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Energy and exergy analysis of wood-based CHP. Case study

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Abstract

The paper presents use of energy and exergy analyses for the assessment of input and output flows in a cogeneration plant, shows points of exergy degradation in a system and allows to make a quantitative evaluation of energy quality changes. The objective of the study is to determine the essential points and values of exergy destruction in a biomass combined heat and power (CHP) plant in Jelgava, as well as to define boundaries of the method's use. A mathematical model is elaborated, used and evaluated as suitable for its application for the real plant and may be used in the plant's further operation for efficiency assessment and improvements. The results are shown with Sankey and Grassmann diagrams; the largest exergy destruction occurs in the boiler (steam generator) and represents 63.7 % of input fuel exergy; second largest exergy destruction is observed in heat exchangers of district heating (DH) system. Exergy efficiency of the plant is influenced by the power to heat ratio (α) and potential of the produced heat (temperature). Increased heat load or decreased temperature of heat delivered to the consumer lowers the value of exergy efficiency of the plant.

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Keywords: cogeneration; combined heat and power; efficiency; energy analysis; exergy analysis; performance assessment; power plant

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1. Introduction

Facing environmental issues, low carbon technology use for dissipated power supply system and district heating (DH) system is becoming an essential point for which to develop possible solutions. Consequently, analysis of all opportunities of fossil fuel replacement with renewable ones becomes vitally significant. One of the solutions for this problem is the integration of a biomass combined heat and power (CHP) plant in a DH system, which leads to

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the increase of energy and exergy efficiency in comparison with separate production of heat in boiler-houses and in power plants.

Cogeneration is a type of energy transformation, which is the focus of attention of many research groups around the world, finding the efficient use of fuel and optimal working modes as a result of fossil resources shortage and price increase for all fuel types [1]. The use of woodchips as fuel in Latvia is also one of the solutions for energy security and independency, as mentioned in [2, 3].

Member states of the European Union are finding solutions for the accomplishing recommendations of the Renewable Energy Directive [4]. Maximal use of local renewables compared to use of imported fossil fuel is a crucial point not only for climate changes mitigation, but also for the energy independence of the European Union, taking into account that the share of imported fossil resources is considerably large in these countries. Analysis of the installed CHP plants is necessary to figure out the advantages and disadvantages of biomass use. Energy and exergy analysis of a wood-based CHP plant in Latvia is presented in [5]. The present publication elaborated in terms of methodology of energy and exergy analysis, compared to [5].

The first and the most widespread method for energy transformation efficiency evaluation is energy analysis. Combined assessment methods, including exergy, exergy destruction and entropy generation concepts, are also getting approved [6, 7]. The aim of the present study is to develop a useful method for plant efficiency evaluation, using a mathematical model, which simulates energy and exergy flows of the plant.

Exergy is defined as the maximal useful work obtained from a system while the system interacts with environment [8]. Nowadays energy and exergy analyses are done for power plants [9] and all the available energy technologies, such as internal combustion engines [10], steam turbines [11, 12], gas turbines [13], as well as for district heating systems [14], technological processes [15], etc. Legislation aspects of exergy are reviewed in [16]. This study represents exergy analysis of the cogeneration plant, which shows the vital points of exergy destruction and might be used for the improvement of operations at power plants.

2. Methodology

Sequence of the analysis consisting of initial data, necessary calculations and graphical illustration of the results are shown in the methodology scheme (Fig. 1).

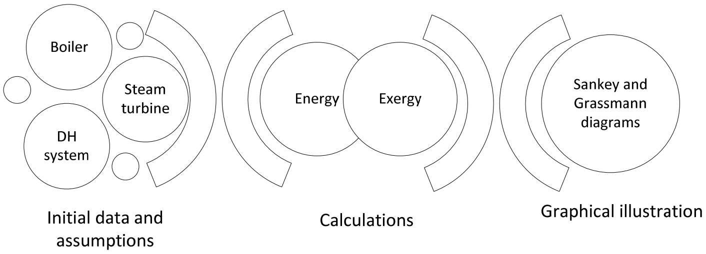

Fig. 1. Algorithm of methodology.

Real initial data from the CHP plant were obtained for the research. Where it was not possible, but data were common for all installations of this type, assumptions were made, e.g., for gear and generator efficiency. Energy and exergy analyses based on calculations were performed, taking into consideration the technological scheme and sequence of the system facilities. In fact, the consecutive calculations in compliance with the technological scheme represent a model, which allows to evaluate the efficiency of every stage of the plant. The model is suitable for the analysed CHP plant and may be used in its further operation for efficiency assessment. For clarity of the results, Sankey and Grassmann diagrams are obtained for both energy and exergy.

2.1. CHP plant description

The analysed plant is a conventional biomass cogeneration plant with two DH heat exchangers installed after the steam turbine. The scheme of the plant includes the fluidized bed boiler and flue gas treatment system; steam turbine; water pre-treatment system; heat exchangers contacting with the DH water circuit; and cooling system, which is used when consumers do not need a part of the heat produced. Fuel is burned in the steam boiler and superheated steam is obtained, which is then supplied to the steam turbine. Woodchips and milled peat are used as fuel, and natural gas is used for the ignition burners. It is possible to co-fire woodchips and milled peat simultaneously.

2.2. Initial data

The initial parameters for energy and exergy analysis are shown in Table 1.

Steam after the turbine is divided into 2 flows, 60 % with higher pressure and 40% with lower (Fig. 2 and 3). Steam expands in the turbine and part of its kinetic energy transforms into heat energy, therefore steam has higher enthalpy and entropy values after the turbine, compared to the theoretical adiabatic process. The coefficient of performance of turbine is used to obtain the corresponding value.

Table 1. Initial parameters for energy and exergy analysis.

Parameter	Value	Unit	Parameter	Value	Unit
Boiler capacity	$N = 88.0$	MW	Steam turbine capacity	$L_{ST} = 18.9$	MW
District heating capacity	$Q_{DH} = 44.2$	MW	Steam temperature	$t_1 = 518.7$	°C
District heating water flow velocity	$V = 1137.0$	m^3/h	Steam pressure	$p_1 = 113.7$	bar
District heating temperature (supply)	$t_s = 87.6$	°C	Steam flow	$m_{st} = 26.0$	kg/sec
District heating temperature (return)	$t_r = 54.2$	°C			

Steam parameters for the calculations are given in Table 2.

Table 2. Steam data of processes in turbine.

Particular	Unit	Value
Enthalpy of inlet steam h_1	kJ/kg	3406
Entropy of inlet steam s_1	kJ/kg·K	6.6
Enthalpy after turbine h_2	kJ/kg	2580
Entropy after turbine s_2	kJ/kg·K	6.9
Theoretical (adiabatic expansion) enthalpy after turbine $h_{2.theor}$	kJ/kg	2457
Enthalpy input DH$_1$ h_{DH1}	kJ/kg	2774
Enthropy input steam in DH$_1$ s_{DH1}	kJ/kg·K	6.8
Enthalpy input DH$_2$ h_{DH2}	kJ/kg	2580
Enthropy input steam in DH$_2$ s_{DH2}	kJ/kg·K	6.9
Temperature input steam in DH$_1$ t_{DH1}	°C	159
Temperature input steam in DH$_2$ t_{DH2}	°C	113

3. Results and discussion

The results of modelling are given in Table 3 and shown in Fig. 1 and Fig. 2 by Sankey and Grassmann diagrams.

Table 3. First law and second law analyses result.

Equipment	First law efficiency	Second law efficiency	Irreversibility
Boiler	88 %	36.3 %	73.5 MW
Turbine	87 %	85 %	1.9 MW
DH heat exchangers		55 %	7.2 MW
Plant	62.4 %	24 %	87.6 MW

Energy and exergy values of input fuel are similar, therefore input energy is of high quality. It differs for output flows, which consist of produced heat and power. Power and its exergy values are equal, hence power is of a high quality. It differs for heat: its exergy is affected by heat carrier and environment temperature. Output to input flows relation determine the efficiency of a plant. Operating in the conventional mode, energetic efficiency of the plant is 62.4 (%), exergetic 24.0 (%).

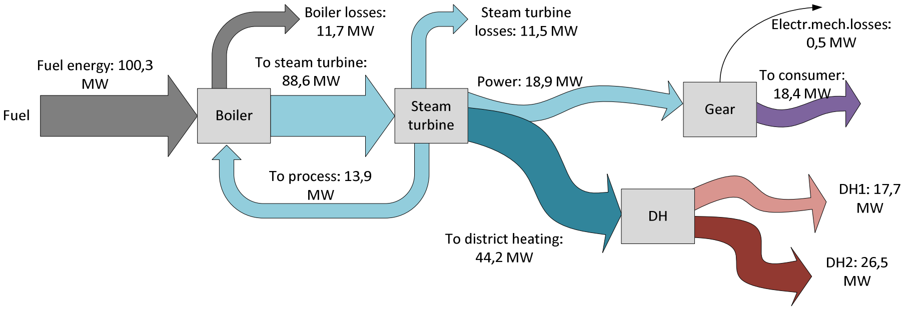

Fig. 2. Sankey diagram of CHP plant.

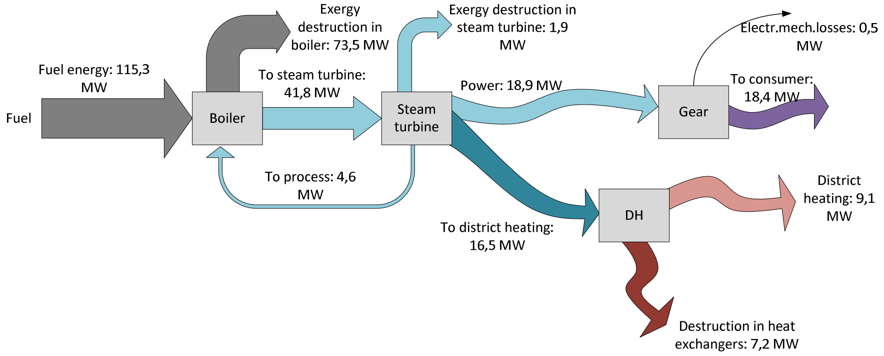

Fig. 3. Grassmann diagram of CHP plant.

The results of energy analysis in Fig. 2 show that energy losses in the boiler, associated with heat losses in flue gases and other losses in the furnace, are comparable with those in the steam turbine, and values are relatively small compared with the exergy destruction. Fig.3 shows the largest exergy destruction occurring in the boiler, which results as 73.5 MW or 63.7 % of the input fuel exergy.

Temperature of combustion products obtained in the furnace is higher than 1200 °C. This heat is used for steam generation with pressure p=114 bar and temperature t=518 °C, so fuel exergy eliminates to steam exergy value.

The second largest exergy destruction is observed in the DH heat exchangers, which can be explained by the decrease of the heat potential: temperature before DH heat exchangers is 113...159 °C, after is 54...88 °C.

4. Conclusion

Facilities of the plant technological scheme, where the essential exergy destruction occurs, are indicated, and exergy values are obtained in the present study. Energy and exergy analyses are done for the plant and the results are shown with Sankey and Grassmann diagrams. Methodology used for the study shows its applicability for decision making about the existing and increasing efficiency of the plant. Exergy analysis allows to carry out a meaningful comparison between elements of the system of different operational modes.

In the present study, the largest exergy destruction occurs in the steam boiler. It represents 63.7 % of input fuel exergy, which means that more than a half of input exergy is not usable. The next largest exergy destruction value is observed in the DH heat exchangers. The indicated facilities are the first for which the possibilities of decreasing exergy losses should be explored.

Exergy efficiency of the plant is influenced by power to heat ratio (α) and potential of the produced heat (temperature). Increased heat load or decreased temperature of heat delivered to consumer decrease the exergy efficiency of the plant.

Exergy analysis is a useful tool for energy-related systems evaluation, showing the quality of energy and its abilities of application wider, than the first law assessment.

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