

Exergy analysis of three cylinder steam turbine from supercritical coal-fired power plant

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Abstract: In this paper is performed exergy analysis of three cylinder steam turbine from the supercritical coal-fired power plant. Exergy analysis parameters were calculated for the whole turbine and each cylinder for the ambient temperature range between 5 °C and 45 °C. The dominant mechanical power producer of all the cylinders is a low pressure cylinder (LPC) which produces 262.06 MW of mechanical power. An increase in the ambient temperature increases exergy destructions and decreases exergy efficiencies of the whole turbine and each cylinder. Exergy analysis shows that LPC is a cylinder with the highest exergy destruction (between 24.67 MW and 28.24 MW) and the lowest exergy efficiency (between 82.27% and 84.16%) in comparison to the other cylinders. Exergy destruction of the whole observed turbine is between 67.85 MW and 77.62 MW, while the whole turbine exergy efficiency ranges between 89.47% and 90.67%. Inside the observed steam turbine, LPC is the most influenced by the ambient temperature change, therefore future research and possible optimization should be specifically based on this cylinder.

KEYWORDS: EXERGY ANALYSIS, THREE CYLINDER STEAM TURBINE, SUPERCRITICAL POWER PLANT, THE AMBIENT TEMPERATURE VARIATION

1. Introduction

The dominant function of steam turbines worldwide is electrical generator drive and electrical power production [1-3]. Steam turbines can today be found in various power plants, such as conventional, cogeneration, combined, marine, as a part of energy systems in various industries, etc. [4-10].

Improvement of steam power plants is today obtained in various different ways [11, 12]. One of important improvements is steam superheating on the temperatures and pressures above the water critical point parameters. Such steam power plants are named supercritical and ultra-supercritical power plants [13, 14]. Due to steam high temperature and pressure, steam turbines in such power plants (especially high pressure steam turbine cylinders) must be carefully designed and maintained with an aim to minimize all the possible losses [15]. Supercritical and ultra-supercritical steam power plants have various disadvantages, but its highest benefit is much higher overall plant efficiency in comparison to conventional steam power plants [16].

From the exergy viewpoint, in this paper is analyzed three cylinder steam turbine, which operates in supercritical coal-fired power plant. Along with calculation of produced mechanical power, it is analyzed exergy destruction (exergy power loss) and exergy efficiency of each cylinder and the whole turbine during the ambient temperature change. A special attention is paid to finding of the component which is the most influenced by the ambient temperature change.

2. Description and characteristics of the analyzed three cylinder steam turbine

Scheme and operating points required for the exergy analysis of three cylinder steam turbine from supercritical coal-fired power plant are presented in Fig. 1. Nominal mechanical power produced by the whole turbine, according to [17], is 660 MW.

High Pressure Cylinder (HPC) is a single flow cylinder which consists of one steam extraction. After HPC, a small part of the steam mass flow rate is delivered to high pressure feed water heating system (operating point 4), while the remaining steam mass flow rate is delivered to steam reheater. Steam reheater in the power plant is mounted in the steam generator (due to better visibility, in Fig. 1 reheater is shown as an independent component).

After steam reheating (increasing of steam temperature), steam expands through Intermediate Pressure Cylinder (IPC) which also has one steam extraction (identical to HPC). As HPC, IPC is also a single flow cylinder. After IPC, a certain steam mass flow rates are delivered to deaerator and Main Feed water Pump Turbine (MFPT) [18], operating points 7 and 8, while the remaining steam mass flow rate (operating point 9) is delivered to Low Pressure Cylinder (LPC).

LPC is a dual flow steam turbine, which means that the steam mass flow rate enters in the middle of the cylinder, one half expand through the left part (LPC-1), while the other part of the steam mass

flow rate expand through the right part (LPC-2). In Fig. 1 LPC is divided in two parts, but all the considerations related to LPC will be performed by using only one part of LPC (the same results will be obtained if considering LPC-1 or LPC-2). The only attention is required during the calculation of LPC produced mechanical power – it will be calculated for LPC-1 and multiplied by two. After expansion in LPC, remaining steam mass flow rate from both parts of the LPC, is delivered to steam condenser for condensation [19].

The scheme shown in Fig. 1 is the most common arrangement of multi-cylinder steam turbines in thermal power plants [20]. Such arrangement is especially beneficial from the viewpoint of steam axial force self-balancing [21].

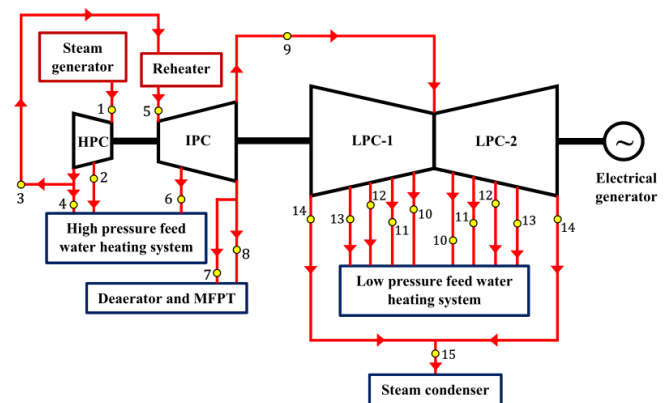


Fig. 1. Three cylinder steam turbine from coal-fired supercritical power plant along with operating points

3. Exergy analysis equations

3.1. General exergy equations, balances and principles

Exergy analysis of any component or a system is based on the second law of thermodynamics and it takes into consideration parameters of the ambient in which component or system operates [22, 23]. From this viewpoint, exergy analysis has the advantage over the energy analysis, which is based on the first law of thermodynamics and which did not take into consideration parameters of the ambient in which component or a system operates [24, 25]. Therefore, energy analysis will provide the same results if any component or a system operates at the ambient temperature of 5 °C or at the ambient temperature of 45 °C, while exergy analysis will show clear differences in the obtained results.

While disregarding kinetic and potential energies, which have a small impact on the overall balance, the overall exergy balance equation, valid for any component or a system, can be written according to recommendations from [26] as:

$$\dot{X}_{\text{HEAT}} + P_{\text{INLET}} + \sum \dot{E}x_{\text{INLET}} = P_{\text{OUTLET}} + \sum \dot{E}x_{\text{OUTLET}} + \dot{E}x_{\text{D}} \quad (1)$$

In Eq. (1), P is used or produced mechanical power in (kW), while $\dot{E}x_D$ is exergy destruction (exergy power loss) in (kW). Other two undefined variables from Eq. (1) are firstly \dot{X}_{HEAT} - the exergy transfer by heat at the temperature T in (kW), defined as [27]:

$$\dot{X}_{HEAT} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q}, \quad (2)$$

where T is temperature in (K), \dot{Q} is an energy transfer by heat in (kW) and 0 is the index related to the ambient state. $\dot{E}x$ is a total exergy power of fluid flow in (kW) defined by an equation [28]:

$$\dot{E}x = \dot{m} \cdot \varepsilon. \quad (3)$$

In Eq. (3) \dot{m} is the fluid mass flow rate in (kg/s), while ε is fluid specific exergy in (kJ/kg), defined according to [29] as:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0). \quad (4)$$

In Eq. (4), h is fluid specific enthalpy in (kJ/kg) and s is fluid specific entropy in (kJ/kg·K). The overall definition of any component or a system exergy efficiency is:

$$\eta x = \frac{\text{CUMULATIVE EXERGY OUTLET}}{\text{CUMULATIVE EXERGY INLET}}, \quad (5)$$

but is should be highlighted that for any component or a system, the proper exergy efficiency definition varies according to operating characteristics and type. In a standard operation, fluid mass flow rate leakage did not occur in any component or a system, so the valid mass flow rate balance is [30]:

$$\sum \dot{m}_{INLET} = \sum \dot{m}_{OUTLET}. \quad (6)$$

These equations, balances and principles will be used in exergy analysis of the whole observed steam turbine and each cylinder.

3.2. Exergy analysis equations of the whole observed turbine and each of its cylinders

Markings in all of the equations from this subsection are performed in relation to Fig. 1.

High Pressure Cylinder (HPC)

- Produced mechanical power:

$$P_{HPC} = \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3). \quad (7)$$

- Exergy destruction:

$$\dot{E}x_{D,HPC} = \dot{E}x_1 - \dot{E}x_2 - \dot{E}x_3 - \dot{E}x_4 - P_{HPC}. \quad (8)$$

- Exergy efficiency:

$$\eta x_{HPC} = \frac{P_{HPC}}{\dot{E}x_{D,HPC} + P_{HPC}}. \quad (9)$$

Intermediate Pressure Cylinder (IPC)

- Produced mechanical power:

$$P_{IPC} = \dot{m}_5 \cdot (h_5 - h_6) + (\dot{m}_5 - \dot{m}_6) \cdot (h_6 - h_7). \quad (10)$$

- Exergy destruction:

$$\dot{E}x_{D,IPC} = \dot{E}x_5 - \dot{E}x_6 - \dot{E}x_7 - \dot{E}x_8 - \dot{E}x_9 - P_{IPC}. \quad (11)$$

- Exergy efficiency:

$$\eta x_{IPC} = \frac{P_{IPC}}{\dot{E}x_{D,IPC} + P_{IPC}}. \quad (12)$$

Low Pressure Cylinder – left part (LPC-1); the same for right part (LPC-2)

- Produced mechanical power:

$$P_{LPC-1} = \frac{\dot{m}_9}{2} \cdot (h_9 - h_{10}) + \left(\frac{\dot{m}_9}{2} - \dot{m}_{10}\right) \cdot (h_{10} - h_{11}) + \left(\frac{\dot{m}_9}{2} - \dot{m}_{10} - \dot{m}_{11}\right) \cdot (h_{11} - h_{12}) + \left(\frac{\dot{m}_9}{2} - \dot{m}_{10} - \dot{m}_{11} - \dot{m}_{12}\right) \cdot (h_{12} - h_{13}) + \left(\frac{\dot{m}_9}{2} - \dot{m}_{10} - \dot{m}_{11} - \dot{m}_{12} - \dot{m}_{13}\right) \cdot (h_{13} - h_{14}). \quad (13)$$

- Exergy destruction:

$$\dot{E}x_{D,LPC-1} = \frac{\dot{E}x_9}{2} - \dot{E}x_{10} - \dot{E}x_{11} - \dot{E}x_{12} - \dot{E}x_{13} - \dot{E}x_{14} - P_{LPC-1}. \quad (14)$$

- Exergy efficiency:

$$\eta x_{LPC-1} = \frac{P_{LPC-1}}{\dot{E}x_{D,LPC-1} + P_{LPC-1}}. \quad (15)$$

Whole Turbine (WT)

- Produced mechanical power:

$$P_{WT} = P_{HPC} + P_{IPC} + 2 \cdot P_{LPC-1}. \quad (16)$$

- Exergy destruction:

$$\dot{E}x_{D,WT} = \dot{E}x_{D,HPC} + \dot{E}x_{D,IPC} + 2 \cdot \dot{E}x_{D,LPC-1}. \quad (17)$$

- Exergy efficiency:

$$\eta x_{WT} = \frac{P_{WT}}{\dot{E}x_{D,WT} + P_{WT}}. \quad (18)$$

4. Steam parameters required for the exergy analysis

Required steam parameters in each operating point from Fig. 1 (steam temperature, steam pressure and steam mass flow rate) are found in [17] and presented in Table 1. Other steam parameters required for the exergy analysis (steam specific enthalpy, steam specific entropy and steam quality) in each operating point of Fig. 1, are calculated from the parameters presented in Table 1, by using NIST REFPROP 9.0 software [31].

From Table 1 can be seen that HPC and IPC of the observed steam turbine operates with a superheated steam, while the last few stages of both LPC parts (LPC-1 and LPC-2) operates with wet steam (steam under the saturation line – operating points 13 and 14). Steam quality of, for example 0.97, means that in that operating point exist 97% of steam and 3% of water droplets.

Steam specific exergies in each operating point from Fig. 1 are calculated by using Eq. (4). The defined ambient parameters for steam specific exergies calculation are always the same ambient pressure equal to 1 bar, while the ambient temperature is varied from 5 °C up to 45 °C, in steps of 10 °C.

Table 1. Steam operating parameters for the exergy analysis

| O.P.* | Mass flow rate (kg/s) | Temperature (°C) | Pressure (bar) | Quality |
|-------|-----------------------|------------------|----------------|-------------|
| 1 | 532.00 | 566.0 | 242.000 | Superheated |
| 2 | 35.50 | 367.2 | 67.970 | Superheated |
| 3 | 448.40 | 315.1 | 45.670 | Superheated |
| 4 | 48.10 | 315.1 | 45.670 | Superheated |
| 5 | 448.40 | 566.0 | 41.100 | Superheated |
| 6 | 20.10 | 457.0 | 20.580 | Superheated |
| 7 | 25.40 | 362.9 | 10.650 | Superheated |
| 8 | 27.90 | 362.9 | 10.650 | Superheated |
| 9 | 375.00 | 362.9 | 10.650 | Superheated |
| 10 | 13.15 | 253.6 | 4.374 | Superheated |
| 11 | 6.55 | 128.8 | 1.333 | Superheated |
| 12 | 8.70 | 88.2 | 0.655 | Superheated |
| 13 | 6.60 | 60.9 | 0.208 | 0.970 |
| 14 | 152.50 | 35.8 | 0.059 | 0.940 |
| 15 | 305.00 | 35.8 | 0.059 | 0.940 |

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

5. Results and discussion

Produced mechanical power for the whole analyzed turbine and each cylinder is presented in Fig. 2.

LPC of the analyzed turbine produces the highest mechanical power of 262.06 MW (each part of the LPC produces 131.03 MW), while the lowest mechanical power is produced in IPC (180.77 MW). HPC produces mechanical power of 216.57 MW.

The whole analyzed turbine produces mechanical power of 659.40 MW. As the nominal mechanical power of the whole analyzed steam turbine is 660 MW, it can be concluded that data from Table 1 are given for the nominal turbine operating conditions.

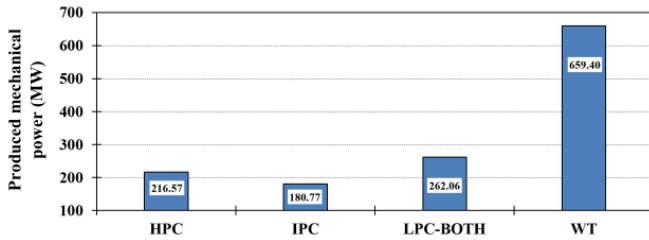


Fig. 2. Produced mechanical power of the whole analyzed turbine and each cylinder

Exergy destruction (exergy power loss) of the whole analyzed steam turbine and each cylinder at the various ambient temperatures is presented in Fig. 3.

By observing turbine cylinders, it can be seen that the highest exergy destruction is observed in LPC (between 24.67 MW and 28.24 MW), while the lowest exergy destruction is observed in IPC (between 6.11 MW and 6.94 MW). The whole analyzed steam turbine has exergy destruction between 67.85 MW and 77.62 MW.

From the ambient temperature viewpoint, it can be concluded that an increase in the ambient temperature results with increase in the exergy destruction of the whole turbine and each turbine cylinder.

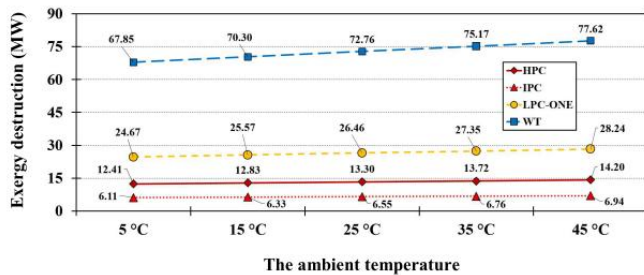


Fig. 3. Exergy destruction of the whole analyzed turbine and each cylinder at the various ambient temperatures

For the most components from steam power plant, exergy destruction and exergy efficiency are reverse proportional during the ambient temperature change. The same reverse proportionality can be seen for the analyzed steam turbine and all of its cylinders by comparing Fig. 3 and Fig. 4.

When observing exergy efficiency of the whole turbine, Fig. 4, it can be noted that the whole turbine has a much higher exergy efficiency than LPC, regardless of much higher exergy destruction, Fig. 3 and Fig. 4, at any ambient temperature.

In the considered ambient temperature range, exergy efficiency of HPC varies between 93.85% and 94.58%, of IPC between 96.30% and 96.73%, while exergy efficiency of the LPC varies between 82.27% and 84.16%. The whole turbine, in the considered ambient temperature range, has an exergy efficiency between 89.47% and 90.67%, what is expected exergy efficiency range of the whole steam turbine from supercritical steam power plant.

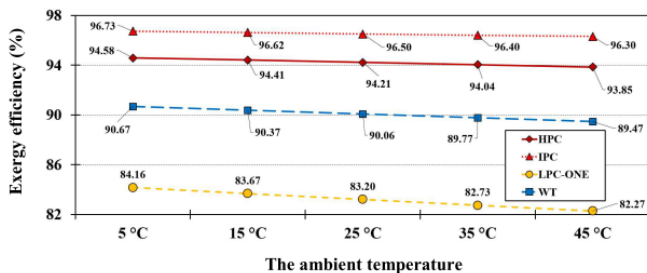


Fig. 4. The exergy efficiency of the whole analyzed turbine and each cylinder at the various ambient temperatures

The final goal of this paper is to investigate which cylinder of the observed steam turbine is the most influenced by the ambient temperature change. Therefore, the average percentage change in exergy destruction and in exergy efficiency of the whole analyzed

turbine and each cylinder between ambient temperatures 5 °C and 45 °C is presented in Fig. 5.

While observing turbine cylinders during the ambient temperature change, it should be noted that the average percentage change in exergy destruction is the highest for HPC and LPC (3.16%), while average exergy destruction percentage change of IPC is much smaller (3.02%). Therefore, from the exergy destruction viewpoint, HPC and LPC are the most influenced by the ambient temperature change.

Average percentage change in exergy efficiency of each cylinder shows that LPC exergy efficiency is much more influenced by the ambient temperature change (0.56%) in comparison to HPC (0.19%), while the IPC is the lowest influenced by the ambient temperature change also from the exergy efficiency viewpoint (0.11%).

During the ambient temperature change, average exergy destruction change of the whole analyzed turbine is equal to 3.15%, while the average exergy efficiency change is equal to 0.33%.

Therefore, the conclusion which can be derived from Fig. 5 is that in the whole observed steam turbine, LPC is the most influenced by the ambient temperature change.

Further analysis of the observed steam turbine and all of its cylinders will be performed by using various artificial intelligence methods already developed by our research team [32-34].

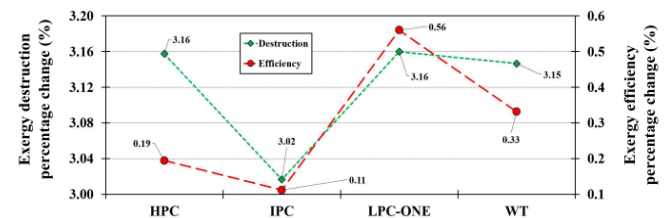


Fig. 5. Average percentage change in exergy destruction and in exergy efficiency of the whole analyzed steam turbine and each cylinder between ambient temperatures 5 °C and 45 °C

6. Conclusions

In this paper is performed an analysis of three cylinder steam turbine from the supercritical coal-fired power plant. Exergy destruction (exergy power loss) and exergy efficiency of each cylinder and the whole turbine during the ambient temperature change were analyzed. The most important conclusions from the performed analysis are:

- Considering all the cylinders, LPC produces the highest mechanical power equal to 262.06 MW (each part of the LPC produces 131.03 MW), followed by HPC (216.57 MW), while the lowest mechanical power is produced in IPC (180.77 MW).
- Exergy destruction and exergy efficiency of turbine cylinders are reverse proportional. LPC has the highest exergy destruction (between 24.67 MW and 28.24 MW) and the lowest exergy efficiency (between 82.27% and 84.16%). IPC has the lowest exergy destruction (between 6.11 MW and 6.94 MW) and consequently the highest exergy efficiency (between 96.30% and 96.73%).
- The exergy destruction of the whole observed turbine is between 67.85 MW and 77.62 MW, while the whole turbine exergy efficiency ranges between 89.47% and 90.67%, what are expected values for steam turbine from supercritical steam power plant.
- Inside the whole observed steam turbine, LPC is the most influenced by the ambient temperature change, followed by HPC, while IPC is the cylinder which exergy efficiency and exergy destruction will be the lowest influenced by the ambient temperature change.

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