneration plants are as equally significant for energy savings as systems with renewable sources. The application of exergy analysis in the micro-combined heat and power unit is presented in [15], where the evaluation of energy and exergy efficiencies is done for performance assessment.

Exergy and energy analysis is used in the cycles that use natural gas. The impact on the exergy efficiency has been observed in relation to the input parameters of pressure and temperature of the gas turbine in the combined cycle natural gas fired power plants [16]. The simplified method of exergy analysis based on the second law of thermodynamics has been used to analyze the useful output of Rankin cycle, with respect to the parameters of exergy analysis of a gas turbine [17].

As previously stated, the comprehensive analysis of energy balance, as well as a detailed exergy analysis could provide a better insight into the process and identify new solutions to improve the process. Understanding energy and exergy efficiency is crucial for designing, analyzing, optimizing and improving the energy systems through variety of measures and strategies for sustainable development [18]. Exergy analysis is intended to determine the maximum work ability of the system as well as to identify the places where losses of “useful energy” occur, *i.e.*, exergy. Identifying the locations where the exergy losses occur, where destruction of exergy takes place, the cause of its destruction, and the real scale of exergy losses represent the directions for future potential improvements of the system and its components [19]. According to the previously discussed examples from the literature, it is clear that exergy analysis is essential for energy planning, resource optimization and global reduction of harmful emissions of greenhouse gases.

In this study, the energy and exergy balance of a gas fired hot water boiler is presented. A model of an actual operating boiler is created. The boiler is subjected to failure issues due to thermo-mechanical strain and stress of the piping on the back of the flue gas diverter chamber. Decomposition of the boiler is done by determining control volumes corresponding to the functional units of the boiler, thus creating a physical model of the boiler. The analysis presents

energy and exergy efficiency of each part of the hot water boiler, as well as the destruction of exergy and energy losses in these components. In this way, the paper describes the properties of energy efficiency of the hot water boiler component-wise, identifies the areas with the major energy and exergy losses, and proposes the modified technical solution regarding exchange surfaces of the boiler. The obtained results are used to address the reliability and availability issues of this type of boilers, caused by severe thermal stress in the piping of the flue gas distribution chamber. A modified physical model of the boiler that should insure an improvement in terms of boiler reliability and availability is analyzed using the same methodology and the results are compared to the actual state model of the boiler. The performance of the boiler without the cooling pipes is analyzed, and efficiencies are compared to the original model performance.

ENERGY AND EXERGY ANALYSIS - METHODOLOGY

The term exergy was first mentioned at the conference in Lindau in 1953 by Z. Rant. The term exergy originates from the prefix “*ex*” before the root “*ergy*”, and the meaning of *from* and *work*, and characterizes the work that can be obtained from the system [20]. This indicates that exergy represents the maximum amount of work that can be extracted from the system in the process of establishing equilibrium with its environment.

It is an opportunity to acquire work from the process whenever there is pressure, temperature, concentration, speed and elevation gradient between the system and the surrounding area. As the system changes the state in the direction of the environment, the availability of work decreases, ceasing to exist when equilibrium is achieved. The referent state is defined as the state of mechanical, thermal and chemical equilibrium between the system and its surroundings. In addition, the relative speed and elevation of the system in relation to the environment are equal to zero. Under these conditions there is no possibility of spontaneous changes within the system or the environment, or there is no possibility to have any interaction between them. The second type of equilibrium state between the system and the environment can also be identified. This is the limited form of equilibrium, where only the conditions of mechanical and thermal equilibrium are satisfied, and it is called the limited referent state.

Energy analysis is one of the most important aspects of engineering analysis. Energy can be transformed from one form to another and can be transferred from one system to another, but the total amount of energy remains constant [21]. The general balance of the system can be written as:

$$\text{INLET} + \text{CREATION} - \text{OUTLET} - \text{CONSUMPTION} = \text{ACCUMULATION}$$

Inlet and outlet are related to the quantities that go in and out of the system boundaries. General equations of equilibrium can be written for the mass and energy balance [22]:

$$\sum_i \dot{m}_{in} - \sum_j \dot{m}_{out} = 0 \quad (1)$$

$$\sum_i \dot{m}_{in} h_{in} - \sum_j \dot{m}_{out} h_{out} - \dot{W}_{in} + \dot{Q}_{in} = 0 \quad (2)$$

The total exergy of the system can be represented as the total amount of physical exergy, Ψ_{PH} , kinetic exergy, Ψ_{KN} , potential exergy, Ψ_{PT} , and chemical exergy Ψ_{CH} [23]:

$$\Psi = \Psi_{PH} + \Psi_{KN} + \Psi_{PT} + \Psi_{CH} \quad (3)$$

Similarly, the total exergy of the system can be expressed in the specific value of exergy, e :

$$e = e_{PH} + e_{KN} + e_{PT} + e_{CH} \quad (4)$$

Physical exergy of the closed system is given:

$$e_{PH} = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) \quad (5)$$

or:

$$e_{PH} = (h - h_0) - T_0(s - s_0) \quad (6)$$

Kinetic and potential exergy are given:

$$e_{KN} = \frac{1}{2} Y^2 \quad (7)$$

$$e_{PT} = gz \quad (8)$$

Typically, kinetic and potential exergy are ignored in exergy analysis.

The chemical exergy of the system represents the measure of the distance of the observed chemical composition from the composition of the system environment. Standard chemical exergy is based on the standard value of environmental temperature T_0 and pressure p_0 , for example $T_0 = 298.15$ K (25 °C) and $p_0 = 1$ atm. The other significant parameter is the molar composition of the atmospheric air. The molar share of nitrogen (N_2) is 77.48% in ambient air, oxy-

gen (O₂) 20.59%, carbon-dioxide (CO₂) 0.03% and water vapor (H₂O_(g)) 1.9% [24].

In order to determine the chemical exergy of the fuel it is necessary to know all the mutual relations of chemical elements in the fuel. However, in thermodynamic practice there is no need to have high accuracy, hence semi-empirical formulas are commonly used to determine the approximate fuel exergy. Rant proposed to determine chemical exergy of fuel through relations $e_{\text{fuel}}/H_{\text{LV}}$. The Rant method of determining chemical exergy of liquid and gaseous fuels is used in this paper [25].

Exergy of gaseous hydrocarbons can be expressed by the Rant method and by using the approximate equations for gas hydrocarbons [26]:

$$\frac{e_{\text{fuel}}}{H_{\text{LV}}} = 1.0334 + 0.0183 \frac{H}{C} - 0.0694 \frac{1}{C} \quad (9)$$

where: H/C - the ratio of number of atoms of hydrogen and carbon in the molecule and $1/C$ - the reciprocal value of the number of carbon atoms in the molecule of fuel.

In the process of fuel combustion, the necessary quantity of oxygen for combustion is provided by bringing the right amount of air. The air, with respect to pressure and temperature, possesses certain exergy, or its exergy is assumed zero if its state is in equilibrium with the environment. Exergy of air can be calculated from the general expression of the exergy [27]:

$$e = h - h_0 - T_0(s - s_0) \quad (10)$$

In hot water boiler thermal plants the following processes can be distinguished: fuel combustion and heat exchange with the working fluid, *i.e.*, water. In combustion processes, chemical energy is converted into thermal energy of combustion products. A combustion process is, as well as many other processes, irreversible in nature. On the one hand, this is caused by irreversible mixing of reaction components and, on the other, by a low medium temperature of combustion. Irreversibility leads to significant portions of input fuel exergy of the combustion process to degenerate into useless energy - anergy. The energy in the combustion process, just as in any other process, remains constant while the exergy decreases transforming into anergy from which work cannot be achieved. Calculating exergy of combustion products is quite complex and can be also calculated according to the general form of exergy (Eq. (10)).

Exergy losses are significant in the process of combustion. It is necessary to introduce an indicator that will directly or indirectly represent their value. If the values of fuel exergy e_{fuel} and exergy of com-

bustion products e_{cp} are known, the exergy efficiency of the combustion process can be determined as the ratio of exergy of combustion products and fuel exergy:

$$\eta_{\text{ex}}^c = \frac{e_{\text{cp}}}{e_{\text{fuel}}} \quad (11)$$

The exergy efficiency, η_{ex} , is a dimensionless quantity that indicates which part of the fuel exergy appears to be useful after the combustion process, *i.e.*, the quantity, $1 - \eta_{\text{ex}}$, defines the exergy losses in the process.

Besides combustion, the most common is the process of heat transfer from hot gases to the water in the boiler. Components of a hot water boiler, where the process of heat transfer takes place, can be considered as cross heat exchangers. The process in a heat exchanger is complex because it two different processes run simultaneously, heat transfer and fluid flow. Since ideal working bodies (fluids) cannot be related to natural (real) processes, there are real gases and liquids instead. During the process of fluid flow exergy losses will occur inevitably as a consequence of friction in the fluid and between the fluid and the surface of heat exchangers [28]. Another source of exergy losses in the heat exchanger occurs due to finite temperature differences during heat transfer. For calculating energy and exergy losses, standard equations for exergy (Eq. (10)) and general equations for mass and energy balance (Eqs. (1) and (2)) are used in this paper. As for exergy efficiency in heat exchangers, the so-called conventional exergy efficiency is used. Conventional exergy efficiency represents the simplest form of exergy efficiency, and its formulation is based on the exergy balance of incoming and outgoing flows. It represents the ratio of total output and input of exergy flow:

$$\dot{\Psi}_{\text{in}} = \dot{\Psi}_{\text{out}} - \dot{i} \quad (12)$$

where \dot{i} reflects the irreversibility of the process, and other forms of exergy in the control volume are included with incoming and outgoing exergy.

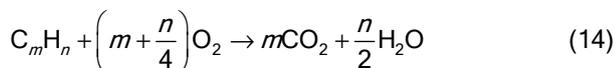
Conventional exergy efficiency can be written in the form of:

$$\eta_{\text{ex}} = \frac{\dot{\Psi}_{\text{out}}}{\dot{\Psi}_{\text{in}}} \quad (13)$$

COMBUSTION PROCESS

As mentioned, the process where energy and exergy losses are likely to occur is the combustion process. It is very important to give a detailed insight

into the process. The stoichiometric equation for the calculation of combustion of gaseous hydrocarbons is:



Based on the previous equations, one can calculate the minimum required amount of oxygen for the combustion of fuel components:

$$O_{\min} = \frac{1}{100} \left[0.5(CO + H_2) + \sum \left(m + \frac{n}{4}\right) C_m H_n - O_2 \right] \quad (15)$$

[m³O₂/m³]

It is necessary to identify the volume of combustion products. Theoretical (minimum) volume, $\lambda = 1$, of combustion products can be represented as:

$$V_{cp}^t = V_{CO_2} - V_{N_2}^t \quad [m_n^3/m_n^3] \quad (16)$$

From the stoichiometric equation, one can obtain the following volumes of combustion products:

- Volume of CO₂:

$$V_{CO_2} = \frac{1}{100} \left[CO_2 + CO + \sum m C_m H_n \right] \quad [m_n^3/m_n^3] \quad (17)$$

- Volume of N₂:

$$V_{N_2}^t = 3.76 O_{\min} + 0.01 V_{L\min} \quad [m_n^3/m_n^3] \quad (18)$$

The actual volume of combustion product, where $\lambda > 1$, is determined by the following equation:

$$V_{cp} = V_{cp}^t + (\lambda - 1) V_{L\min} \quad [m_n^3/m_n^3] \quad (19)$$

For energy and exergy calculation, it is also necessary to determine the enthalpy of combustion products. Enthalpy of combustion products at temperature t^c can be calculated based on the equation:

$$h_{cp} = h_{cp}^t + (\lambda - 1) h_{L\min} \quad [kJ/kg, kJ/m_n^3] \quad (20)$$

Enthalpy of the theoretical amount of combustion products ($\lambda = 1$) at t^c is defined as the sum of the enthalpy of dry three-atom gases, the theoretical volume of nitrogen and theoretical volume of water vapour:

$$h_{cp}^t = \left(V_{CO_2}^t c_{pCO_2} + V_{N_2}^t c_{pN_2} + V_{H_2O}^t c_{pH_2O} \right) t^c \quad (21)$$

[kJ/kg, kJ/m_n³]

where $h_{L\min}$ represents the enthalpy of theoretical amount of air:

$$h_{L\min} = V_{L\min} c_{pL} t^c \quad [kJ/kg, kJ/m_n^3] \quad (22)$$

where c_{pL} represents the average specific heat capacity at constant pressure.

The values of average specific heat capacity and enthalpy of gases are mostly given as tabular values and can be found in [29].

Heating value is defined as the amount of heat that is released with complete combustion by fuel unit mass (1 kg of solid or liquid fuel) or unit volume (1 m_n³ of dry gas) fuel. One can differentiate between the higher heating value (H_{HV}) and the lower heating value (H_{LV}). The connection between these two values is given by:

$$H_{HV} = H_{LV} + 2500 \left(\frac{9H + W}{100} \right) = H_{LV} + 25(9H + W) \quad [kJ/kg, kJ/m_n^3] \quad (23)$$

Heating value of gaseous fuel, when the contents of the fuel components are known, can be determined using the following equation:

$$H_{LV} = \frac{1}{100} (H_{LV,H_2} H_2 + H_{LV,CO} CO + H_{LV,CH_4} CH_4 + H_{LV,C_2H_5} C_2H_5 + \dots) \quad [kJ/m_n^3] \quad (24)$$

where H₂, CO, CH₄, C₂H₅,... [%] are the volume contents of fuel component and $H_{LV,H_2}, H_{LV,CO}, H_{LV,CH_4}, H_{LV,C_2H_5}, \dots$ [kJ/m_n³] are the lower heating values of fuel components.

The basic characteristics of the gases that are part of the gaseous fuel (higher heating value, lower heating value) can also be found in literature [29].

GENERAL DESCRIPTION OF THE HOT WATER PLANT

Thermal plant "Technical faculties" in Niš, with the total capacity of 25.7 MW, uses a natural gas fired hot water boiler type "TE110V", manufactured by "Minel - kotlogradnja". Basic technical specifications of this hot water boiler are [30]:

- boiler type: TE 110V;
- capacity: 8700 kW;
- efficiency: 0.91;
- furnace resistance: 10.7 mbar;
- mass: 41000 kg;
- boiler length: 8060 mm;
- water temperature level: 130/70 °C;
- maximum allowed overpressure: 12 bar;
- operating pressure: 6 bar;
- total surface for heat transfer: 351 m²;
- water content in boiler: 27.8 m³.

The boiler is shaped as a cylindrical tube, closed with chambers on both sides and thermally insulated all over the volume (Figure 1). The boiler has three pressurized gas channels. The flame pipe (first pass),

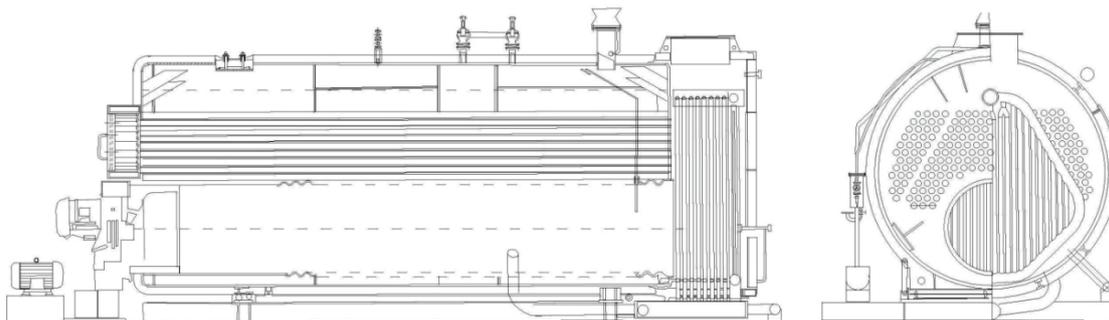


Figure 1. Schematic overview of the hot water boiler "Minel - kotlogradnja".

located in the pressurized water body, is heated by thermal energy generated by combustion of natural gas. After combustion, exhaust gasses pass through a diverter chamber coated by water piping, and go into the second pass gas piping (II pass gas pipes), placed above the flame tube. On the front side of the boiler is a frontal diverting chamber that redirects the exhaust gasses and leads them into the third pass gas piping, located on the sides of the boiler (III pass gas pipes). After leaving III pass gas pipes, exhaust gasses splash the water-cooled front of the diverting chamber, passing through the deflection chamber and then leaving the chamber through the chimney. During operations hot water boilers are normally completely filled with water. As for the water flow, the boiler is being filled with water on its bottom side, below the flame tube. After filling the boiler, the portion of the water goes into the water-cooled front of reversing chamber, while the remaining volume of water is heated by radiation and convection passing through flue pipes (flame tube, gas pipes II and III

pass). This water flow at the exit of the boiler is mixed with the water from the water-cooled front of diverting chamber and is then pumped to the consumers.

Gas and water flow of the boiler can be distinguished, as shown below. The simplified view of the gas flow of the boiler is shown in Figure 2a.

While the boiler volume is full of water, the water flow of the boiler cannot be precisely distinguished, because there are no clearly defined boundaries of the boiler components. For further analysis, the only logical arrangement of the components of the water flow is adopted, which follows the arrangement of the components of the gas flow where the water flows. So the adopted arrangement of components of water flow is presented in Figure 2b.

For the nominal operation mode and for each of the components of the hot water boiler, shown in Figures 2 and 3, such as control volume, the quantity of the irreversibility of the process (exergy loss) and exergy efficiency (Table 1) can be defined. Exergy efficiency of the total cycle can be defined in different

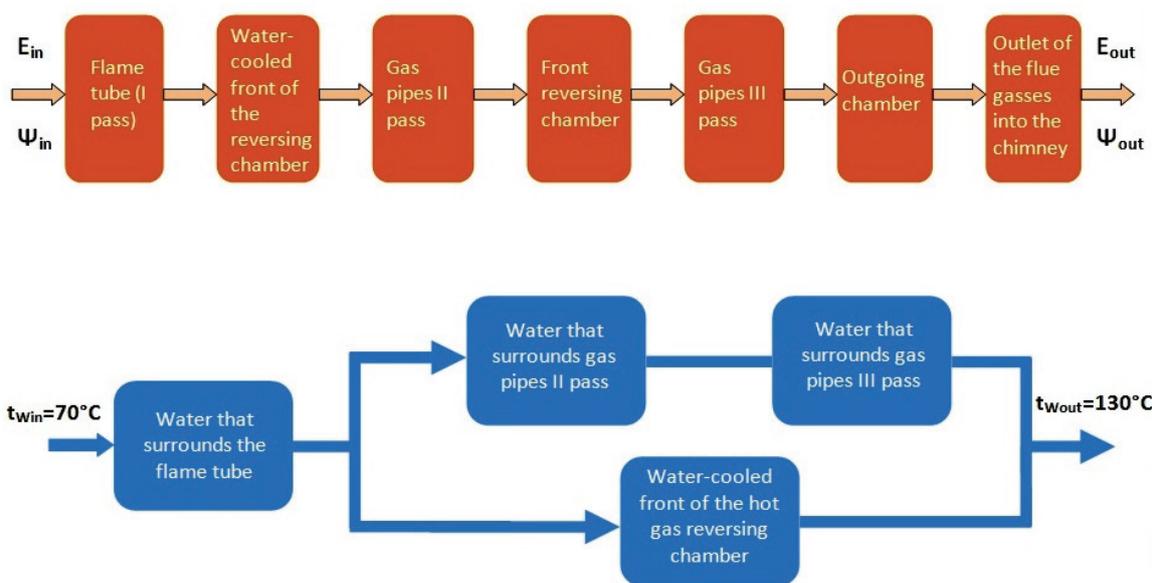


Figure 2. Hot water boiler decomposition. Gas flow (a) and water flow (b) through the hot water boiler.

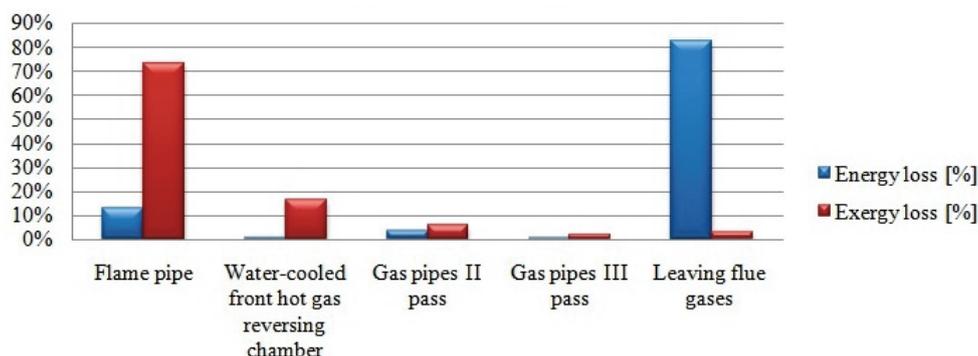


Figure 3. Comparative graphical review of energy and exergy analysis of the hot water boiler.

ways. Table 1 represents the irreversibility of the process of heat transfer from the combustion products to the hot water, and the destruction of exergy during the combustion of natural gas and internal friction of the fluid flow (water and gas), as well as the exergy loss with flue gas leaving the boiler [31].

Energy analysis for each component of the hot water boiler and defined quantities can be represented as in Table 2.

RESULTS

When the analytical results are obtained, the following assumptions are adopted:

1. Water and gas temperature fields are uniform on the control boundaries of each component of the hot water boiler.
2. The air temperature on the control surface is equal to the ambient temperature, so its exergy value is zero.

Table 1. Exergy analysis of the components of the hot water boiler

Component	Exergy loss	Exergy efficiency
Flame tube	$\dot{i}_{fp} = (\dot{\Psi}_{in}^w + \dot{\Psi}_{fuel} + \dot{\Psi}_{air}) - (\dot{\Psi}_{out}^w + \dot{\Psi}_{out}^g)$	$\eta_{ex}^{fp} = \frac{\dot{\Psi}_{out}^w + \dot{\Psi}_{out}^g}{\dot{\Psi}_{in}^w + \dot{\Psi}_{fuel} + \dot{\Psi}_{air}}$
Water-cooled front of the reversing chamber	$\dot{i}_{wrc} = (\dot{\Psi}_{in}^w + \dot{\Psi}_{in}^g) - (\dot{\Psi}_{out}^w + \dot{\Psi}_{out}^g)$	$\eta_{ex}^{wrc} = \frac{\dot{\Psi}_{out}^w + \dot{\Psi}_{out}^g}{\dot{\Psi}_{in}^w + \dot{\Psi}_{in}^g}$
Gas pipes II pass	$\dot{i}_{gpII} = (\dot{\Psi}_{in}^w + \dot{\Psi}_{in}^g) - (\dot{\Psi}_{out}^w + \dot{\Psi}_{out}^g)$	$\eta_{ex}^{gpII} = \frac{\dot{\Psi}_{out}^w + \dot{\Psi}_{out}^g}{\dot{\Psi}_{in}^w + \dot{\Psi}_{in}^g}$
Gas pipes III pass	$\dot{i}_{gpIII} = (\dot{\Psi}_{in}^w + \dot{\Psi}_{in}^g) - (\dot{\Psi}_{out}^w + \dot{\Psi}_{out}^g)$	$\eta_{ex}^{gpIII} = \frac{\dot{\Psi}_{out}^w + \dot{\Psi}_{out}^g}{\dot{\Psi}_{in}^w + \dot{\Psi}_{in}^g}$
Total cycle	$\dot{i}_{total} = \sum \dot{i}_i$	$\eta_{ex}^t = \frac{\dot{\Psi}_{out}^t}{\dot{\Psi}_{in}^t}$

Table 2. Energy analysis of the components of the hot water boiler

Component	Energy loss	Energy efficiency
Flame tube	$\dot{E}_{loss,fp} = (\dot{E}_{in}^w + \dot{E}_{fuel} + \dot{E}_{air}) - (\dot{E}_{out}^w + \dot{E}_{out}^g)$	$\eta_i^{fp} = \frac{\dot{E}_{out}^w + \dot{E}_{out}^g}{\dot{E}_{in}^w + \dot{E}_{fuel} + \dot{E}_{air}}$
Water-cooled front of the reversing chamber	$\dot{E}_{loss,wrc} = (\dot{E}_{in}^w + \dot{E}_{in}^g) - (\dot{E}_{out}^w + \dot{E}_{out}^g)$	$\eta_i^{wrc} = \frac{\dot{E}_{out}^w + \dot{E}_{out}^g}{\dot{E}_{in}^w + \dot{E}_{in}^g}$
Gas pipes II pass	$\dot{E}_{loss,gpII} = (\dot{E}_{in}^w + \dot{E}_{in}^g) - (\dot{E}_{out}^w + \dot{E}_{out}^g)$	$\eta_i^{gpII} = \frac{\dot{E}_{out}^w + \dot{E}_{out}^g}{\dot{E}_{in}^w + \dot{E}_{in}^g}$
Gas pipes III pass	$\dot{E}_{loss,gpIII} = (\dot{E}_{in}^w + \dot{E}_{in}^g) - (\dot{E}_{out}^w + \dot{E}_{out}^g)$	$\eta_i^{gpIII} = \frac{\dot{E}_{out}^w + \dot{E}_{out}^g}{\dot{E}_{in}^w + \dot{E}_{in}^g}$
Total cycle	$\dot{E}_{loss,total} = \sum \dot{E}_{loss,i}$	$\eta_i^t = \frac{\dot{E}_{out}^t}{\dot{E}_{in}^t}$

3. The entire amount of thermal energy in the flame tube and in the irradiated chamber is transferred by radiation.

4. As the gas speed is quite great compared to the size of the front diverter chamber, it is considered that there is no heat transfer between the gas and water in the front chamber.

The calculation is performed in line with the previous method and assumptions. The total energy efficiency for the complete hot water boiler is 89.9%, while the exergy efficiency is only 60.97%, and the entire system suffers the destruction of exergy of 39.03%, which is irreversibly lost to the environment. The calculation results for each component are given in Table 3. In order to make the representation of results more clearly and to see what is going on in the system, it is necessary to consider energy and exergy losses in relation to the system in general.

Based on the given results of energy and exergy analysis, it can be concluded that the greatest exergy loss occurs in the flame tube of the hot water boiler, while the largest energy loss of the system takes place in the area where the gases leave the boiler. The exergy loss through each of the components of the gas flow of the hot water boiler can be traced. Exergy loss, obtained analytically, amounts to 73.06% in the flame tube, 16.11% in the water-cooled front of the reversing chamber, 5.85% in the gas pipes II pass, 2.01% in the gas pipes III pass, while the exergy loss of flue gases leaving the boiler through the chimney is 2.97%. The major exergy loss occurs in the flame tube, which was expected, because of the chemically irreversible process of fuel combustion. Exergy of exhaust gasses depends on the temperature at which the combustion heat is transferred to the flue gases. Due to the large temperature difference of combustion products in the flame pipe at high temperatures (1350–1450 °C) and hot water heated to 90–100 °C, and heat transfer done by radiation, the greatest exergy destruction can be related to the flame pipe.

It may also be noted that, following the gas flow of the boiler, the reduction of exergy losses and increase in exergy efficiency take place. Based on the obtained results, it can be seen that the trend of in-

creasing exergy efficiency is not present in the water-cooled front, which can be explained by a different type of heat exchangers. Namely, II and III pass gas pipes are associated with cross-section exchangers, where water flows around the pipes, while in the water-cooled front of reversing chamber water flows along the pipes, while exhaust gasses flow around the pipes, directed by diverter chamber. Analytic analysis of energy and exergy balance shows that the greatest potential for increasing overall efficiency of the plant is actually in the flame tube of the hot water boiler. Figure 3 graphically represents the distribution of energy and exergy loss for each of the components of the hot water boiler.

Proposed improvement

The water-cooled pipes on the back of the flue gas diverter chamber are exposed to high temperature strain, which results in the damage of this part of the diverter chamber and drop outs of the boiler. This fact reduces the availability and reliability of the boiler. In this paper, the effect of modification of this part of the construction of the boiler was investigated and its impact on the overall efficiency of the boiler by means of exergy and energy analysis. The proposed solution analyzed in this paper is a retrofit design of the diverter chamber, by omitting the piping from the walls of the chamber. In this case, the complete volume flow of the water would flow over the flame pipe, and II and III pass gas pipes in the main body of the boiler. It is assumed that an equal amount of energy and exergy is delivered with the fuel and air to the boiler. In the case of modified contraction, due to the lack of the water-cooled pipes on the walls of the diverter chamber, the available heat is transferred completely to the main body of the water, and the flue gasses, after leaving the III pass gas pipes, are redirected through the deflection chamber through the chimney. Although the same amount of energy and exergy is assumed to be transferred to the water body, in the modified case scenario, the exhaust gasses leave the boiler at a higher temperature level, since their heat is not rejected to the water flowing through the reflection chamber wall piping. This results in slightly higher energy and exergy losses for

Table 3. The results of calculations for each of the components of the hot water boiler in relation to the entire system

Component	Energy loss, kJ/s	Energy loss, %	Exergy loss, kJ/s	Exergy loss, %
Flame tube	126.495	12.57	5497.087	73.06
Water-cooled front of the reversing chamber	8.674	0.86	1212.384	16.11
Gas pipes II pass	34.993	3.48	440.308	5.85
Gas pipes III pass	5.456	0.54	151.565	2.01
Flue gases leaving the boiler	830.752	82.55	223.157	2.97

the analyzed retrofit boiler model. The results of calculation of the proposed scenario are given in Table 4. The total energy efficiency for the complete hot water boiler is 89.93%, while the exergy efficiency is now 57.27% and the destruction of exergy is 42.73%, which represents the amount of energy that is irreversibly lost in the environment.

DISCUSSION

The results presented in Table 3 and Table 4 are summarized in Figures 3 and 4, respectively. By comparing these results, it is clear that the distribution of component specific energy loss and exergy destruction remains the same in the proposed boiler construction compared to the actual state. However, energy and exergy leaving the boiler through the chimney have now increased, since the temperature of the flue gasses is higher in the proposed model than in the actual state model. Energy efficiency of the proposed boiler model has changed slightly, from 89.895% for the actual state mode to 89.93% for the proposed boiler model. The total boiler exergy destruction has changed from 39.03% for the actual state model, to 42.73% for the proposed model. The greatest difference of exergy loss between the two models is found in the flame pipe, which has changed from 73.06% for the actual state model to 80.44% for the proposed state model, compared to the total exergy loss of the system. Additionally, the output of the boiler has changed for the proposed model as a

consequence of reduced heat transfer to the water in the piping on the back of the flue gas diverter chamber by flue gasses flowing along the piping after leaving the III pass gas pipes on the way to the chimney. Hence, the consequence of the proposed boiler modification is twofold: energy loss has increased in the flame pipe, and decreased in the part where flue gasses are leaving the boiler. The exergy loss of the proposed modified model is slightly higher in the flame pipe, while exergy losses in the II and III pass gas pipes are redistributed in a new way.

CONCLUSION

The performed analysis shows that energy and exergy analysis can be used to pinpoint energy and exergy loss and exergy destruction in the structure of hot water boiler plants. In order to pinpoint the locations of these losses, it is necessary to create a physical model of the boiler, by applying the decomposition of the boiler with respect to the function of each of its components. The major exergy loss in the flame tube is the consequence of an irreversible chemical combustion process on the one hand, and a large temperature gradient between combustion products and hot water heated by radiation, on the other. Significant energy losses are found in the chimney, since the flue gasses leave the boiler at a high temperature level.

The obtained results are used to investigate possibilities of design modification to address reli-

Table 4. The results of calculations for each of the components of the hot water boiler without water-cooled pipes in relation to the entire system

Component	Energy loss, kJ/s	Energy loss, %	Exergy loss, kJ/s	Exergy loss, %
Flame tube	145.438	14.93	5740.507	80.44
Gas pipes II pass	34.993	3.59	1345.974	18.86
Gas pipes III pass	5.456	0.56	27.751	0.39
Flue gases leaving the boiler	788.549	80.92	21.75	0.30

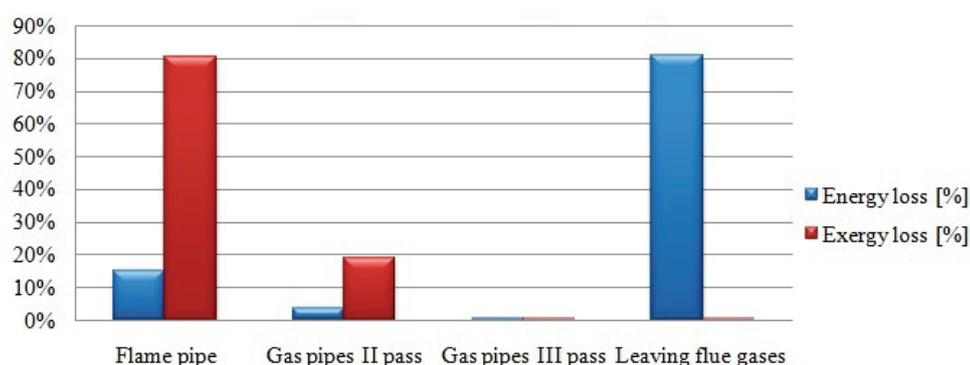


Figure 4. Comparative graphical review of energy and exergy analysis of the hot water boiler without water-cooled pipes of the reversing chamber

ability and availability issues, caused by regular damage of water-cooled pipes in the gas diverter chamber. The proposed case model was analyzed by means of exergy and energy analysis, to determine the impact of omitting this part from the diverter chamber contraction to the boiler efficiencies. However, exergo-economic optimization should be addressed to these issues to further investigate the viability and profitability of the proposed solution and help in decision-making.

Nomenclature

c	average specific heat capacity, kJ/(kg K), kJ/kgm _n ³
e	specific exergy, kJ/s
E	total energy rate, kJ/s
g	Earth's standard acceleration due to gravity, m/s ²
h	specific enthalpy, J/kg
H	heating value rate of fuel, kJ/kg, kJ/m _n ³
i	exergy loss rate, kJ/s
\dot{m}	mass flow rate, kg/s
p	pressure, Pa
\dot{Q}	heat transfer rate to the system, kJ/kg
s	specific entropy, J/kgK
T	temperature, K
u	thermal energy, W
V	total volume, m ³
W	work rate or power done by the system, W
z	distance, m

Greek Letters

λ	excess air ratio, -
v	specific volume, m ³
Y	velocity, m/s
η	efficiency, -
Ψ	total exergy rate, kJ/kg

Subscripts

0	dead state conditions
CH	chemical exergy
cp	combustion product
ex	exergy factor
fuel	fuel
jp	flame pipe
gp	gas pipes with convection heating surface
HV	higher heating value
i	energy factor
in	inlet
KN	kinetic exergy
L	air
loss	losses in the process
LV	lower heating value
m	number of carbon atoms
min	minimal value
n	number of hydrogen atoms

out	outlet
p	process of constant pressure
PH	physical exergy
PT	potential exergy
wcrc	water-cooled front hot gas reversing chamber
total	total

Superscripts

c	combustion process
g	gas
t	theoretical value
w	water

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MILENA N. TODOROVIĆ
DRAGOLJUB S. ŽIVKOVIĆ
MARKO V. MANČIĆ
GRADIMIR S. ILIĆ

Mašinski fakultet, Univerzitet u Nišu,
Srbija

NAUČNI RAD

PRIMENA ENERGETSKE I EKSERGETSKE ANALIZE ZA POBOLJŠANJE EFIKASNOSTI VRELOVODNOG KOTLA

U inženjerskoj praksi se eksergetska analiza može koristiti za tehničku i ekonomsku optimizaciju energetske procesa. Problem sve većeg korišćenja energije nalaže da toplane, tj. vrelođoni kotlovi, kao energetske isporučioce toplote za domaćinstva, budu analizirani u eksergetskom i energetske smislu. Toplane su uglavnom projektovane kako bi ispunile energetske zahteve, ne praveći pri tom razliku između kvaliteta i kvantiteta proizvedene toplote. U ovom radu izvršena je energetska i eksergetska analiza vrelovodnog kotla na prirodni gas. Energetska analiza daje samo kvantitativne rezultate, dok eksergetska analiza omogućava uvid u stvarno raspoloživu korisnu energiju u odnosu na okolinu. U ovom radu, izvršena je dekompozicija vrelovodnog kotla na kontrolne zapremine, poštujući funkcionalnost svake od komponenata ponaosob. Izvedena je energetska i eksergetska analiza formiranog fizičkog modela vrelovodnog kotla sa proračunom destrukcije eksergije i energetske gubitaka u svakoj od komponenata. U ovom radu opisano je trenutno stanje energetske i eksergetske stepena korisnosti vrelovodnog kotla. Dobijeni rezultati su analizirani i korišćeni za ispitivanje mogućnosti poboljšanja raspoloživosti i pouzdanosti kotla. Predstavljeno je poređenje rezultata između sadašnjeg i predloženog pouzdanijeg rešenja.

Ključne reči: vrelođoni kotao, eksergija, energija, raspoloživost, pouzdanost.