EXERGY ANALYSIS OF LOW-PRESSURE CONDENSATE HEATING SYSTEM FROM COGENERATION POWER PLANT

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Abstract: *The paper presents an exergy analysis of condensate low-pressure heating system of a cogeneration power plant, which consists of one heater, one condensate pump and one pressure reduction valve. The entire system is investigated at three different plant loads. Regardless of the plant load, the highest exergy destruction is noted for the condensate heater (between 416.41 kW and 771.46 kW), after which follows pressure reduction valve with exergy destruction between 57.43 kW and 120.61 kW. Exergy destruction of condensate pump is almost negligible at any plant load and therefore condensate pump has the highest exergy efficiency (between 75.86 % and 77.08 %). Exergy efficiency of condensate heater is between 56.13 % and 59.29 %, while pressure reduction valve has the lowest exergy efficiency of all three analyzed system components and is between 36.98 % and 48.42 %.*

KEYWORDS: CONDENSATE HEATING, EXERGY ANALYSIS, EXERGY DESTRUCTION, EXERGY EFFICIENCY

1. Introduction

Steam power plants nowadays, regardless of its type, function or developed power, consist of various complex sub-systems [1]. Each sub-system has a function to improve plant operation and, if possible, increase power plant efficiency.

One of such complex sub-systems is condensate/feed water heating system mounted between steam condenser [2] and steam generator [3]. The main function of this sub-system is to increase condensate/feed water temperature before the water enters again into the steam generator. Heating in complete system is ensured with steam extractions from the main turbine, regardless of the number of turbine cylinders [4]. In such way, fuel savings in the steam generator are obtained and increase of plant overall efficiency.

Condensate/feed water heating system in all steam power plants is divided in two parts – low-pressure condensate heating system and high-pressure feed water heating system [5]. The component which makes this division is deaerator with its dual function (water heating and removing of dissolved gasses from the water). Depending on plant type and operation, low-pressure and high-pressure heating systems can consist of several pumps, heaters and pressure reduction valves [6].

In this paper exergy analysis of the low-pressure condensate heating system from steam cogeneration power plant at three different plant loads is performed. This heating system consists of one condensate pump, one low-pressure condensate heater and one pressure reduction valve for condensate (condensate obtained from heating steam) returning to the main steam condenser. Calculation of exergy power losses (exergy destructions) as well as exergy efficiencies of each low-pressure condensate heating system component at each plant load was performed. The aim was to investigate operation characteristics of each component during the increase of power plant load.

2. Description of condensate low-pressure heating system from cogeneration power plant

Analyzed condensate low-pressure heating system operates in sugarcane bagasse cogeneration power plant [7]. The system is used for condensate heating on condensate returning line from the steam condenser to deaerator (analyzed system is a part of complete condensate/feed water heating system on water returning line from the steam condenser to steam generator [8]).

The condensate low-pressure heating system consists of three components: condensate pump, condensate heater and pressure reduction valve, Fig. 1. Condensate pump is used for condensate pressure increasing and its delivering to deaerator [9]. For such operation, condensate pump requires power delivered from any power producer. Before deaerator and after the pump, condensate passes through the low-pressure heater [10] which increases condensate temperature using steam extracted from the steam turbine. After the heat transfer in low-pressure heater, steam extracted from turbine turns into a condensate, which is led from heater to steam condenser through the pressure reduction valve. Pressure reduction valve decreases condensate pressure, while condensate specific enthalpy before and after valve remains constant. Each pressure reduction valve has the same described operating principle, regardless of fluid which passes through the valve [11].

Exergy analysis of condensate low-pressure heating system is the analysis of each component from such system. The main goal is to determine exergy losses (exergy destruction) and efficiencies of each component and, if possible, propose methods for improving each component operation.

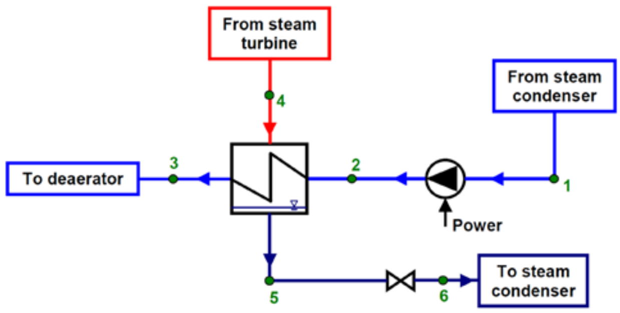

Fig. 1. *Scheme and operating points of the analyzed low-pressure condensate heating system*

3. Equations for condensate low-pressure heating system exergy analysis

3.1. Overall exergy analysis equations for control volume

For any volume or system in steady state, mass balance equation (disregarding potential and kinetic energy), is [12]:

$$\sum \dot{m}_{\mathrm{IN}} = \sum \dot{m}_{\mathrm{OUT}} \tag{1}$$

The second law of thermodynamics defines exergy analysis [13]. The main exergy balance equation (for a volume in steady state) is defined according to [14] as:

$$\dot{X}_{\mathrm{heat}} - P = \sum \dot{m}_{\mathrm{OUT}} \cdot \varepsilon_{\mathrm{OUT}} - \sum \dot{m}_{\mathrm{IN}} \cdot \varepsilon_{\mathrm{IN}} + \dot{E}_{\mathrm{ex,D}} \tag{2}$$

Exergy transfer by heat ($\dot{X}_{\mathrm{heat}}$) at the temperature T is:

$$\dot{X}_{\mathrm{heat}} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} \tag{3}$$

Specific exergy is defined according to [15] by an equation:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) \tag{4}$$

The exergy power of fluid flow is defined, according to [16] as:

$$\dot{E}_{\text{ex}} = \dot{m} \cdot \varepsilon = \dot{m} \cdot \left[(h - h_0) - T_0 \cdot (s - s_0) \right] \quad (5)$$

Exergy efficiency, according to [17], is defined by an equation:

$$\eta_{\text{ex}} = \frac{\text{Exergy output}}{\text{Exergy input}} \quad (6)$$

3.2. Exergy analysis equations of each condensate heating system component

In this chapter equations for the exergy analysis of each condensate heating system component are presented – the first is condensate pump, then the low-pressure feed water heater and finally pressure reduction valve. Equations for each component are defined according to operating points presented in Fig. 1.

The exergy analysis is dependable on the conditions of the ambient in which component or system operates [18]. In this analysis, the selected ambient state is ambient pressure of 1 bar and ambient temperature of 25 °C, as proposed in [19].

The condensate pump (according to [9]):

→ Mass balance: $$\dot{m}_1 = \dot{m}_2 \quad (7)$$

→ Exergy power input (only condensate flow): $$\dot{E}_{\text{ex,pump,IN,co}} = \dot{m}_1 \cdot \varepsilon_1 \quad (8)$$

→ Exergy power input (cumulative): $$\dot{E}_{\text{ex,pump,IN,cu}} = \dot{m}_1 \cdot \varepsilon_1 + P_{\text{pump}} \quad (9)$$

→ Exergy power output: $$\dot{E}_{\text{ex,pump,OUT}} = \dot{m}_2 \cdot \varepsilon_2 \quad (10)$$

→ Exergy destruction: $$\dot{E}_{\text{ex,pump,D}} = \dot{E}_{\text{ex,pump,IN,cu}} - \dot{E}_{\text{ex,pump,OUT}} \quad (11)$$

→ Exergy efficiency: $$\eta_{\text{ex,pump}} = \frac{\dot{E}_{\text{ex,pump,OUT}} - \dot{E}_{\text{ex,pump,IN,co}}}{P_{\text{pump}}} \quad (12)$$

The low-pressure condensate heater (according to [10]):

→ Mass balance-steam: $$\dot{m}_4 = \dot{m}_5 \quad (13)$$

→ Mass balance-condensate: $$\dot{m}_2 = \dot{m}_3 \quad (14)$$

→ Exergy power input: $$\dot{E}_{\text{ex,heater,IN}} = \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_5 \cdot \varepsilon_5 \quad (15)$$

→ Exergy power output: $$\dot{E}_{\text{ex,heater,OUT}} = \dot{m}_3 \cdot \varepsilon_3 - \dot{m}_2 \cdot \varepsilon_2 \quad (16)$$

→ Exergy destruction: $$\dot{E}_{\text{ex,heater,D}} = \dot{E}_{\text{ex,heater,IN}} - \dot{E}_{\text{ex,heater,OUT}} \quad (17)$$

→ Exergy efficiency: $$\eta_{\text{ex,heater}} = \frac{\dot{E}_{\text{ex,heater,OUT}}}{\dot{E}_{\text{ex,heater,IN}}} \quad (18)$$

The pressure reduction valve (according to [11]):

→ Mass balance: $$\dot{m}_5 = \dot{m}_6 \quad (19)$$

→ Exergy power input: $$\dot{E}_{\text{ex,valve,IN}} = \dot{m}_5 \cdot \varepsilon_5 \quad (20)$$

→ Exergy power output: $$\dot{E}_{\text{ex,valve,OUT}} = \dot{m}_6 \cdot \varepsilon_6 \quad (21)$$

→ Exergy destruction: $$\dot{E}_{\text{ex,valve,D}} = \dot{E}_{\text{ex,valve,IN}} - \dot{E}_{\text{ex,valve,OUT}} \quad (22)$$

→ Exergy efficiency: $$\eta_{\text{ex,valve}} = \frac{\dot{E}_{\text{ex,valve,OUT}}}{\dot{E}_{\text{ex,valve,IN}}} \quad (23)$$

4. Operating parameters of the analyzed condensate heating system at three different loads

Data for each operating point of the analyzed low-pressure condensate heating system (temperature, pressure and mass flow of each fluid stream) were found in [7]. The low-pressure condensate heating system is analyzed in three cogeneration power plant loads, according to main steam turbine developed power. The operating parameters of the low-pressure condensate heating system at low power plant load are presented in Table 1, at middle plant load in Table 2 and at high power plant load in Table 3.

At each power plant load, specific enthalpies, specific entropies and specific exergies of each fluid stream were calculated using NIST REFPROP 9.0 software [20].

Table 1. *Operating parameters of the condensate low-pressure heating system-low load*

LOW LOAD – P_{pump} = 11.0 kW						
OP*	**Temperature (°C)**	**Pressure (bar)**	**Mass flow (kg/s)**	**Specific enthalpy (kJ/kg)**	**Specific entropy (kJ/kg·K)**	**Specific exergy (kJ/kg)**
1	41.51	0.08	16.583	175.8	0.5987	1.853
2	42.02	5.00	16.583	176.4	0.5991	2.356
3	100.13	5.00	16.583	420.0	1.3083	34.483
4	116.91	1.80	1.833	2688.0	7.1277	567.440
5	116.91	1.80	1.833	490.8	1.4947	49.707
6	41.51	0.08	1.833	490.8	1.5998	18.380

* Operating points are defined according to Fig. 1.

Table 2. *Operating parameters of the condensate low-pressure heating system-middle load*

MIDDLE LOAD – P_{pump} = 29.1 kW						
OP*	**Temperature (°C)**	**Pressure (bar)**	**Mass flow (kg/s)**	**Specific enthalpy (kJ/kg)**	**Specific entropy (kJ/kg·K)**	**Specific exergy (kJ/kg)**
1	49.42	0.12	25.583	207.7	0.6987	3.936
2	49.70	8.60	25.583	208.8	0.6995	4.813
3	115.29	8.60	25.583	484.3	1.4762	48.736
4	145.70	3.10	3.222	2751.0	7.0402	656.520
5	134.22	3.10	3.222	564.4	1.6790	68.369
6	49.42	0.12	3.222	564.4	1.8045	30.939

* Operating points are defined according to Fig. 1.

Table 3. *Operating parameters of the condensate low-pressure heating system-high load*

HIGH LOAD – P_{pump} = 28.1 kW						
OP*	**Temperature (°C)**	**Pressure (bar)**	**Mass flow (kg/s)**	**Specific enthalpy (kJ/kg)**	**Specific entropy (kJ/kg·K)**	**Specific exergy (kJ/kg)**
1	50.40	0.13	26.556	211.0	0.7089	4.193
2	50.48	7.90	26.556	212.0	0.7096	4.996
3	110.97	7.90	26.556	466.0	1.4290	44.504
4	131.19	2.80	3.139	2713.0	6.9931	632.570
5	131.19	2.80	3.139	553.6	1.6525	65.473
6	51.03	0.13	3.139	553.6	1.7657	31.704

* Operating points are defined according to Fig. 1.

5. The results of low-pressure condensate heating system exergy analysis and discussion

As presented in Eq. (9), condensate pump is the only low-pressure condensate heating system component which cumulative exergy power input must be divided in two parts-the first part is the exergy power input of condensate flow and the second part is the power delivered from any power producer for pump operation.

Delivered power share in cumulative pump exergy power input is 26.36 % at low plant load, 22.42 % at middle plant load and 20.15 % at high plant load, Fig. 2. Firstly, it can be concluded that at any plant load exergy power input of condensate flow is the dominant element of cumulative pump exergy power input. Secondly, increase in plant load resulted with a decrease of delivered power share in cumulative pump exergy power input (and simultaneously with an increase of the condensate flow share in cumulative pump exergy power input).

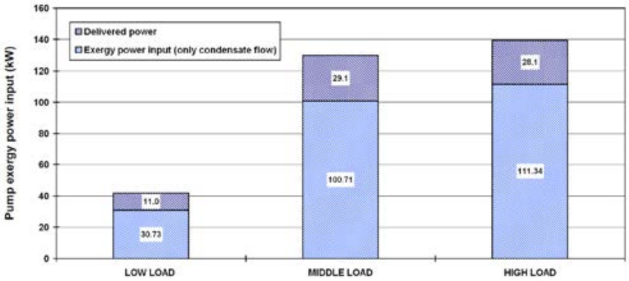

Fig. 2. *Change in distribution of cumulative pump exergy power input at three plant loads*

Cumulative exergy power input for all the condensate low-pressure heating system components shows that only the condensate pump has the highest cumulative exergy power input at the highest plant load (139.44 kW), while the highest cumulative exergy power input of the heater and valve occurs at the middle plant load (1895.15 kW for heater and 220.30 kW for pressure reduction valve), Fig. 3.

At any plant load, the highest amount of exergy power is delivered in the condensate heater, after which follows valve and the lowest amount of exergy power is delivered for condensate pump operation. This is an expected occurrence because the highest exergy power is brought to condensate low-pressure heating system by steam extracted from a steam turbine.

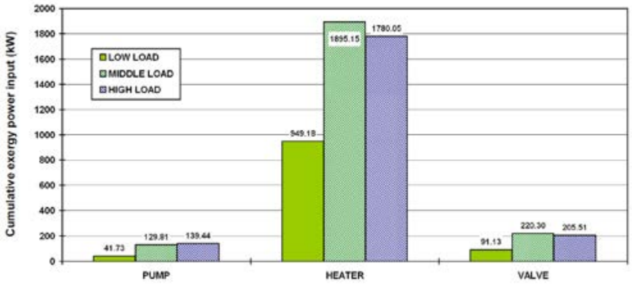

Fig. 3. *Change in cumulative exergy power inputs at three plant loads for all the condensate low-pressure heating system components*

Change of exergy power outputs during the increase in power plant load has the same trend for all condensate low-pressure heating system components as the change of cumulative exergy power inputs, Fig. 3 and Fig. 4.

The highest exergy power outputs can be seen for a condensate heater at any plant load, Fig. 4. Interesting phenomena is that pressure reduction valve exergy power outputs at any plant load are lower when compared to exergy power outputs of condensate pump. Since the valve exergy power inputs are higher than exergy power inputs of condensate pump at any plant load, Fig. 3, it can be expected that exergy efficiencies of pressure reduction valve will be much lower than exergy efficiencies of condensate pump - regardless of plant load.

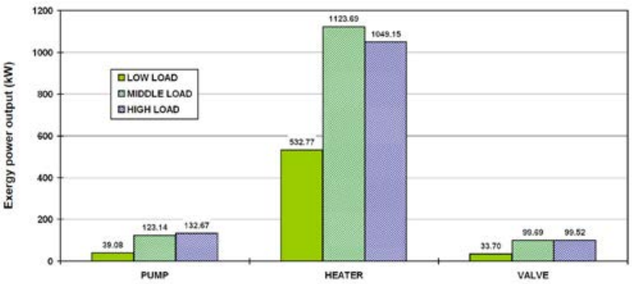

Fig. 4. *Change in exergy power outputs at three plant loads for all the condensate low-pressure heating system components*

In the condensate low-pressure heating system the highest exergy power inputs, outputs and exergy destructions can be seen for condensate heater, regardless of plant load, Fig. 5. At low plant load, exergy destruction for a condensate heater is 416.41 kW. At high plant load condensate heater exergy destruction is lower than at middle plant load (771.46 kW at middle and 730.90 kW at high plant load), what is different when compared to most of conventional steam power plant components [1] which have the highest exergy destruction at the high plant load.

Pressure reduction valve exergy destruction increases from the low to middle plant load (from 57.43 kW up to 120.61 kW), while between middle and high plant load valve exergy destruction decreases (from 120.61 kW to 106.00 kW).

Condensate pump exergy destruction is almost negligible at any plant load, if compared to condensate heater and pressure reduction valve exergy destructions, Fig. 5. At low plant load, condensate pump has exergy destruction equal to 2.66 kW. Increase in power plant load resulted in an increase in pump exergy destruction. It is 6.67 kW at middle and 6.77 kW at high power plant load.

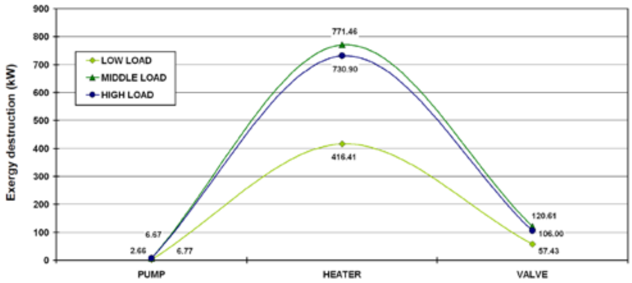

Fig. 5. *Change in exergy destructions at three plant loads for all the condensate low-pressure heating system components*

Exergy efficiency of pressure reduction valve continuously increases during the increase in plant load and is 36.98 % at low plant load, 45.25 % at middle plant load and 48.42 % at high plant load, Fig. 6.

The highest exergy efficiencies of condensate heater and condensate pump are not obtained at the highest plant load. They were obtained at middle plant load and are 59.29 % for heater and 77.08 % for the pump. At low plant load exergy efficiency of heater and pump is 56.13 % and 75.86 %, while at high plant load exergy efficiency of the same components is 58.94 % and 75.91 %, Fig. 6.

From the obtained results it can be concluded that in condensate low-pressure heating system condensate pump has the highest exergy efficiencies at any plant load, while pressure reduction valve has the lowest exergy efficiencies. A change in plant load has an almost negligible influence on condensate pump because its exergy efficiency change is the lowest when compared to other heating system components. The highest change in exergy efficiency during the increase in plant load can be noted for a pressure reduction valve.

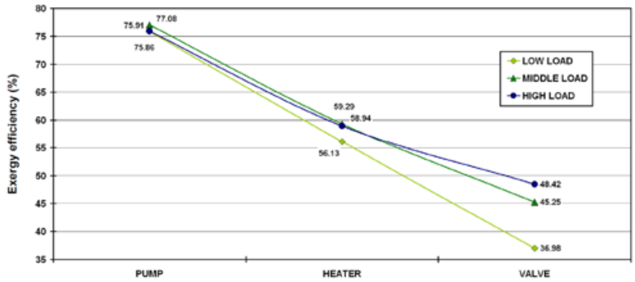

Fig. 6. *Change in exergy efficiency at three plant loads for all the condensate low-pressure heating system components*

6. Conclusions

In this paper the exergy analysis of the low-pressure condensate heating system from cogeneration power plant is performed. Heating system consist of one condensate heater, one condensate pump and one pressure reduction valve. The low-pressure condensate heating system is investigated at three different plant loads. The main conclusions of the analysis are:

- Condensate heater, at any plant load, has exergy power inputs and outputs much higher in comparison with condensate pump and pressure reduction valve.
- Pressure reduction valve has higher cumulative exergy power inputs and lower exergy power outputs when compared to condensate pump, at any plant load. This fact indicates the low valve exergy efficiency.
- The dominant element of condensate pump cumulative exergy power input, at any plant load, is the exergy power of condensate flow.
- The highest exergy destruction, regardless of plant load, is found in condensate heater (between 416.41 kW and 771.46 kW). The pressure reduction valve is the second component of the low-pressure condensate heating system according to exergy destruction values (valve exergy destruction is between 57.43 kW and 120.61 kW). Exergy destruction of condensate pump is almost negligible (between 2.66 kW and 6.77 kW).
- Element with the highest exergy efficiency in the analyzed low-pressure condensate heating system, regardless of the plant load, is a condensate pump (with exergy efficiency between 75.86 % and 77.08 %). In comparison with condensate pump, condensate heater has much lower exergy efficiency (between 56.13 % and 59.29 %). The lowest exergy efficiency is obtained for pressure reduction valve (between 36.98 % and 48.42 %).

7. Acknowledgment

This work has been fully supported by the Croatian Science Foundation under the project IP-2018-01-3739.

8. Nomenclature

Latin Symbols:		***Greek symbols:***	
$\dot{E}$	the total exergy of a flow, kW	ε	specific exergy, kJ/kg
h	specific enthalpy, kJ/kg	η	efficiency, -
$\dot{m}$	mass flow rate, kg/s		
p	pressure, bar	***Subscripts:***	
P	power, kW	0	ambient state
$\dot{Q}$	heat transfer, kW	co	condensate
s	specific entropy, kJ/kg·K	cu	cumulative
T	temperature, °C or K	D	destruction (ex. loss)
$\dot{X}_{\mathrm{heat}}$	heat exergy transfer, kW	ex	exergy
		IN	inlet (input)
		OUT	outlet (output)

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PROCEEDINGS

YEAR III,
ISSN 2535-0315(Print),
ISSN 2535-0323 (Online)
ISSUE 1 (7),
SOFIA, BULGARIA 2019

VOLUME 1

ENGINEERING. TECHNOLOGIES.
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