Exergy analysis of steam condenser at various loads during the ambient temperature change

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Abstract: *The paper presents an exergy analysis of steam condenser at three different loads and in the ambient temperature range between 5 °C and 20 °C. An increase in the condenser load and increase in the ambient temperature resulted with an increase in steam condenser exergy destruction (exergy power losses). At low load, condenser exergy destruction is for the order of magnitude lower if compared to middle and high condenser loads. Decrease of the condenser load and decrease of the ambient temperature resulted with an increase in condenser exergy efficiency. The highest steam condenser exergy efficiencies are obtained at the lowest observed ambient temperature of 5 °C and amounts 81.47 % at low condenser load, 76.10 % at middle condenser load and 74.54 % at high condenser load. From the exergy viewpoint, the optimal condenser operating regime is low load and the lowest possible ambient temperature.*

KEYWORDS: STEAM CONDENSER, EXERGY ANALYSIS, LOAD CHANGE, THE AMBIENT TEMPERATURE CHANGE

1. Introduction

A constituent component of any steam power plant, regardless of plant type, operation or produced power is steam condenser. Steam produced in steam generator expanded through the turbine (or more of them) after which is led to the condenser. Condenser ensures steam condensation with heat transferring from steam to cooling water [1] (or in some cases heat is transferred from steam to cooling air [2]).

Pressure inside the steam condenser is significantly lower than the atmospheric pressure (usually vacuum between 90 % and 95 %), so condenser operation also has an important influence on the low-pressure turbine process, [3, 4]. Primary vacuum in the steam condenser is ensured with steam condensation process (significant decrease in the steam volume) after which the vacuum is maintained with steam ejectors, in the most of the cases.

For the steam condenser exergy analysis, heat transfer inside the condenser, number of condenser tubes or cooling water passages through the condenser, as well as condensation type which occurs on the condenser tubes are not essential elements. Steam condenser exergy analysis can be performed by knowing temperatures, pressures and mass flows of all the fluid streams at the steam condenser inlet and outlet [5].

In this paper are presented the results of the steam condenser exergy analysis at three different loads. The analyzed steam condenser is a water cooled condenser. As the exergy analysis is very dependable on the ambient temperature, at each condenser load the ambient temperature is varied in order to obtain steam condenser exergy losses and efficiencies at different ambient temperatures.

2. Analyzed steam condenser description, scheme and required operating points

Analyzed steam condenser operates in a cogeneration power plant [6]. Steam condenser main scheme and operating points necessary for the exergy analysis are presented in Fig. 1.

Condenser main function is to condense steam after expansion in a steam turbine. In an ideal situation, condensate temperature is the same as steam temperature, but in the real process due to losses, condensate has lower temperature. Analyzed condenser, along with steam condensation must ensure complete condensation of the additional condensate stream which is delivered to condenser from the low-pressure condensate heater (operating point 2, Fig. 1).

To ensure steam condensation, heat is transferred from steam to cooling water which passes through condenser tubes. Cooling water is delivered to steam condenser by pump from cooling tower, and after heat transferring, cooling water with increased temperature is delivered back into the cooling tower which decreases its temperature. There are several types of condensation process which can occur on the condenser tubes [7]. After steam condensation, obtained condensate at the condenser bottom is taken by condensate pump [8] and delivered to condensate heating system.

The analyzed steam condenser is closed heat exchanger (operating fluids exchange heat, but are not mixed together - heat exchange occurs on the condenser tubes). So, steam condenser exergy analysis can be performed as for any other closed heat exchanger [9].

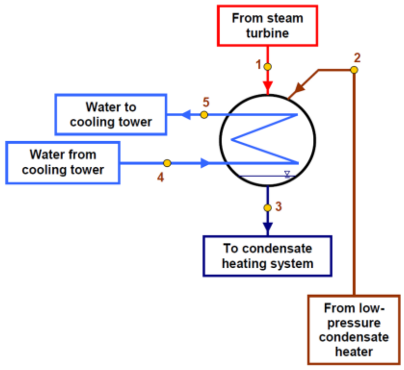

Fig. 1. *Steam condenser scheme and marked operating points necessary for the exergy analysis*

3. Equations necessary for the exergy analysis

3.1. Exergy analysis overall equations

Exergy analysis of any system or a control volume is defined according to the second law of thermodynamics, [10, 11]. The exergy balance equation for a control volume or a system in steady state, according to [12], can be defined by following equation:

$$\dot{X}_{\text{heat}} - P = \sum \dot{m}_{\text{OUT}} \cdot \varepsilon_{\text{OUT}} - \sum \dot{m}_{\text{IN}} \cdot \varepsilon_{\text{IN}} + \dot{E}_{\text{ex,D}} . \quad (1)$$

The mass balance equation for a control volume or a system in steady state, according to [13, 14], with assuming of no leakage occurrence, is defined as:

$$\sum \dot{m}_{\text{IN}} = \sum \dot{m}_{\text{OUT}} . \quad (2)$$

Specific exergy is defined by an equation [15]:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) . \quad (3)$$

The heat exergy transfer ($\dot{X}_{\text{heat}}$) at temperature T [16], is:

$$\dot{X}_{\text{heat}} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} . \quad (4)$$

The exergy power of any fluid flow, according to [17], can be defined as:

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

The overall definition of exergy efficiency is [18]:

$$\eta_{ex} = \frac{\text{Exergy output}}{\text{Exergy input}} . \tag{6}$$

3.2. Analyzed steam condenser exergy analysis equations

Exergy analysis of the steam condenser is performed with the same equations at each observed load (the changeable elements were temperatures, pressures and mass flows in each condenser operating point presented in Fig. 1). Steam condenser exergy analysis (as well as exergy analysis of any control volume or entire system) is dependable on the conditions of the ambient in which control volume or system operates.

The selected ambient conditions for the steam condenser exergy analysis are the ambient pressure of 1 bar and the ambient temperature of 15 °C. These ambient conditions are declared as the base ambient state. Ambient state in the steam condenser exergy analysis will be changed with a change in the ambient temperature (the ambient pressure will remain unchanged and equal to 1 bar).

Several scientists performed an exergy analysis of steam systems [2] or its components [19] by varying the ambient temperature. Change in the ambient temperature during steam system or its component operation can be significant and can have a notable impact on the exergy analysis [20].

Equations for the exergy analysis of steam condenser investigated in this paper are presented in relation to steam condenser operating points from Fig. 1:

<u>Mass flow balance</u>

- Steam/condensate mass flow balance:

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 . \tag{7}$$

- Cooling water mass flow balance:

$$\dot{m}_4 = \dot{m}_5 . \tag{8}$$

<u>Exergy balance</u>

- Steam condenser exergy power input:

$$\dot{E}_{ex,IN} = \dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 - \dot{m}_3 \cdot \varepsilon_3 . \tag{9}$$

- Steam condenser exergy power output:

$$\dot{E}_{ex,OUT} = \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_4 \cdot \varepsilon_4 . \tag{10}$$

- Steam condenser exergy destruction:

$$\begin{aligned} \dot{E}_{ex,D} &= \dot{E}_{ex,IN} - \dot{E}_{ex,OUT} = \\ &= \dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_3 \cdot \varepsilon_3 - \dot{m}_5 \cdot \varepsilon_5 \end{aligned} . \tag{11}$$

- Steam condenser exergy efficiency:

$$\eta_{ex} = \frac{\dot{E}_{ex,OUT}}{\dot{E}_{ex,IN}} = \frac{\dot{m}_5 \cdot \varepsilon_5 - \dot{m}_4 \cdot \varepsilon_4}{\dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 - \dot{m}_3 \cdot \varepsilon_3} . \tag{12}$$

4. Steam condenser operating parameters at three different loads

Data for steam condenser exergy analysis (temperatures, pressures and mass flows of each fluid stream) are found in [6] for each condenser load. The steam condenser load is defined according to steam mass flow which enters into the condenser after expansion in the turbine (operating point 1, Fig. 1) - higher steam mass flow which enters into the condenser denotes higher load, Table 1, Table 2 and Table 3.

For any fluid flow stream at each observed steam condenser load specific enthalpies and specific exergies were calculated by using NIST REFPROP 9.0 software [21]. Specific exergy of each fluid flow stream is dependable on the ambient conditions; therefore specific exergies of each fluid flow stream in Table 1, Table 2 and Table 3 are presented for the base ambient state.

Table 1. *Operating parameters of the analyzed steam condenser - low condenser load*

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
1	41.51	0.08	14.750	2348.00	187.880
2	41.51	0.08	1.833	490.80	31.415
3	41.51	0.08	16.583	175.80	4.878
4	29.41	5.00	826.389	123.70	1.857
5	38.84	5.00	826.389	163.10	4.306

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

Table 2. *Operating parameters of the analyzed steam condenser - middle condenser load*

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
1	49.42	0.12	22.361	2372.00	238.900
2	49.42	0.12	3.222	564.40	46.022
3	49.42	0.12	25.583	207.70	7.961
4	30.48	5.00	826.389	128.20	2.079
5	44.82	5.00	826.389	188.10	6.435

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

Table 3. *Operating parameters of the analyzed steam condenser - high condenser load*

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
1	51.03	0.13	23.417	2358.00	246.960
2	51.03	0.13	3.139	553.60	46.399
3	50.40	0.13	26.556	211.00	8.320
4	30.58	5.00	826.389	128.60	2.100
5	45.44	5.00	826.389	190.70	6.681

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

5. Results of steam condenser exergy analysis at three different loads and discussion

Each calculated operating parameter in the steam condenser exergy analysis is presented for the various ambient temperatures. The ambient temperature was varied in a range from 5 °C to 20 °C, with a step of 5 °C.

The change in exergy power of three the most dominant exergy flows from the analyzed steam condenser are presented in Fig. 2 - at high condenser load. The exergy power of each flow stream, at any ambient temperature, is calculated by using Eq. 5.

The most dominant exergy flows are steam flow at the condenser inlet (operating point 1, Fig. 1) due to the highest specific exergy when compared with other stream flows. The second and third most dominant flows are cooling water flow at the steam condenser inlet and outlet (operating points 4 and 5, Fig. 1) due to the highest mass flows when compared with other stream flows.

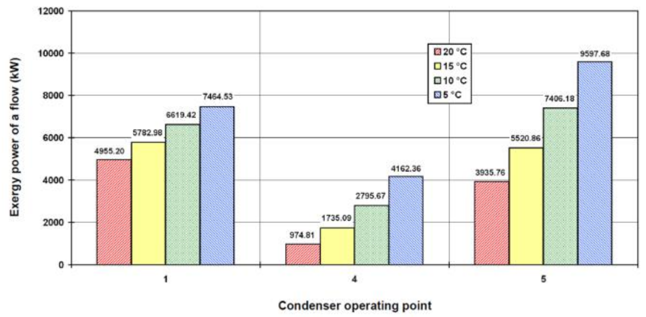

Fig. 2. *Change in exergy power of three dominant steam condenser flows for the different ambient temperatures - high condenser load*

Steam condenser exergy power input at each condenser load and at each ambient temperature is calculated by using Eq. 9.

Considering of steam condenser load, the highest condenser exergy power input can be seen at the high condenser load, while the lowest condenser exergy power input is calculated on low condenser load, Fig. 3, regardless of the ambient temperature. Decrease of the ambient temperature resulted with an increase in condenser exergy power input, regardless of condenser load.

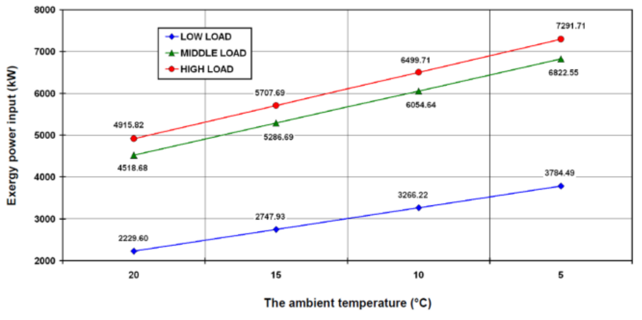

Fig. 3. *Change in analyzed steam condenser exergy power input for the different ambient temperatures at three condenser loads*

At each condenser load and at each ambient temperature analyzed steam condenser exergy power output is calculated according to Eq. 10.

Change in condenser exergy power output at any load and at any ambient temperature has identical trend as the change in condenser exergy power input, Fig. 4. The highest condenser exergy power output is calculated at high condenser load and the lowest condenser exergy power output is calculated at low condenser load, regardless of the ambient temperature. An increase in the ambient temperature resulted with a decrease in condenser exergy power output, regardless of condenser load.

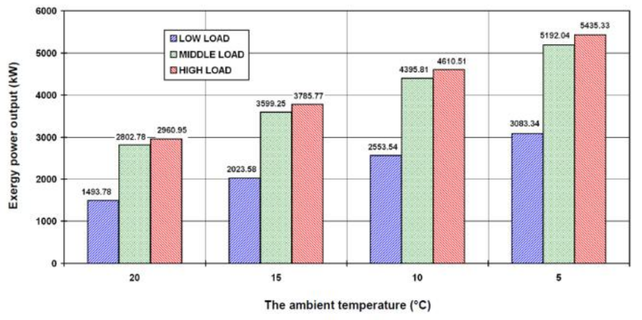

Fig. 4. *Change in analyzed steam condenser exergy power output for the different ambient temperatures at three condenser loads*

Exergy destruction (exergy loss) of the analyzed steam condenser at any ambient temperature and at any load is calculated by using Eq. 11. From Fig. 5 can be seen that condenser exergy destructions at low load are much smaller in comparison with exergy destructions at middle and high condenser load, therefore they cannot be presented at the same vertical axis. Regardless of the condenser load, decrease in the ambient temperature resulted with a decrease in condenser exergy destruction, so the lowest condenser exergy destructions are obtained at the lowest observed ambient temperature.

Regardless of the ambient temperature, steam condenser exergy destructions are the lowest at low condenser load and then increases with an increase in condenser load. At the base ambient state (the ambient temperature of 15 °C), condenser exergy destructions amounts 724.35 kW - low load, 1687.44 kW - middle load and 1921.92 kW - high load. From the lowest to the highest observed condenser load, exergy destructions are the lowest at the ambient temperature of 5 °C and amounts 701.16 kW, 1630.52 kW and 1856.39 kW, while at the highest observed ambient temperature of 20 °C condenser exergy destructions are the highest and amounts 735.82 kW, 1715.90 kW and 1954.87 kW, Fig. 5.

From the viewpoint of steam condenser exergy destruction only, for the analyzed steam condenser will be preferable to operate at the ambient temperature as low as possible.

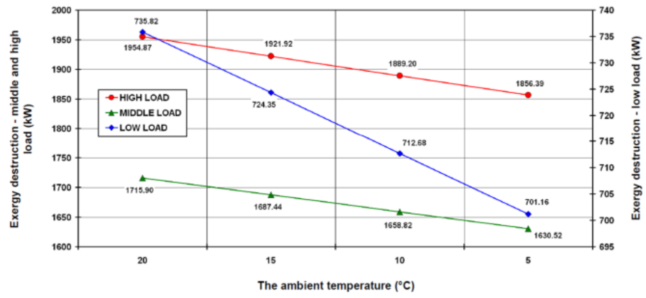

Fig. 5. *Change in analyzed steam condenser exergy destruction for the different ambient temperatures at three condenser loads*

Eq. 12 is used for calculation of the analyzed steam condenser exergy efficiency at all observed ambient temperatures and at all observed condenser loads.

Exergy efficiency of steam condenser is the highest at low condenser load and ranges between 67.00 % and 81.47 % in the observed ambient temperature range, Fig. 6. In the same observed ambient temperature range, condenser exergy efficiency is between 62.03 % and 76.10 % at middle and between 60.23 % and 74.54 % at high condenser load. Therefore, it can be concluded that the lowest condenser exergy efficiencies will be obtained at the high condenser load - decrease in condenser load will result with an increase in condenser exergy efficiency, regardless of the ambient temperature. At each observed steam condenser load, the highest exergy efficiencies are obtained for the lowest observed ambient temperature of 5 °C - 81.47 % at low condenser load, 76.10 % at middle condenser load and 74.54 % at high condenser load.

An increase in the ambient temperature significantly decreases analyzed steam condenser exergy efficiency, regardless of observed condenser load, Fig. 6.

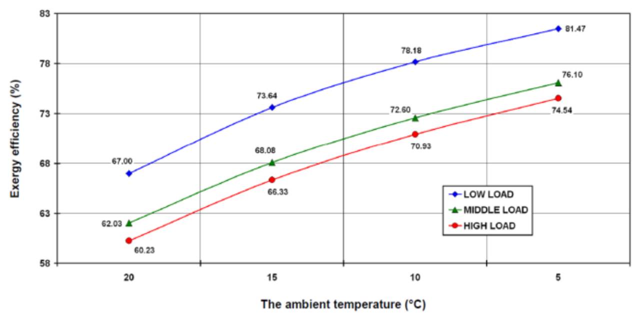

Fig. 6. *Change in analyzed steam condenser exergy efficiency for the different ambient temperatures at three condenser loads*

Further research of the analyzed steam condenser will be based on its optimization by using several artificial intelligence approaches [22, 23].

6. Conclusions

The paper presents an exergy analysis of steam condenser from cogeneration power plant. Steam condenser is analyzed at three different loads and in a range of the ambient temperatures (ambient temperature is varied between 5 °C and 20 °C). Presented analysis detected steam condenser operating regime and the ambient temperature at which the condenser operation will be preferable from the exergy aspect. The most important conclusions of the steam condenser analysis are:

- The change in steam condenser exergy power inputs and outputs has the same trend - condenser exergy power inputs and outputs increases with an increase in condenser load and also increases with a decrease in the ambient temperature.

- Steam condenser exergy destruction is for the order of magnitude lower at the low condenser load when compared to middle and high condenser loads.
- An increase in the ambient temperature resulted with an increase in condenser exergy destruction, what is a valid conclusion regardless of condenser load.
- The highest steam condenser exergy efficiencies will be obtained at low condenser load - increase in condenser load resulted with a decrease of condenser exergy efficiencies, regardless of the ambient temperature.
- The highest steam condenser exergy efficiencies are obtained at the lowest observed ambient temperature of 5 °C and amounts 81.47 % at low condenser load, 76.10 % at middle condenser load and 74.54 % at high condenser load.
- The analyzed steam condenser should operate at the low load and at the lowest possible ambient temperature.

7. Acknowledgment

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

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