Energy and exergy losses analysis of back-pressure steam turbine from CHP plant

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Abstract: *In this paper is analyzed back-pressure steam turbine which operates in CHP (Combined Heat and Power) plant from the aspect of energy and exergy losses. Produced turbine power, used for electricity generator drive equals 62548.77 kW, while the turbine mechanical loss is 1934.50 kW. Exergy analysis of the turbine shows that cumulative exergy loss is composed of two losses - mechanical loss and steam exergy loss. Steam exergy loss is additional loss which takes into account the state of the ambient in which turbine operates (unlike energy analysis which is independent of the ambient state). Change in the ambient temperature resulted with a change in turbine exergy efficiency and exergy loss. Ambient temperature change for 10 °C resulted with change in turbine exergy efficiency for less than 0.5 % on average, while the change in the turbine exergy loss (for the same temperature change) equals 266.21 kW on average.*
KEYWORDS*: BACK-PRESSURE STEAM TURBINE, ENERGY LOSS, EXERGY LOSS, CHP PLANT*

1. Introduction

Steam turbines are nowadays the basic power producers which drive electricity generators and produce electric power [1, 2]. The majority of such steam turbines (for electricity generator drive) are condensation type, which mean that steam after expansion through the turbine has pressure lower than atmospheric pressure – such steam is delivered to a steam condenser (or more of them) [3, 4].

Some steam turbines which operate in steam power plants are also used for electricity generators drive, but are of back-pressure type (steam after expansion in the turbine has pressure above the atmospheric pressure and is used for heating of any heat consumer [5]). Such steam turbine is analyzed in this paper.

Based on measured steam operating parameters from the literature [6] it is performed energy and exergy analysis of back-pressure steam turbine. Energy analysis involved mechanical loss which occurs in the turbine cylinder. It is investigated energy and exergy flow streams throughout analyzed steam turbine and it is compared energy and exergy losses. Cumulative exergy loss of the analyzed turbine contains additional steam loss which cannot be obtained through energy analysis of the same turbine. The variation of the ambient temperature is also performed – to investigate turbine operating parameters, exergy loss and exergy efficiency at different ambient conditions.

2. Description of the analyzed back-pressure steam turbine from CHP plant

Back-pressure steam turbine which operates in CHP plant [6] is analyzed in this paper from the energy and exergy aspect. General operating scheme of the analyzed turbine is presented in Fig. 1.

Produced power from the analyzed steam turbine is used for electricity generator drive. In the energy analysis, mechanical loss which occurs into the turbine is taken into account. In this case, steam turbine drive electricity generator directly (without the gearbox usage). If the steam turbine drives any other power consumer through the gearbox, than the mechanical loss of the gearbox also must be taken into account when calculating power amount distributed to power consumer.

Complete energy and exergy analysis of back-pressure steam turbine is based on three turbine operating points presented in Fig 1. – the first operating point is turbine inlet, the second is steam extraction and last third operating point is turbine outlet. As the exergy analysis of any component in the steam power plant is dependable on the conditions of the ambient (the ambient temperature and pressure) [7, 8] this analysis also includes variation of the ambient temperature in order to obtain turbine exergy loss and exergy efficiency at different ambient conditions.

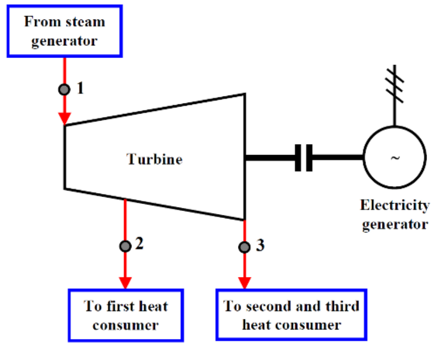

Fig. 1. *Scheme and operating points of the analyzed back-pressure steam turbine from CHP plant*

3. Equations for energy and exergy analysis

3.1. General equations

For any analyzed control volume or a system in which mass flow rate leakage does not occur is valid a following mass flow rate balance [9]:

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

where: IN = inlet (input), OUT = outlet (output), $\dot{m}$ = fluid mass flow rate (kg/s). The first law of thermodynamics gives a definition of energy analysis [10], which is completely independent of the ambient conditions in which analyzed control volume or a system operates [11]. Basic energy balance for a control volume or a system in steady state while disregarding potential and kinetic energy, according to [12, 13] is:

$$\sum \dot{m}_{\mathrm{IN}} \cdot h_{\mathrm{IN}} + \dot{Q} = \sum \dot{m}_{\mathrm{OUT}} \cdot h_{\mathrm{OUT}} + P , \tag{2}$$

where: h = fluid specific enthalpy (kJ/kg), $\dot{Q}$ = heat transfer (kW), P = produced power (kW). Energy power of any fluid flow (n), according to [14] is defined as:

$$\dot{E}_{\mathrm{EN,n}} = \dot{m}_{\mathrm{n}} \cdot h_{\mathrm{n}} , \tag{3}$$

where: $\dot{E}_{\mathrm{EN,n}}$ = energy power of fluid flow (kW), n = index for observed operating point (fluid flow). Unlike energy analysis, exergy analysis of control volume or a system is defined by the second law of thermodynamics [15]. Exergy analysis is based on the ambient conditions in which control volume or a system operates [16]. The main exergy balance equation, according to [17, 18] can be written as:

$$\sum \dot{m}_{\mathrm{IN}} \cdot \varepsilon_{\mathrm{IN}} + \dot{X}_{\mathrm{heat}} = \sum \dot{m}_{\mathrm{OUT}} \cdot \varepsilon_{\mathrm{OUT}} + P + \dot{E}_{\mathrm{EX,D}} , \tag{4}$$

where: $\dot{E}_{\mathrm{EX,D}}$ = exergy destruction = exergy loss (kW). In Eq. 4, $\dot{X}_{\mathrm{heat}}$ is the exergy transfer by heat (kW) at the temperature T (K) which is defined, according to [19, 20] as:

$$\dot{X}_{\text{heat}} = \Sigma(1 - \frac{T_0}{T}) \cdot \dot{Q}\,, \tag{5}$$

where: 0 = index of the ambient condition. The last undefined parameter from Eq. 4 is specific exergy of the fluid stream (ε), which definition can be found in [21]:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0)\,, \tag{6}$$

where: s = fluid specific entropy (kJ/kg·K). Similar to energy power of fluid flow, exergy power of any fluid flow (n) can be defined by following equation [22]:

$$\dot{E}_{\text{EX,n}} = \dot{m}_{\text{n}} \cdot \varepsilon_{\text{n}}\,, \tag{7}$$

where: $\dot{E}_{\text{EX,n}}$ = exergy power of fluid flow (kW). For any control volume or a system, general definition of exergy efficiency (η_{EX}), according to [23] is:

$$\eta_{\text{EX}} = \frac{\text{Exergy output}}{\text{Exergy input}}\,. \tag{8}$$

3.2. Energy and exergy analysis of back-pressure steam turbine from CHP plant

All the equations for the energy and exergy analysis of back-pressure steam turbine from CHP plant in this section will be based on turbine operating points from Fig. 1.

3.2.1. Energy analysis

Turbine power, without taking into account the mechanical loss, is calculated from steam expansion throughout the turbine as:

$$P_{\text{T}} = \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3)\,, \tag{9}$$

where: P_{T}= turbine power without mechanical loss (kW). Turbine real power, with taking into account the mechanical loss is:

$$P_{\text{RE}} = \left[\dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3)\right] \cdot \eta_{\text{MECH}} = P_{\text{T}} \cdot \eta_{\text{MECH}}\,, \tag{10}$$

where: P_{RE} = turbine real developed power with mechanical loss (kW), η_{MECH} = turbine mechanical efficiency (%). In the analysis is assumed that mechanical efficiency of the observed back-pressure steam turbine is equal to 97 %. From Eq. 9 and Eq. 10, analyzed turbine mechanical loss is:

$$P_{\text{MECH}} = P_{\text{T}} - P_{\text{RE}} = P_{\text{T}} - P_{\text{T}} \cdot \eta_{\text{MECH}} = P_{\text{T}} \cdot (1 - \eta_{\text{MECH}})\,, \tag{11}$$

where: P_{MECH} = turbine mechanical loss (kW). Energy power of fluid (steam) flow in each operating point of the analyzed turbine (Fig. 1) is calculated by using Eq. 3.

3.2.2. Exergy analysis

Cumulative exergy loss (cumulative exergy destruction) of the analyzed turbine is:

$$\dot{E}_{\text{EX,D,CUM}} = \dot{E}_{\text{EX,1}} - \dot{E}_{\text{EX,2}} - \dot{E}_{\text{EX,3}} - P_{\text{RE}} = \dot{E}_{\text{EX,1}} - \dot{E}_{\text{EX,2}} - \dot{E}_{\text{EX,3}} - P_{\text{T}} + P_{\text{MECH}}\,, \tag{12}$$

where: $\dot{E}_{\text{EX,D,CUM}}$ = turbine cumulative exergy loss (kW). Cumulative exergy loss of the turbine ($\dot{E}_{\text{EX,D,CUM}}$) can be divided on two different losses - the first is a steam exergy loss ($\dot{E}_{\text{EX,D,steam}}$) and the second is mechanical loss (P_{MECH}) defined by Eq. 11. Therefore, steam exergy loss is:

$$\dot{E}_{\text{EX,D,steam}} = \dot{E}_{\text{EX,1}} - \dot{E}_{\text{EX,2}} - \dot{E}_{\text{EX,3}} - P_{\text{T}}\,, \tag{13}$$

where: $\dot{E}_{\text{EX,D,steam}}$ = steam exergy loss (kW). Analyzed back-pressure steam turbine exergy efficiency is:

$$\eta_{\text{EX}} = \frac{P_{\text{RE}}}{\dot{E}_{\text{EX,1}} - \dot{E}_{\text{EX,2}} - \dot{E}_{\text{EX,3}}} = \frac{P_{\text{T}} \cdot \eta_{\text{MECH}}}{\dot{E}_{\text{EX,1}} - \dot{E}_{\text{EX,2}} - \dot{E}_{\text{EX,3}}}\,. \tag{14}$$

Exergy power of fluid (steam) flow in each operating point of the analyzed turbine (Fig. 1) is calculated by using Eq. 7.

4. Steam operating parameters of the analyzed back-pressure turbine

Steam operating parameters (pressure, temperature and mass flow rate) in each operating point of the analyzed back-pressure turbine (Fig. 1) were found in [6] and presented in Table 1. In all operating points steam is superheated.

Table 1. *Steam operating parameters in each operating point of analyzed back-pressure turbine [6]*

Operating point*	Pressure (bar)	Temperature (°C)	Mass flow rate (kg/s)
1	84.0	500.0	103.7
2	11.0	232.5	15.6
3	3.5	147.0	88.1

***** Operating points refer to Fig. 1.

To perform complete energy and exergy analysis along with calculation of losses, steam operating parameters from Table 1 is used for calculation of specific enthalpy, specific entropy and specific exergy again in each operating point of the observed turbine. Those operating parameters were calculated by using NIST-REFPROP 9.0 software [24] and presented in Table 2.

Table 2. *Steam specific enthalpy, specific entropy and specific exergy in each operating point of analyzed turbine*

Operating point*	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Specific exergy (kJ/kg)
1	3394.7	6.70	1401.80
2	2899.8	6.80	876.91
3	2750.4	6.99	672.54

***** Operating points refer to Fig. 1.

Steam specific exergies in Table 2 are calculated for the base ambient state which is in this paper selected as: the ambient pressure = 1 bar, the ambient temperature = 25 °C = 298 K.

5. The results of performed analysis and discussion

5.1. Back-pressure steam turbine energy and exergy losses at the base ambient state

In Fig. 2 are presented energy flow streams throughout the analyzed steam turbine (steam energy streams at turbine inlet, outlet and at turbine extraction). While neglecting steam mass flow rates lost on the turbine front and rear gland seals, cumulative produced power of the analyzed turbine (power without taking into account the mechanical loss) is equal to the steam energy flow stream at the turbine inlet lowered for steam energy flow streams at turbine outlet and at turbine extraction.

A power which will be used for any power consumer drive (in this case electricity generator drive) is lower (in comparison with power without taking into account the mechanical loss) for mechanical loss into the analyzed turbine. The calculation of this power is ensured with Eq. 10 (power with taking into account the mechanical loss). According to steam operating parameters of the analyzed back-pressure turbine (Table 1 and Table 2), mechanical loss is equal to 1934.50 kW, while power for the electricity generator drive will be equal to 62548.77 kW, Fig. 2. It should be noted that if the power consumer is driven by the analyzed turbine indirectly (by using gearbox) mechanical power delivered to such power consumer should be additionally lowered for mechanical loss in the gearbox.

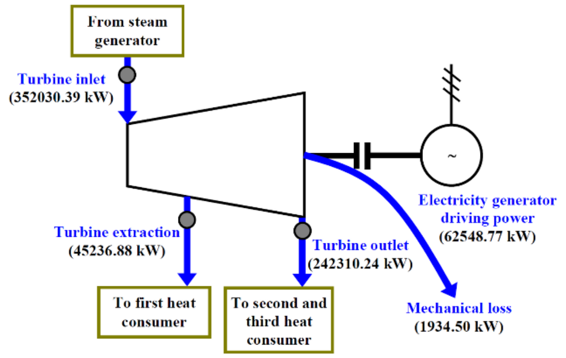

Fig. 2. *Energy flow streams of the analyzed back-pressure steam turbine*

Exergy flow streams and exergy loss throughout the analyzed back-pressure turbine at the base ambient state are presented in Fig. 3. First of all, it should be noted that steam exergy streams (at turbine inlet, outlet and at turbine extraction) are much lower when compared to the same steam energy streams (Fig. 2).

Analyzed turbine power produced, mechanical loss and power used for electricity generator drive are the same as in energy analysis (Fig. 2). As the exergy analysis takes into account the conditions of the ambient in which turbine operates, a cumulative turbine exergy loss which amount 9887.32 kW can be divided in two parts – the first is mechanical loss and the second is a steam exergy loss which is for the analyzed turbine equal to 7952.82 kW, Fig. 3. Like in energy analysis, in the turbine exergy analysis are also neglected steam mass flow rates lost through front and rear gland seals.

The analyzed back-pressure steam turbine is a good example that exergy analysis (in comparison with energy analysis) involves additional loss related to the ambient conditions.

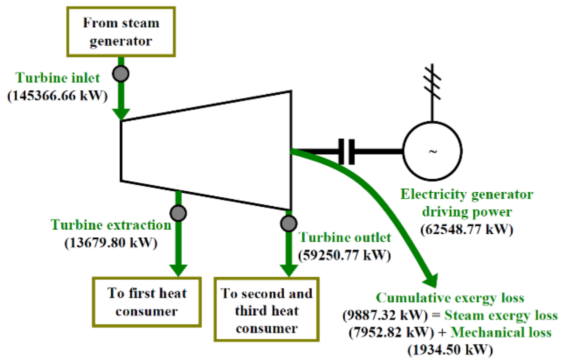

Fig. 3. *Exergy flow streams of the analyzed back-pressure steam turbine (the base ambient state)*

5.2. Back-pressure steam turbine exergy loss during the ambient temperature change

The analyzed back-pressure steam turbine has three operating points – the first is turbine inlet, the second is turbine extraction and the third is turbine outlet, Fig. 1. Exergy flow streams (steam exergy streams) in each turbine operating point, during the change in the ambient temperature are presented in Fig. 4. From Fig. 4 can clearly be seen that the change in ambient temperature significantly influenced steam exergy streams of the analyzed turbine – increase in the ambient temperature decreases each steam exergy stream in all operating points.

The ambient temperature in which analyzed turbine operates is varied from 5 °C to 55 °C. In such ambient temperature range, steam exergy stream at the turbine inlet decreases the most during the ambient temperature increase, for 32499.58 kW (from 158806.18 kW at the ambient temperature of 5 °C to 126306.6 kW at the ambient temperature of 55 °C), while the lowest decrease in the steam exergy stream during the ambient temperature increase can be observed for steam extraction (Operating point 2), Fig. 4.

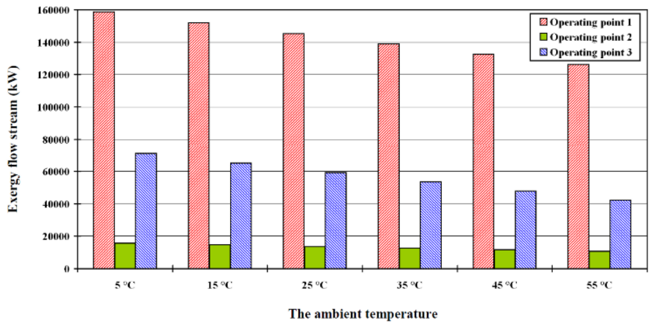

Fig. 4. *Exergy flow streams (steam exergy streams) in each operating point of the analyzed back-pressure turbine during the ambient temperature change (according to Fig. 1)*

Decrease in all analyzed turbine steam exergy streams during the increase in the ambient temperature resulted with an increase in turbine cumulative exergy loss (from 9362.71 kW at the ambient temperature of 5 °C to 10693.75 kW at the ambient temperature of 55 °C), Fig. 5. It should be noted that in cumulative turbine exergy loss, mechanical loss remains the same at all observed ambient temperatures, while steam exergy loss notably increases during the increase in the ambient temperature.

An increase in the ambient temperature simultaneously increases analyzed turbine cumulative exergy loss and decreases turbine exergy efficiency, from 86.98 % at 5 °C to 85.40 % at 55 °C. It can be concluded that an increase in the ambient temperature for 10 °C reduces analyzed back-pressure turbine exergy efficiency for less than 0.5 % on average, so the analyzed turbine exergy efficiency is not significantly influenced by the ambient temperature change. However, the ambient temperature change notably influenced analyzed turbine cumulative exergy loss which increase for 266.21 kW on average for every increase in the ambient temperature in step of 10 °C.

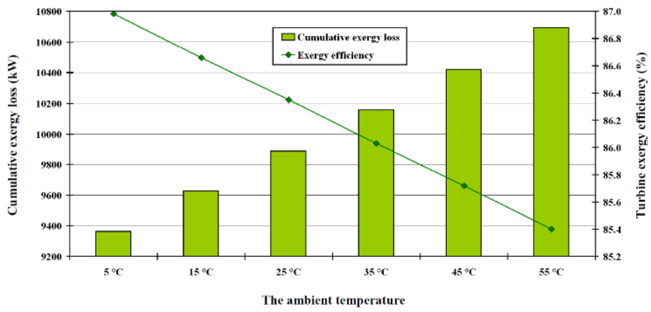

Fig. 5. *Cumulative exergy loss and exergy efficiency of analyzed steam turbine during the ambient temperature change*

Further research and possible optimization of the observed steam turbine will be performed by the application of many artificial intelligence methods and processes already developed and implemented by our research team [25-30].

6. Conclusions

In this paper is presented energy and exergy losses analysis of back-pressure steam turbine from a CHP plant. Energy analysis takes into account only mechanical loss (energy flows lost through front and rear gland seals are neglected). Exergy analysis is performed for the selected base ambient state and then the ambient temperature is varied in order to obtain the change in turbine exergy efficiency and loss. The major conclusions of this analysis are:

- Analyzed back-pressure steam turbine, for the known steam operating parameters and mechanical efficiency equal to 97 %, has mechanical loss equal to 1934.50 kW and produced 62548.77 kW of power used for electricity generator drive. Energy analysis of this (and any other steam turbine) is always the same - it did not depend on the ambient conditions in which turbine operates.

- Exergy analysis shows that cumulative exergy loss of the analyzed turbine is composed of the sum of two losses - mechanical loss and steam exergy loss. Therefore, exergy analysis takes into account additional loss related to the state of the ambient in which steam turbine operates.
- An increase in the ambient temperature resulted with a decrease in all steam exergy streams of the analyzed turbine. The most notable change in steam exergy streams during the ambient temperature change is observed for the steam stream at the turbine inlet.
- An increase in the ambient temperature reduces turbine exergy efficiency (and vice versa) but the change is small. Notable change during the ambient temperature change is observed in the turbine exergy loss. An increase in the ambient temperature for 10 °C resulted with an average decrease of analyzed turbine exergy efficiency for less than 0.5 % and simultaneously with an average increase of turbine exergy loss for 266.21 kW.

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