EXERGY ANALYSIS OF HIGH-PRESSURE FEED WATER HEATING SYSTEM AT THREE POWER PLANT LOADS

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Abstract: The paper presents an exergy analysis of high-pressure feed water heating system from cogeneration power plant at three different loads. Analyzed system consists of feed water pump, feed water heater and pressure reduction valve. Each feed water high-pressure heating system component has the highest exergy destruction at low plant load-188.96 kW for feed water pump, 1064.73 kW for feed water heater and 93.57 kW for pressure reduction valve. Feed water pump has the lowest exergy efficiencies which range is between 77.11 % and 81.35 %, feed water heater has exergy efficiencies between 86.07 % and 89.82 %, while pressure reduction valve has the highest exergy efficiencies (between 93.78 % and 95.67 %).

Introduction

In order to improve steam power plant operation and increase its efficiency, each steam power plant today, regardless of type or developed power, has complex condensate/feed water heating system [1]. Such system is mounted on water returning line to the steam generator, between steam condenser [2] and steam generator [3]. The main purpose of condensate/feed water heating system is increasing water temperature (by water heating with steam extracted from the main turbine). Water heating resulted with fuel savings in the steam generator and simultaneously with increasing the steam power plant efficiency.

Description of the analyzed high-pressure feed water heating system

High-pressure feed water heating system analyzed in this paper operates in low-power cogeneration power plant [4]. Analyzed system consists of three components: feed water pump, feed water heater and pressure reduction valve, as presented in Fig. 1. Feed water pump increases water pressure and delivers it (through the feed water heater) to steam generator. After the pump, feed water passes through heater, which uses steam extracted from the main turbine for a feed water heating. Steam extracted from the main turbine, after heat transfer to feed water in the heater, condenses and that condensate was lead back to the deaerator through the pressure reduction valve. Pressure reduction valve decreases condensate pressure, while condensate specific enthalpy remains constant.

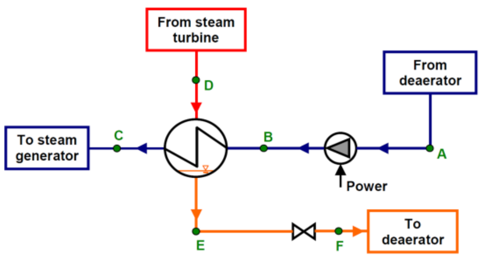

Fig. 1 Scheme and operating points of the analyzed high-pressure feed water heating system

Equations for high-pressure feed water heating system exergy analysis

Overall exergy analysis equations

For a volume in steady state, mass balance equation can be defined as [5]:

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

The main exergy balance equation for a volume in steady state can be defined according to [6] and [7] as:

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

The exergy transfer by heat ($\dot{X}_{heat}$) at temperature T, according to [8] is defined by an equation:

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

Specific exergy, according to [9] and [10], can be defined by an equation:

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

The exergy power of any fluid flow (for each observed fluid stream) is defined, according to [11], as:

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

Exergy efficiency can be defined, according to [12] by an equation:

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

Exergy analysis equations of each high-pressure feed water heating system component

Exergy analysis equations for each component of high-pressure feed water heating system are presented in this section. Exergy analysis equations for each component are defined by using heating system operating points from Fig. 1. The ambient conditions (dead state) for the exergy analysis are taken as proposed in [13]: pressure of 1 bar and temperature of 25 °C.

The feed water pump (according to [14]):

→ Mass balance: $\dot{m}_A = \dot{m}_B$, (7)

→ Exergy power input (only water flow): $\dot{E}_{ex,p,IN,w} = \dot{m}_A \cdot \varepsilon_A$, (8)

→ Exergy power input (cumulative): $\dot{E}_{ex,p,IN,cu} = \dot{m}_A \cdot \varepsilon_A + P_p$, (9)

→ Exergy power output: $\dot{E}_{ex,p,OUT} = \dot{m}_B \cdot \varepsilon_B$, (10)

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

→ Exergy efficiency: $\eta_{ex,p} = \frac{\dot{E}_{ex,p,OUT} - \dot{E}_{ex,p,IN,w}}{P_p}$. (12)

The high-pressure feed water heater (according to [15]):

→ Mass balance-steam: $\dot{m}_D = \dot{m}_E$, (13)

→ Mass balance-feed water: $\dot{m}_B = \dot{m}_C$, (14)

→ Exergy power input: $\dot{E}_{ex,h,IN} = \dot{m}_D \cdot \varepsilon_D - \dot{m}_E \cdot \varepsilon_E$, (15)

→ Exergy power output: $\dot{E}_{ex,h,OUT} = \dot{m}_C \cdot \varepsilon_C - \dot{m}_B \cdot \varepsilon_B$, (16)

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

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

The pressure reduction valve (according to [16]):

→ Mass balance: $\dot{m}_E = \dot{m}_F$, (19)

→ Exergy power input: $\dot{E}_{ex,v,IN} = \dot{m}_E \cdot \varepsilon_E$, (20)

→ Exergy power output: $\dot{E}_{ex,v,OUT} = \dot{m}_F \cdot \varepsilon_F$, (21)

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

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

Operating parameters of the feed water high-pressure heating system at three loads

At each observed cogeneration power plant load (according to the main steam turbine developed power), data for each operating point from Fig. 1 (temperatures, pressures and mass flows) were found in [4] and presented in Table 1 for low plant load, in Table 2 for middle plant load and in Table 3 for high plant load. For each power plant load, specific enthalpies and specific exergies of each fluid stream (in each operating point from Fig. 1) were calculated with NIST REFPROP 9.0 software [17].

Table 1. Operating parameters of the feed water high-pressure heating system-low plant load

LOW PLANT LOAD – P_p = 1013 kW					
O.P.*	**Temperature (°C)**	**Pressure (bar)**	**Mass flow rate (kg/s)**	**Specific enthalpy (kJ/kg)**	**Specific exergy (kJ/kg)**
A	151.83	5.0	96.639	640.4	90.07
B	153.23	77.0	96.639	650.5	98.60
C	199.55	77.0	96.639	852.8	166.65
D	340.54	17.5	8.778	3122.0	1041.80
E	205.40	17.5	8.778	876.7	171.25
F	151.83	5.0	8.778	876.7	160.59

Table 2. Operating parameters of the feed water high-pressure heating system-middle plant load

MIDDLE PLANT LOAD – P_p = 319 kW					
O.P.*	**Temperature (°C)**	**Pressure (bar)**	**Mass flow rate (kg/s)**	**Specific enthalpy (kJ/kg)**	**Specific exergy (kJ/kg)**
A	173.27	8.6	32.194	733.4	119.70
B	174.56	71.0	32.194	742.4	127.34
C	217.21	71.0	32.194	932.2	196.45
D	366.08	23.3	2.750	3167.0	1103.30
E	217.69	22.2	2.750	932.9	193.22
F	169.89	7.9	2.750	932.9	184.85

Table 3. Operating parameters of the feed water high-pressure heating system-high plant load

HIGH PLANT LOAD – P_p = 319 kW					
O.P.*	**Temperature (°C)**	**Pressure (bar)**	**Mass flow rate (kg/s)**	**Specific enthalpy (kJ/kg)**	**Specific exergy (kJ/kg)**
A	169.89	7.9	33.611	719.8	115.16
B	171.38	72.0	33.611	728.6	122.84
C	214.48	72.0	33.611	919.8	191.68
D	340.73	22.2	2.944	3112.0	1068.10
E	217.69	22.2	2.944	932.9	193.22
F	169.89	7.9	2.944	932.9	184.85

* Operating points are presented according to Fig. 1.

The results of high-pressure feed water heating system exergy analysis with discussion

Cumulative exergy power input, which enters into the feed water pump, must be divided in two parts-feed water flow and delivered power for pump operation, Fig. 2 and Eq. 9. For all observed power plant loads is valid conclusions that pump delivered power takes a low share in cumulative pump exergy power input. Pump cumulative exergy power input is the highest at low power plant load, due to the highest feed water mass flow at the pump inlet (in comparison with middle and high plant load), Table 1.

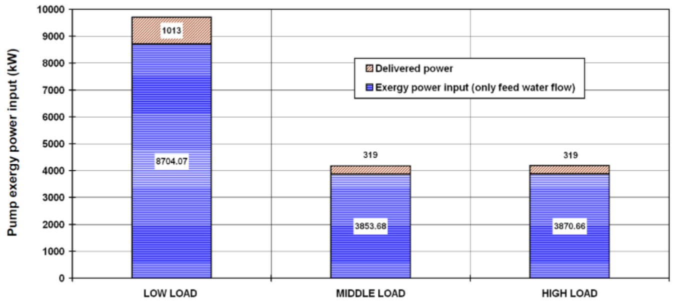

Fig. 2 Change in distribution of cumulative pump exergy power input at three plant loads

Exergy power outputs for all high-pressure feed water heating system components are presented in Fig. 3. The largest exergy power outputs for all feed water heating system components occurs at the low power plant load and amounts 9528.11 kW for feed water pump, 6576.76 kW for feed water high-pressure heater and 1409.62 kW for pressure reduction valve. The lowest exergy power outputs at any power plant load can be seen for pressure reduction valve, while the highest exergy power outputs have the feed water pump, Fig. 3.

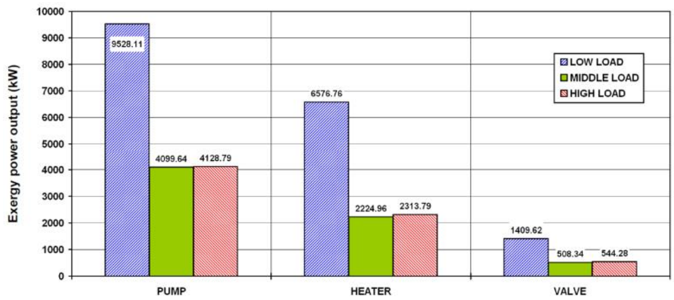

Fig. 3 Change in exergy power outputs at three plant loads for all feed water high-pressure heating system components

Exergy destructions (exergy power losses) for all high-pressure feed water heating system components are highest for low plant load and amounts 188.96 kW for feed water pump, 1064.73 kW for feed water high-pressure heater and 93.57 kW for pressure reduction valve, Fig. 4. The change in exergy destructions for all high-pressure feed water heating system components leads to a conclusion that increase in power plant load resulted with a continuous decrease of exergy destructions for feed water pump and high-pressure feed water heater, while pressure reduction valve does not follow the same trend.

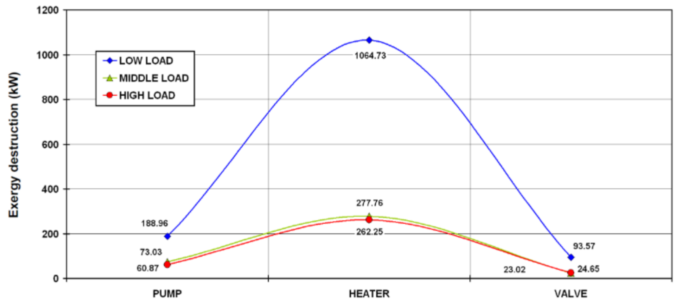

Fig. 4 Change in exergy destruction at three plant loads for all feed water high-pressure heating system components

In the entire analyzed high-pressure feed water heating system, the lowest exergy efficiency at any plant load has a feed water pump, Fig. 5. Increase in power plant load resulted with continuous increase in high-pressure feed water heater exergy efficiency. The exergy efficiency change of pressure reduction valve during the increase in plant load is similar to feed water heater, with a difference that pressure reduction valve has the same exergy efficiency at middle and high plant load (which amounts 95.67 %).

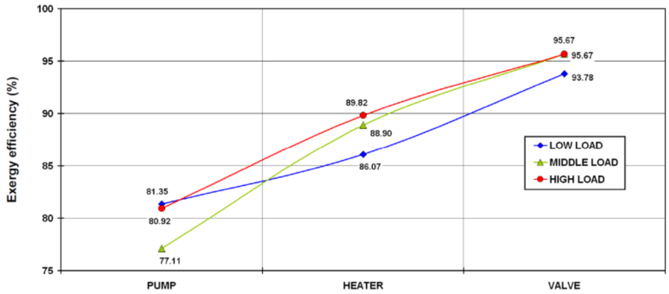

Fig. 5 Change in exergy efficiency at three plant loads for all feed water high-pressure heating system components

Conclusions

In the paper has performed exergy analysis of high-pressure feed water heating system from cogeneration power plant at three different loads. The main conclusions of the performed analysis are:

- All feed water high-pressure heating system components have the highest exergy destructions at low plant load. The lowest exergy destructions for feed water heater and feed water pump were observed at high plant load (262.25 kW for heater and 60.87 kW for pump). The pressure reduction valve has the lowest exergy destruction (23.02 kW) at middle plant load.
- In feed water high-pressure heating system, feed water pump has the lowest exergy efficiencies which range is between 77.11 % and 81.35 %. The feed water high-pressure heater has exergy efficiencies between 86.07 % and 89.82 %, while pressure reduction valve has the highest exergy efficiencies (between 93.78 % and 95.67 %).
- Power plant operation at high load will be preferable for the analyzed high-pressure feed water heating system - high power plant load ensures the highest exergy efficiencies and the lowest exergy destructions for the most of feed water heating system components.

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Nomenclature

Latin symbols: $\dot{E}$ = the total flow exergy (kW), h = specific enthalpy (kJ/kg), $\dot{m}$ = mass flow rate (kg/s), p = pressure (bar), P = power (kW), $\dot{Q}$ = heat transfer (kW), s = specific entropy (kJ/kg·K), T = temperature (°C or K), $\dot{X}_{heat}$ = heat exergy transfer (kW). _Greek symbols:_ ε = specific exergy (kJ/kg), η = efficiency (%). _Subscripts:_ 0 = ambient state, cu = cumulative, D = destruction (exergy loss), ex = exergy, h = heater, IN = inlet (input), OUT = outlet (output), p = pump, v = valve, w = water.

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