Nuclear power plant steam re-heating system - exergy analysis at four different operating regimes

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Abstract: *In this paper is performed exergy analysis of steam re-heating system, through all of its components, which operate in nuclear power plant. Analyzed re-heating system consists of the moisture separator (MS) and two re-heaters (RH1 and RH2) and is observed in four different operating regimes. MS has significantly lower exergy destructions and significantly higher exergy efficiencies in comparison to both re-heaters, regardless of the observed operating regime. MS and both re-heaters did not achieve the lowest exergy destructions and the highest exergy efficiencies in the same operating regime which notably complicated possible improvements. Further research of presented re-heating system will be based on operation improvement of RH1 and RH2 - performed exergy analysis shows that MS operation in any operating regime leaves no room for further improvement.*

KEYWORDS*: STEAM RE-HEATING SYSTEM, NUCLEAR POWER PLANT, EXERGY ANALYSIS, VARIOUS OPERATING REGIMES*

1. Introduction

Nowadays, in the commercial thermal power plants, regardless of its size, type or produced power, re-heating system is often (almost standard) used for steam temperature increase [1]. Steam re-heater (or re-heating system) is mounted between high pressure and medium pressure steam turbine cylinders in conventional steam power plants [2], while in nuclear power plants steam re-heating system is mounted between high pressure and low pressure steam turbine cylinders (nuclear power plants did not poses medium steam turbine cylinder) [3]. Steam re-heating brings several benefits into the power plant process, it significantly increases power plant produced power and efficiency (when compared to plants without re-heating) [4, 5].

In conventional steam power plants, steam re-heating process is performed with burning of additional fossil fuel, regardless of the fact is it steam re-heater mounted inside the steam generator (the most common composition) [6], or steam re-heater is an independent power plant component [7].

Nuclear power plants did not use any fossil fuels, therefore steam re-heating system cannot be performed identically as in conventional steam power plants. As nuclear power plants operate with saturated steam in the most of the turbine process, steam re-heating in such power plants is performed by combining moisture separation process and additional main steam heating process (main steam is heated with a steam flow stream of higher temperature) [8]. Additional heating process can be performed with one or two heaters (re-heaters).

In this paper is performed an exergy analysis of steam re-heating system used in nuclear power plant which consists of moisture separator and two additional main steam heaters (re-heaters). It is observed operation as well as exergy efficiencies and destructions of each system component in four different operating regimes.

2. Analyzed steam re-heating system from nuclear power plant - structure and operating characteristics

The analyzed steam re-heating system, which operates in a PWR (Pressurized Water Reactor) nuclear power plant [8] consist of three components, as presented in Fig. 1. Those components are Moisture Separator (MS), Re-Heater of lower pressure (RH1) and Re-Heater of higher pressure (RH2).

The operation principle of the whole system is that the majority of steam mass flow rate produced in steam generators is lead to high pressure turbine cylinder (main steam), while a small amount of that steam (with the highest pressure and temperature inside whole observed nuclear power plant) is delivered to RH2 and will be used for additional heating of main steam - operating point 4, Fig. 1. The main steam expands through high pressure turbine cylinder after which is delivered to re-heating system (operating point 1, Fig. 1). Moisture separator (MS) removes the majority of water droplets inside main steam (after moisture separator main steam state is very close to saturation line). Collected condensate in MS is delivered to the deaerator. In the first re-heater (RH1), main steam (of lower temperature) is heated with steam extracted from the high pressure turbine cylinder (which has higher temperature). Second main steam heating process is performed in RH2 with a small amount of steam produced in steam generators (regardless of the observed operating regime, heating steam in RH2 must have higher temperature in comparison with main steam). In the observed re-heating process, heating steam in RH2 has notably higher pressure in comparison to heating steam in RH1. In Fig. 1 are also presented operating points required for the exergy analysis of each component.

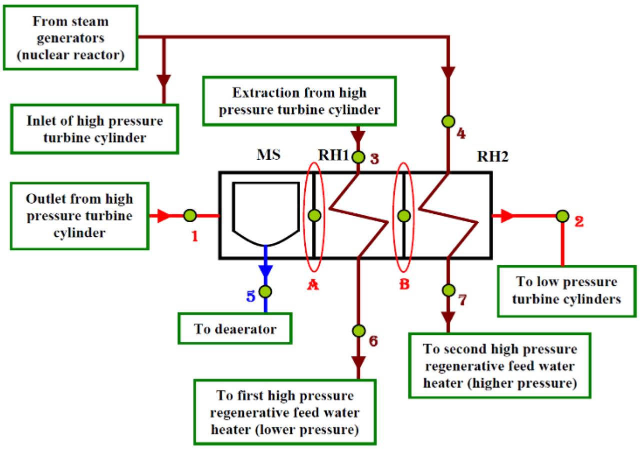

Fig. 1. *Scheme of observed steam re-heating system from nuclear power plant along with operating points required for the analysis*

3. Equations for the analysis of re-heating system

3.1. The principle of main steam operating parameters calculation in operating points A and B

Before defining equations of observed steam re-heating system exergy analysis, it should be explained calculation procedure for defining main steam operating parameters in operating points A and B, Fig. 1. Those operating parameters enable observing each steam re-heating system component (MS, RH1 and RH2) independently in each operating regime. For all operating points presented in Fig. 1 which are marked with numbers are known required operating parameters at each observed operating regime. For operating points A and B are calculated two main steam operating parameters (pressure and specific enthalpy), which are used for the calculation of all the other required operating parameters. All the unknown operating parameters in each operating point presented in Fig. 1 are calculated by using NIST REFPROP 9.0 software [9].

Main steam pressure in operating points A and B is obtained by the uniform distribution of pressure difference between steam re-heating system inlet (operating point 1, Fig. 1) and outlet (operating point 2, Fig. 1), because required operating parameters from the literature (presented later in a paper) show steam pressure decrease from the system inlet to the outlet (due to losses). Therefore, each steam re-heating system component proportionally participates in the cumulative steam pressure drop throughout observed system.

Main steam specific enthalpies in operating points A and B are obtained by assuming energy efficiencies of RH1 and RH2. As the other analyses show [10, 11], heat exchangers have very high energy efficiencies, so for both RH1 and RH2 are assumed energy efficiencies equal to 96 %. From the definition of RH2 energy efficiency:

$$\eta_{\text{en,RH2}} = \frac{\dot{m}_2 \cdot h_2 - \dot{m}_\text{B} \cdot h_\text{B}}{\dot{m}_4 \cdot h_4 - \dot{m}_7 \cdot h_7}, \tag{1}$$

is obtained equation for main steam specific enthalpy in point B:

$$h_\text{B} = \frac{\dot{m}_2 \cdot h_2 - \dot{m}_4 \cdot (h_4 - h_7) \cdot \eta_{\text{en,RH2}}}{\dot{m}_\text{B}}, \tag{2}$$

where should be highlighted that in each observed operating regime is valid:

$$\dot{m}_4 = \dot{m}_7, \tag{3}$$

$$\dot{m}_\text{B} = \dot{m}_2 = \dot{m}_1 - \dot{m}_5. \tag{4}$$

The same principle is used for calculation of main steam specific enthalpy in operating point A, so the final obtained equation is:

$$h_\text{A} = \frac{\dot{m}_\text{B} \cdot h_\text{B} - \dot{m}_3 \cdot (h_3 - h_6) \cdot \eta_{\text{en,RH1}}}{\dot{m}_\text{A}}, \tag{5}$$

where in each observed operating regime is valid:

$$\dot{m}_3 = \dot{m}_6, \tag{6}$$

$$\dot{m}_\text{A} = \dot{m}_\text{B} = \dot{m}_2 = \dot{m}_1 - \dot{m}_5. \tag{7}$$

In the above equations, h is operating fluid specific enthalpy in (kJ/kg), $\dot{m}$ is operating fluid mass flow rate in (kg/s) and η_en is energy efficiency. Markings of all operating points are defined according to Fig. 1.

3.2. General exergy analysis equations

Second law of thermodynamics defines exergy analysis of any system or a control volume [12, 13]. As the analyzed steam re-heating system did not use or produce any mechanical power, the exergy balance equation can be defined as [14]:

$$\sum \dot{E}_{\text{ex,in}} + \dot{X}_\text{heat} = \sum \dot{E}_{\text{ex,out}} + \dot{E}_{\text{ex,D}}, \tag{8}$$

where $\dot{E}_{\text{ex,D}}$ is exergy destruction in (kW), indexes in and out denotes input and output, $\dot{X}_\text{heat}$ is the exergy transfer by heat at the temperature T, which can be defined according to [15]:

$$\dot{X}_\text{heat} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q}. \tag{9}$$

In all equations from this sub-section, T is temperature in (K) and $\dot{Q}$ is energy heat transfer in (kW), while index 0 denotes the ambient state. The last undefined element from Eq. 8 is $\dot{E}_\text{ex}$ - exergy flow of any operating fluid in (kW), which can be calculated as [16]:

$$\dot{E}_\text{ex} = \dot{m} \cdot \varepsilon, \tag{10}$$

where ε is specific exergy of any operating fluid in (kJ/kg) which definition can be found in [17]:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0). \tag{11}$$

In Eq. 11, s is operating fluid specific entropy in (kJ/kg·K). During the exergy analysis, is valid mass flow rate balance [18]:

$$\sum \dot{m}_\text{in} = \sum \dot{m}_\text{out}. \tag{12}$$

In general form, exergy efficiency of any system or a control volume can be defined as [19, 20]:

$$\eta_\text{ex} = \frac{\text{cumulative exergy output}}{\text{cumulative exergy input}}. \tag{13}$$

3.3. Exergy analysis equations of steam re-heating system

Observed steam re-heating system is analyzed through all of its constituent components. Here will be presented final exergy analysis equations (equations for exergy destruction and exergy efficiency calculation) of MS, RH1 and RH2. All of the markings in the following equations are presented in regards to operating points from Fig. 1. Equations presented in this sub-section remains the same regardless of the observed operating regime.

Moisture Separator (MS)

- Exergy destruction:

$$\dot{E}_{\text{ex,D,MS}} = \dot{m}_1 \cdot \varepsilon_1 - \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_\text{A} \cdot \varepsilon_\text{A}. \tag{14}$$

- Exergy efficiency:

$$\eta_{\text{ex,MS}} = \frac{\dot{m}_5 \cdot \varepsilon_5 + \dot{m}_\text{A} \cdot \varepsilon_\text{A}}{\dot{m}_1 \cdot \varepsilon_1}. \tag{15}$$

Re-Heater 1 (RH1)

- Exergy destruction:

$$\dot{E}_{\text{ex,D,RH1}} = \dot{m}_\text{A} \cdot \varepsilon_\text{A} + \dot{m}_3 \cdot \varepsilon_3 - \dot{m}_\text{B} \cdot \varepsilon_\text{B} - \dot{m}_6 \cdot \varepsilon_6. \tag{16}$$

- Exergy efficiency:

$$\eta_{\text{ex,RH1}} = \frac{\dot{m}_\text{B} \cdot \varepsilon_\text{B} - \dot{m}_\text{A} \cdot \varepsilon_\text{A}}{\dot{m}_3 \cdot \varepsilon_3 - \dot{m}_6 \cdot \varepsilon_6}. \tag{17}$$

Re-Heater 2 (RH2)

- Exergy destruction:

$$\dot{E}_{\text{ex,D,RH2}} = \dot{m}_\text{B} \cdot \varepsilon_\text{B} + \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_2 \cdot \varepsilon_2 - \dot{m}_7 \cdot \varepsilon_7. \tag{18}$$

- Exergy efficiency:

$$\eta_{\text{ex,RH2}} = \frac{\dot{m}_2 \cdot \varepsilon_2 - \dot{m}_\text{B} \cdot \varepsilon_\text{B}}{\dot{m}_4 \cdot \varepsilon_4 - \dot{m}_7 \cdot \varepsilon_7}. \tag{19}$$

4. The operating parameters of fluid streams required for steam re-heating system exergy analysis

Required operating parameters of each fluid stream at each observed operating regime of analyzed steam re-heating system are found in [8]. It is observed four different operating regimes - operating regime with the highest main steam mass flow rate at the entrance into the system (operating point 1, Fig. 1) is denoted as operating regime 1. Higher operating regime number denotes lower main steam mass flow rate at the re-heating system entrance. In [8] are found operating fluid mass flow rate, specific enthalpy, pressure and temperature in each required operating point (according to Fig. 1) at each observed operating regime. Other operating parameters of each fluid stream (in each operating point from Fig. 1) are calculated by using NIST REFPROP 9.0 software [9].

In each operating point from Fig. 1, specific exergies are calculated by using Eq. 11 for the ambient temperature of 25 °C and ambient pressure of 1 bar, as proposed in the literature [21, 22].

Table 1 presents operating parameters of each fluid stream required for the exergy analysis in Operating regime 1 (main steam mass flow rate at the re-heating system entrance, operating point 1, Fig. 1, is equal to 1239 kg/s), while Table 2 presents operating parameters of each required fluid stream for main steam mass flow rate at the re-heating system entrance equal to 1234 kg/s - Operating regime 2. Table 3 presents operating parameters of each fluid stream in Operating regime 3 (main steam mass flow rate at the re-heating system entrance, operating point 1, Fig. 1, is equal to 1231.8 kg/s), while Table 4 presents operating parameters of each required fluid stream for main steam mass flow rate at the re-heating system entrance equal to 1208.5 kg/s - Operating regime 4.

Table 1. *Operating parameters of fluid streams required for the exergy analysis - Operating regime 1*

O.P.*	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Pressure (MPa)	Temp. (°C)	Steam content (%)	Specific exergy (kJ/kg)
1	1239.00	2467.0	0.879	174.3	85.0	698.28
2	1057.40	2979.5	0.838	264.1	Superheated	874.91
3	86.41	2632.9	2.960	233.0	90.5	891.92
4	63.48	2757.5	7.150	287.3	99.1	1038.60
5	181.50	735.4	0.865	173.7	0	120.36
6	86.41	995.4	2.850	231.1	0	218.72
7	63.48	1269.7	7.040	286.3	Subcooled	342.26
B	1057.40	2893.8	0.852	225.1	Superheated	840.80
A	1057.40	2765.3	0.865	173.7	99.7	795.78

* O.P. = Operating Point (according to Fig. 1)

Table 2. *Operating parameters of fluid streams required for the exergy analysis - Operating regime 2*

O.P.*	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Pressure (MPa)	Temp. (°C)	Steam content (%)	Specific exergy (kJ/kg)
1	1234.00	2467.4	0.857	173.3	85.1	695.64
2	1054.30	2976.5	0.818	262.4	Superheated	870.34
3	77.51	2635.8	2.920	232.4	90.7	891.65
4	70.65	2759.4	7.020	286.0	99.1	1037.60
5	179.70	730.8	0.844	172.6	0	118.82
6	77.51	992.4	2.820	230.5	0	217.47
7	70.65	1263.0	6.910	285.0	Subcooled	339.04
B	1054.30	2880.2	0.831	218.5	Superheated	832.09
A	1054.30	2764.2	0.844	172.6	99.7	792.25

* O.P. = Operating Point (according to Fig. 1)

Table 3. *Operating parameters of fluid streams required for the exergy analysis - Operating regime 3*

O.P.*	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Pressure (MPa)	Temp. (°C)	Steam content (%)	Specific exergy (kJ/kg)
1	1231.80	2466.6	0.869	173.9	85.0	696.90
2	1051.50	2978.8	0.829	263.6	Superheated	873.15
3	83.07	2633.8	2.940	232.8	90.6	891.56
4	65.87	2758.1	7.110	286.9	99.1	1038.30
5	180.30	733.3	0.855	173.2	0	119.66
6	83.07	994.3	2.840	230.9	0	218.26
7	65.87	1267.6	7.000	285.9	Subcooled	341.25
B	1051.50	2889.2	0.842	222.8	Superheated	837.40
A	1051.50	2764.8	0.856	173.2	99.7	794.27

* O.P. = Operating Point (according to Fig. 1)

Table 4. *Operating parameters of fluid streams required for the exergy analysis - Operating regime 4*

O.P.*	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Pressure (MPa)	Temp. (°C)	Steam content (%)	Specific exergy (kJ/kg)
1	1208.50	2476.3	0.783	169.5	85.8	688.60
2	1042.70	2984.5	0.747	265.1	Superheated	861.72
3	72.01	2652.4	2.760	229.2	91.7	892.34
4	79.30	2768.9	6.320	279.0	99.2	1031.30
5	165.80	714.2	0.771	168.9	0	113.32
6	72.01	974.6	2.630	226.7	0	210.11
7	79.30	1220.1	6.110	276.8	0	318.65
B	1042.70	2871.4	0.759	213.1	Superheated	816.66
A	1042.70	2760.2	0.771	168.9	99.7	779.29

* O.P. = Operating Point (according to Fig. 1)

5. Results and discussion

Steam re-heating process for operating regime 1 in specific enthalpy-specific entropy diagram is presented in Fig. 2. It also should be noted that in all the other operating regimes presented diagram is very similar (exact values can be found in Table 2, Table 3 and Table 4), but the main conclusions are identical in all operating regimes (due to small differences, main steam re-heating process is shown only for operating regime 1).

In operating point 1, Fig. 1 and Fig. 2, main steam content is low (high amount of water droplets inside main steam). Moisture separator (MS) removes almost all water droplets from main steam and after MS, main steam is almost saturated (operating point A, Fig. 1 and Fig. 2). First re-heater (RH1) increases main steam temperature up to operating point B in which main steam is superheated, Fig. 2. Additional re-heating occurs in the second re-heater (RH2) which operates with higher pressure of heating steam in comparison to RH1. Complete observed re-heating process ends in operating point 2, Fig. 2, after which the main steam is sent to low pressure turbine cylinders (nuclear power plant in which analyzed steam re-heating system operates has three dual flow low pressure cylinders).

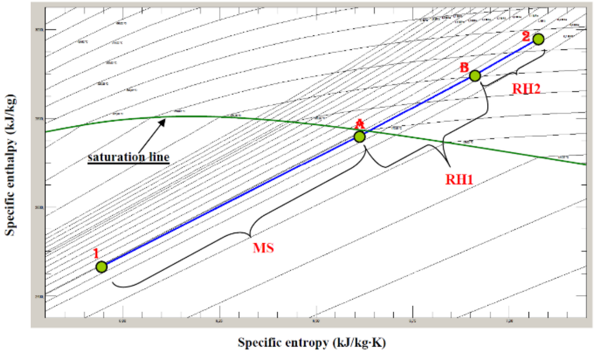

Fig. 2. *Steam re-heating process from the observed nuclear power plant in h-s diagram*

The exergy analysis of all steam re-heating system constituent components gives exergy destructions (Fig. 3) and exergy efficiencies (Fig. 4) at each of four observed operating regimes.

Considering exergy destructions of all components, it should be highlighted that both re-heaters (RH1 and RH2) have significantly higher exergy destructions than moisture separator (MS), regardless of the observed operating regime, Fig. 3. Also, RH1 has higher exergy destruction in comparison to RH2 in all operating regimes.

Comparison of all operating regimes show that MS obtain the lowest exergy destruction equal to 818.96 kW in operating regime 4. Also in operating regime 4, RH1 has the lowest exergy destruction equal to 10161.68 kW. Unlike MS and RH1, RH2 has the lowest exergy destruction in operating regime 1 equal to 8135.75 kW.

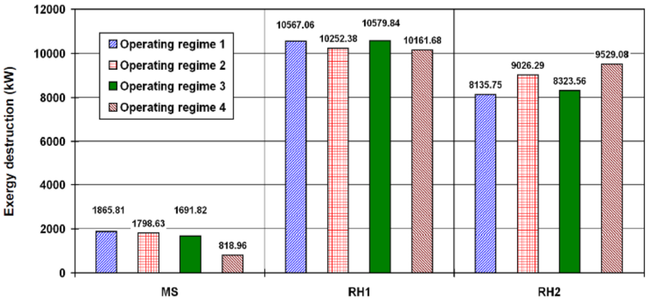

Fig. 3. *Exergy destruction change of steam re-heating system components in four observed operating regimes*

Exergy efficiency change of all steam re-heating system components in all observed operating regimes show that moisture separator (MS) has significantly higher exergy efficiencies in comparison to both re-heaters (RH1 and RH2), Fig. 4. Also, it can be observed that RH2 has higher exergy efficiencies in comparison to RH1 in all operating regimes except the operating regime 1. When observing various operating regimes, it can be concluded that MS and RH2 have the highest exergy efficiencies (equal to 99.90 % and 83.14 %, respectively) in operating regime 4, while RH1 has the highest exergy efficiency in operating regime 1 equal to 81.83 %.

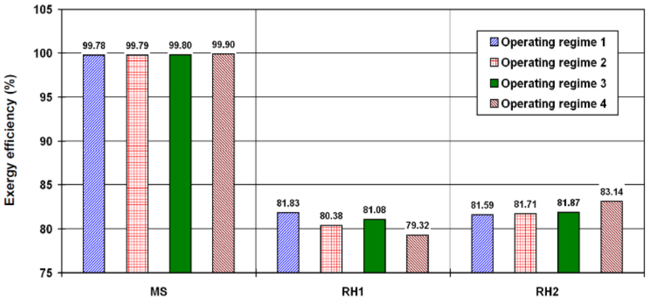

Fig. 4. *Exergy efficiency change of steam re-heating system components in four observed operating regimes*

6. Conclusions

This paper presents an exergy analysis of steam re-heating system which operates in nuclear power plant. Steam re-heating system is analyzed through all of its components at four different operating regimes. The most important conclusions are:

- Both re-heaters (RH1 and RH2) have significantly higher exergy destructions than moisture separator (MS), regardless of the observed operating regime.
- MS and RH1 have the lowest exergy destructions (equal to 818.96 kW and 10161.68 kW, respectively) in operating regime 4, while RH2 has the lowest exergy destruction equal to 8135.75 kW in operating regime 1.
- Moisture separator (MS) has significantly higher exergy efficiencies in comparison to both re-heaters (RH1 and RH2). Also, RH2 has higher exergy efficiencies in comparison to RH1 in all operating regimes except the operating regime 1.
- MS and RH2 have the highest exergy efficiencies (equal to 99.90 % and 83.14 %, respectively) in operating regime 4, while RH1 has the highest exergy efficiency in operating regime 1 equal to 81.83 %.
- Further improvement for all steam re-heating system components will be a challenge due to different behavior of system components at various operating regimes. Improvements can be based on both re-heaters (RH1 and RH2), while the performed analysis show that moisture separator (MS) can hardly be further improved.

7. Acknowledgment

This research has been supported by the Croatian Science Foundation under the project IP-2018-01-3739, CEEPUS network CIII-HR-0108, European Regional Development Fund under the grant KK.01.1.1.01.0009 (DATACROSS), project CEKOM under the grant KK.01.2.2.03.0004, CEI project "COVIDAi" (305.6019-20), University of Rijeka scientific grants: uniri-tehnic-18-275-1447, uniri-tehnic-18-18-1146 and uniri-tehnic-18-14.

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