Thermodynamic analysis of steam turbine and condenser from combined cycle power plant

Mrzljak Vedran[1], Prpić-Oršić Jasna[1], Baressi Šegota Sandi[2], Lorencin Ivan[2]
[1]Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia
[2]Faculty of Informatics, Juraj Dobrila University of Pula, 52100 Pula, Croatia
E-mail: vedran.mrzljak@riteh.uniri.hr, jasna.prpic.orsic@riteh.uniri.hr, sandi.baressi.segota@unipu.hr, ivan.lorencin@unipu.hr

Abstract: *Energy and exergy analyses results of steam turbine and steam condenser, which operate in commercial combined cycle power plant are presented in this paper. Energy analysis shows that steam turbine has high energy (isentropic) loss equal to 71.71 MW, and very low energy (isentropic) efficiency of 58.79% only. Simultaneously, steam condenser is an almost perfect component from the energy viewpoint. At the base ambient state, steam turbine has high exergy destruction of 61.80 MW and low exergy efficiency of 62.34%, so both used analyses show that steam turbine operation can and should be notably improved. Steam condenser has an exergy destruction of 17.12 MW and exergy efficiency of 55.17% at the base ambient state, what are acceptable results. Observed steam condenser is much more sensitive to the ambient temperature change than steam turbine. Increase in the ambient temperature from 5 °C to 35 °C decreases steam condenser exergy efficiency for 35.90%, while the same increase in the ambient temperature decreases steam turbine exergy efficiency for 2.39% only.*

KEYWORDS*: ENERGY ANALYSIS, EXERGY ANALYSIS, STEAM TURBINE, STEAM CONDENSER, THE AMBIENT TEMPERATURE CHANGE*

1. Introduction

Due to the high efficiency, combined cycle power plants are standard and often used power systems in the entire energy sector [1, 2]. These plants offer many benefits, however, its shortcomings must always be considered and cannot be neglected [3].

Combined cycle power plants are composed of two parts – the first part is related to the gas turbine (or more of them) and the second part is related to the steam turbine (or more of them) [4]. Combustion gases from the gas turbine are not released to the atmosphere, they are used in HRSG (Heat Recovery Steam Generator) which produces steam for the steam turbine. Therefore, HRSG represents a connection between gas turbine and steam turbine parts of the combined cycle power plant [5]. As the heat from gas turbine exhaust is effectively used in HRSG (heat utilization for the steam production), efficiency of combined cycle power plant is notably higher in comparison to the individual gas turbine or steam turbine power plant [6, 7].

Steam turbines in combined cycle power plants can be composed of only one or several cylinders, they can be arranged in various configurations, but they always drive an electric generator for the electricity production [8, 9]. Steam after steam turbines in combined cycle power plants have low pressure and temperature and must be delivered to steam condenser for condensation [10, 11].

In this paper are performed energy and exergy analyses of the steam turbine and its corresponding steam condenser from the commercial combined cycle power plant. It is presented did both components show the expected performance. A statement from the available literature that energy analysis should be avoided for any heat exchanger is confirmed in the observed steam condenser. It is investigated and presented which component is more influenced by the ambient temperature change (from the exergy viewpoint).

2. Description and operating characteristics of the analyzed steam turbine and steam condenser

Simplified scheme of the analyzed steam turbine and steam condenser is presented in Fig. 1. Observed steam turbine and steam condenser are constituent components of the combined cycle power plant [12]. However, in this paper both steam turbine and steam condenser will be observed as independent components.

Steam turbine analyzed in this paper gets steam of the highest possible pressure and temperature inside combined cycle power plant from HRSG, operating point 1, Fig. 1. Steam turbine did not possess any steam extraction, so the entire steam mass flow rate delivered to the turbine inlet expands through the turbine until the outlet, operating point 2, Fig. 1. Mechanical power produced in the steam turbine stages is used for the electric generator drive and electricity production.

From the turbine outlet, entire steam mass flow rate is delivered to the steam condenser, Fig. 1. It should be highlighted that at the turbine outlet steam is still superheated (operating point 2, Fig. 1), so the observed steam condenser has two functions: first function is steam cooling and after cooling when the steam is in the two-phase zone (wet steam) the second condenser function is steam condensing. Analyzed steam condenser is counter flow heat exchanger in which steam from the steam turbine transfer heat to the cooling water through the pipe wall (two convections and conduction through the pipe wall). After heat transfer, obtained condensate (operating point 3, Fig. 1) is delivered to the condensate pump. Steam condenser cooling is performed by using cooling water – colder cooling water is delivered to the condenser (operating point 4, Fig. 1) and warmer cooling water, after the heat transfer (operating point 5, Fig. 1) exits steam condenser. Analyzed steam condenser is similar to marine steam condensers which, in some operating regimes (at low plant loads), along with condensation must ensure steam cooling [13].

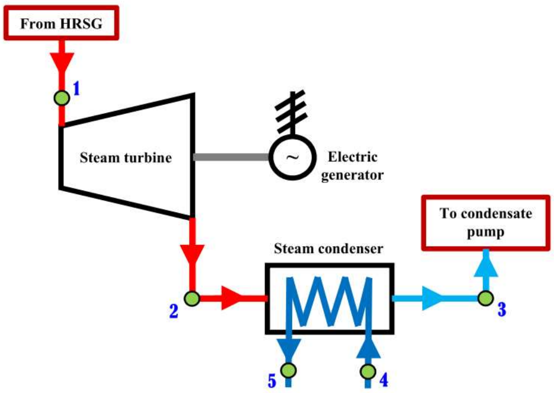


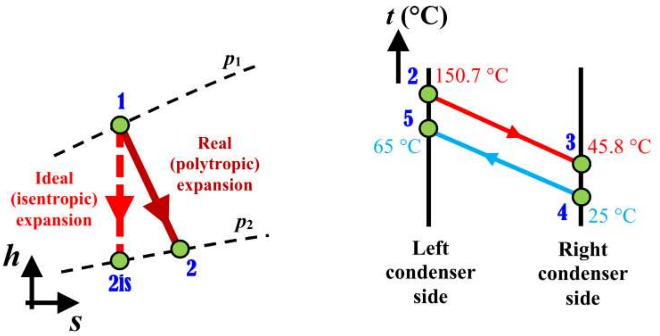
Fig. 1. *General scheme of the analyzed steam turbine and steam condenser along with marked operating points required for the energy (isentropic) and exergy analyses*

Exergy analysis of both steam turbine and steam condenser is performed by using data from the plant exploitation [12]. In the exergy analysis of any plant or a component, only data from the real exploitation conditions are required, there is no need for any comparison with ideal processes.

Energy analysis did not consider parameters of the ambient and therefore, it cannot be performed in a same manner as exergy analysis for any system or a component. For a steam condenser, energy analysis is performed in a standard way (steam condenser is considered as counter flow heat exchanger with two fluid flow streams). Temperatures of both fluid flow streams at the left and right condenser side (at the steam condenser input and output) are presented in Fig. 2 (b).

Considering steam turbine, energy analysis is actually isentropic analysis which shows a comparison between real (polytropic) and ideal (isentropic) steam expansion processes [14]. Regardless of the observed steam expansion process in the turbine, performed energy (isentropic) analysis did not consider the ambient parameters in any way. Real (polytropic) steam expansion process in turbine (process between operating points 1 and 2, Fig. 2 (a)) is defined by the increase in steam specific entropy. Mentioned increase in steam specific entropy during expansion represents losses which occur in the turbine stages. In comparison to real expansion process, ideal (isentropic) steam expansion process (process between operating points 1 and 2is, Fig. 2 (a)) did not consider any losses in the turbine, so steam specific entropy during ideal expansion remains always the same. For both ideal and real turbine expansion processes, inlet and outlet steam pressures are the same. Steam turbine is a mechanical power producer, so in the ideal (isentropic) expansion process, turbine will produce the highest possible mechanical power. The same steam turbine in the real (polytropic) expansion process will produce lower mechanical power in comparison to the ideal process (because real process involves all losses which occur during expansion) [15].

Operating points of the steam turbine and steam condenser presented in both Fig. 2 parts are consistent with operating points from Fig. 1.



(a) (b)

Fig. 2. *Turbine and condenser processes: (a) Ideal and real expansion in the turbine for the energy (isentropic) analysis, (b) Fluid temperatures during the heat exchange in the condenser*

3. Energy and exergy analyses equations

In the energy (isentropic) analysis of any system or component, the ambient parameters (ambient pressure and temperature) are not considered, what means that energy (isentropic) analysis is independent of the environment [16, 17]. In contrast to energy (isentropic) analysis, exergy analysis considers the ambient parameters, therefore, in exergy analysis are considered different kinds of losses in comparison to energy (isentropic) analysis [18, 19]. It should be highlighted that in real exploitation conditions the change in ambient pressure is small and it did not have a notable influence on any system or component exergy parameters, however, the ambient temperature change can be significant and it notably influences exergy parameters of any observed system or component [20]. Energy (isentropic) and exergy analyses equations of the observed steam turbine and steam condenser are defined according to recommendations from the literature [21, 22] as well as by using operating points numeration presented in Fig. 1 and Fig. 2.

3.1. Energy analysis equations of the steam turbine and steam condenser

Turbine:

- Real (polytropic) mechanical power:

$$P_{\text{re,Turbine}} = \dot{m}_1 \cdot (h_1 \text{-} h_2)\ , \tag{1}$$

where P is mechanical power, re is an index of real (polytropic) steam expansion process, $\dot{m}$ is fluid (steam) mass flow rate and h is fluid specific enthalpy.

- Ideal (isentropic) mechanical power:

$$P_{\text{id,Turbine}} = \dot{m}_1 \cdot (h_1 \text{-} h_{2\text{is}})\ , \tag{2}$$

where id is an index of ideal (isentropic) expansion process.

- Energy (isentropic) loss:

$$En_{\text{Loss,Turbine}} = P_{\text{id,Turbine}} - P_{\text{re,Turbine}}\ , \tag{3}$$

where En is marking for the energy analysis.

- Energy (isentropic) efficiency:

$$\eta_{\text{En,Turbine}} = \frac{P_{\text{re,Turbine}}}{P_{\text{id,Turbine}}}\ , \tag{4}$$

where η is efficiency. Markings presented in the above four equations remain the same also in all other equations below.

Condenser:

- Total energy input:

$$En_{\text{Input,Condenser}} = \dot{m}_2 \cdot h_2 - \dot{m}_3 \cdot h_3\ . \tag{5}$$

- Total energy output:

$$En_{\text{Output,Condenser}} = \dot{m}_5 \cdot h_5 - \dot{m}_4 \cdot h_4\ . \tag{6}$$

- Energy loss:

$$En_{\text{Loss,Condenser}} = En_{\text{Input,Condenser}} - En_{\text{Output,Condenser}}\ . \tag{7}$$

- Energy efficiency:

$$\eta_{\text{En,Condenser}} = \frac{En_{\text{Output,Condenser}}}{En_{\text{Input,Condenser}}}\ . \tag{8}$$

3.2. Exergy analysis equations of the steam turbine and steam condenser

Turbine:

- Total exergy input:

$$Ex_{\text{Input,Turbine}} = \dot{m}_1 \cdot \varepsilon_1\ , \tag{9}$$

where Ex is marking for the exergy analysis and ε is fluid specific exergy.

- Total exergy output:

$$Ex_{\text{Output,Turbine}} = \dot{m}_2 \cdot \varepsilon_2 + P_{\text{re,Turbine}}\ . \tag{10}$$

- Exergy destruction:

$$Ex_{\text{Destruction,Turbine}} = Ex_{\text{Input,Turbine}} - Ex_{\text{Output,Turbine}}\ . \tag{11}$$

- Exergy efficiency:

$$\eta_{\text{Ex,Turbine}} = \frac{P_{\text{re,Turbine}}}{\dot{m}_1 \cdot \varepsilon_1 - \dot{m}_2 \cdot \varepsilon_2}\ . \tag{12}$$

Condenser:

- Total exergy input:

$$Ex_{\text{Input,Condenser}} = \dot{m}_2 \cdot \varepsilon_2 - \dot{m}_3 \cdot \varepsilon_3\ . \tag{13}$$

- Total exergy output:

$$Ex_{\text{Output,Condenser}} = \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_4 \cdot \varepsilon_4\ . \tag{14}$$

- Exergy destruction:

$$Ex_{\text{Destruction,Condenser}} = Ex_{\text{Input,Condenser}} - Ex_{\text{Output,Condenser}}\ . \tag{15}$$

- Exergy efficiency:

$$\eta_{\text{Ex,Condenser}} = \frac{Ex_{\text{Output,Condenser}}}{Ex_{\text{Input,Condenser}}}\ . \tag{16}$$

4. Steam and condensate operating parameters for the energy (isentropic) and exergy analyses

Operating parameters of steam and condensate (water) in real exploitation process are found in [12] and presented in Table 1. Operating parameters which are not known from the literature in each operating point from Fig. 1 are calculated by using NIST-REFPROP 9.0 software [23]. It should be highlighted that at the end of ideal (isentropic) steam expansion process in the turbine (operating point 2is, Fig. 2 (a)), steam specific enthalpy is equal to 2240 kJ/kg – this specific enthalpy is required for the turbine ideal mechanical power calculation.

The exergy analysis baseline for any system or component is the definition of the base ambient state [24]. In the exergy analysis performed in this paper, the base ambient state is defined by the ambient temperature of 25 °C and the ambient pressure of 1 bar.

Table 1. *Steam operating parameters from turbine and condenser exploitation (real process)*

O. P.*	Temp. (°C)	Press. (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality (-)**	Specific exergy (kJ/kg)***
1	575.4	106.4	131.9	3559.20	6.8000	SH	1536.40
2	150.7	0.2	131.9	2783.70	8.3712	SH	292.37
3	45.8	0.1	131.9	191.78	0.6491	SC	2.81
4	25.0	3.0	2044.0	105.10	0.3672	SC	0.20
5	65.0	3.0	2044.0	272.34	0.8935	SC	10.51

* O. P. = Operating point (in accordance to Fig. 1)
** SH = Superheated steam; SC = Subcooled (condensate)
*** At the base ambient state

5. Results and discussion

Energy (isentropic) analysis results of the steam turbine are presented in Fig. 3.

Ideal (isentropic) steam expansion process in the turbine did not consider any losses, so the ideal mechanical power which can theoretically be developed in the turbine is always higher in comparison to the real mechanical power. Ideal mechanical power cannot be developed by the turbine in real exploitation conditions, but it can be a guideline for any turbine improvements and modifications. Real mechanical power is calculated from the real (polytropic) steam expansion process in the turbine which considers all losses during expansion. Observed steam turbine has high energy (isentropic) loss equal to 71.71 MW, and very low energy (isentropic) efficiency of 58.79% only. Considering the fact that observed turbine develop more than 100 MW of mechanical power in real exploitation conditions, obtained energy (isentropic) efficiency is too low for such turbine (it is in the range of low power auxiliary steam turbines [25]). Therefore, steam turbine energy (isentropic) analysis shows that its operation is far from optimal and that it can be notably improved.

Energy analysis results of the steam condenser are not presented. For heat exchangers in general, available literature suggests to avoid energy analysis because it is highly dependable on the accuracy and precision of measuring equipment which is used for obtaining operating parameters [26]. Moreover, any properly operating heat exchanger will always have extremely high energy efficiency (just slightly lower than 100%) and very low energy loss (which can almost be neglected). The same is obtained in the energy analysis of the observed steam condenser. For heat exchangers, only the exergy analysis can be recommended.

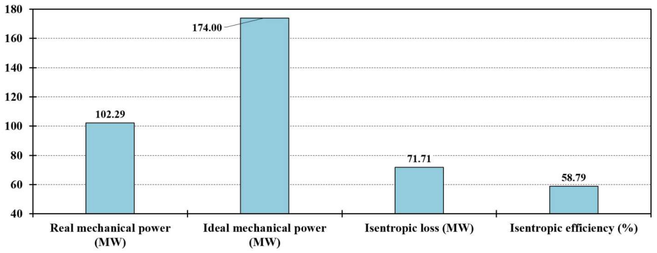


Fig. 3. *Results of the steam turbine energy (isentropic) analysis*

Exergy analysis results of the steam turbine and steam condenser at the base ambient state are presented in Fig. 4.

Comparison of steam turbine and steam condenser total exergy inputs and outputs show that steam condenser has notably lower both total exergy inputs and outputs. Steam turbine has high exergy destruction of 61.80 MW and low exergy efficiency of 62.34%. For a steam turbine which develops real (polytropic) mechanical power higher than 100 MW, Fig. 3, also exergy analysis shows very high exergy destruction and too low exergy efficiency. Both energy and exergy analyses of the observed steam turbine show that its operation can and should be notably improved.

Steam condenser has exergy destruction of 17.12 MW and exergy efficiency of 55.17%, what is in the range of similar steam condensers from the literature [27].

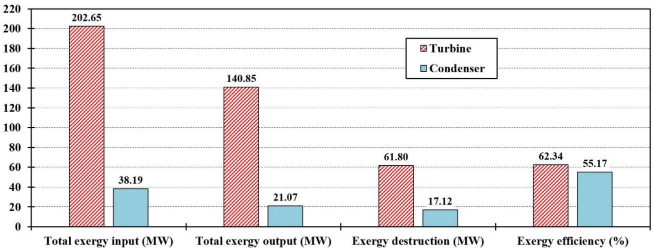


Fig. 4. *Results of the steam turbine and steam condenser exergy analysis at the base ambient state*

Observed steam turbine and steam condenser are also analyzed during the ambient temperature change. Both steam turbine and steam condenser are observed in the ambient temperature range from 5 °C up to 35 °C in steps of 10 °C, Fig. 5. Regardless of the ambient temperature, ambient pressure remains always the same and identical as at the base ambient state. In real exploitation, ambient pressure change is small and its influence on the observed steam turbine or steam condenser exergy parameters can be neglected.

For both steam turbine and steam condenser, increase in the ambient temperature simultaneously increases exergy destruction and decreases exergy efficiency, Fig. 5.

It is clear that steam condenser is much more sensitive to the ambient temperature change than steam turbine. At the ambient temperature of 5 °C steam condenser exergy efficiency is equal to 72.72% and it decreases to 36.82% at the ambient temperature of 35 °C (decrease in exergy efficiency of 35.90%), while in the same temperature range steam turbine exergy efficiency decreases for 2.39% only (from 63.95% up to 61.56%).

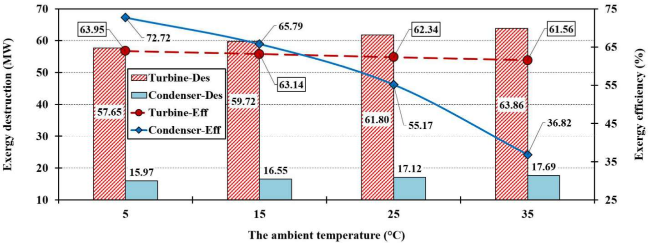


Fig. 5. *Results of the steam turbine and steam condenser exergy analysis during the ambient temperature change*

In further research related to the steam turbine and steam condenser analyzed in this paper will be applied various artificial intelligence procedures with the main aim to optimize performance of both components. As such procedures gives many beneficial results in improving various systems and components from the energy sector [28, 29], it can be expected that performance of the analyzed steam turbine and steam condenser will be notably improved.

6. Conclusions

In this paper are presented energy and exergy analyses results of steam turbine and steam condenser, which operate in commercial combined cycle power plant. For both steam turbine and steam condenser, exergy analysis is performed at the base ambient state and during the ambient temperature variation. The most important conclusions of the performed research are:

- Energy analysis shows that steam turbine has high energy (isentropic) loss equal to 71.71 MW, and very low energy (isentropic) efficiency of 58.79% only, which is in the range of low power auxiliary steam turbines.

- From the energy viewpoint, steam condenser is an almost perfect component. For the observed steam condenser, as well as for any other heat exchanger, only the exergy analysis can be recommended.
- At the base ambient state, steam turbine has high exergy destruction of 61.80 MW and low exergy efficiency of 62.34%. Therefore, both energy and exergy analyses show that steam turbine operation can and should be notably improved.
- Steam condenser has an exergy destruction of 17.12 MW and exergy efficiency of 55.17% at the base ambient state, what is in the range of similar steam condensers.
- For both steam turbine and steam condenser, increase in the ambient temperature simultaneously increases exergy destruction and decreases exergy efficiency.
- Steam condenser is much more sensitive to the ambient temperature change than steam turbine. Increase in the ambient temperature from 5 °C to 35 °C decreases steam condenser exergy efficiency for 35.90%, while the same increase in the ambient temperature decreases steam turbine exergy efficiency for 2.39% only.

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