Energy analysis of two-cylinder steam turbine from nuclear power plant

Mrzljak Vedran[1], Prpić-Oršić Jasna[1], Baressi Šegota Sandi[1], Medica-Viola Vedran[1]
[1]Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia
E-mail: vedran.mrzljak@riteh.hr, jasna.prpic-orsic@riteh.hr, sbaressisegota@riteh.hr, vmedica@riteh.hr

Abstract: *In this paper, two-cylinder steam turbine, which operates in nuclear power plant is analyzed from the energy viewpoint. Along with the whole turbine, energy analysis is performed for each turbine cylinder (High Pressure Cylinder – HPC and Low Pressure Cylinder – LPC). A comparison of both cylinders shows that the dominant mechanical power producer is LPC, which also has much higher energy loss and much lower energy efficiency. Therefore, any potential improvement of this steam turbine should be based dominantly on the LPC, which also has a dominant influence on energy analysis parameters of the whole observed turbine. The whole turbine produces real (polytropic) mechanical power equal to 1247.69 MW, has energy loss equal to 352.70 MW and energy efficiency equal to 77.96%. According to obtained energy efficiency value it can be concluded that the whole analyzed steam turbine is comparable to main marine propulsion steam turbines, while its energy efficiency is much lower in comparison to steam turbines from conventional steam power plants which operates by using superheated steam.*

KEYWORDS: TWO-CYLINDER STEAM TURBINE, NUCLEAR POWER PLANT, ENERGY LOSSES, ENERGY EFFICIENCIES

1. Introduction

The highest percentage of electrical power worldwide is produced by using various steam turbines. Steam turbines today can be found not only in many different power plants [1-5] but also it can be used in ship steam propulsion systems [6-8], for simultaneous production of heat and electrical power [9, 10], and for various other purposes.

Nuclear power plants also use steam turbines for the electrical power production. The specificity of such steam turbines can be found in a fact that they dominantly operate with wet steam, while the most steam turbines from other power plants dominantly operate by using superheated steam [11]. The reason of wet steam usage in nuclear power plants is steam temperature and pressure, which are much lower in comparison to conventional steam power plants and which are limited according to nuclear reactor specifications. On the other side, nuclear reactors produced high steam mass flow rate, much higher than is produced in conventional steam power plants [12, 13]. Due to condensate droplets, wet steam brings several additional losses in the turbine inner process which did not occur when turbine operates by using superheated steam.

In this paper is performed energy analysis of a steam turbine from nuclear power plant. It is detected which cylinder has the dominant influence of the whole turbine energy analysis parameters. Also, it is detected cylinder which should be a baseline for further improvement of the analyzed steam turbine and its process. According to obtained energy analysis parameters, the whole observed steam turbine is compared with other steam turbines from conventional and marine steam power plants.

2. Scheme and operating characteristics of two-cylinder steam turbine from nuclear power plant

The scheme of the analyzed steam turbine, which operates in nuclear power plant is presented in Fig. 1. Steam turbine consists of two cylinders: High Pressure Cylinder (HPC) and Low Pressure Cylinder (LPC). Both cylinders are connected to the same shaft which drives an Electrical Generator (EG).

Steam produced in the nuclear reactor cycle is delivered from steam generators to the HPC. HPC has one steam extraction through which a certain steam mass flow rate is delivered to high pressure feed water heating system. Remaining steam mass flow rate, after expansion in HPC, is sent to reheating system.

Reheating process in the analyzed nuclear power plant is performed in a standard configuration – this process consists of moisture separation firstly and then steam reheating. In a moisture separation process, obtained condensate from wet steam is delivered to high pressure feed water heating system, therefore the steam mass flow rate at the HPC outlet (operating point 3, Fig. 1) will be higher than the steam mass flow rate at the LPC inlet (operating point 4, Fig. 1). Steam reheating is performed with a certain amount of additional steam of the highest temperature and pressure in the process, taken directly from steam generators. So, reheater in nuclear power plant is steam-steam heat exchanger [14]. Moisture separation and steam reheating processes occur between HPC and LPC.

LPC of the analyzed turbine has four steam extractions. Steam mass flow rate extracted in each LPC extraction is delivered to low pressure condensate heating system. After expansion in the LPC, remaining steam mass flow rate is delivered to the main condenser for condensation [15]. It should be highlighted that in this analysis all additional losses related to a steam turbine and both of its cylinders (steam mass flow rate leakage through gland seals, losses in power transmission, heat losses, etc. [16, 17]) are neglected.

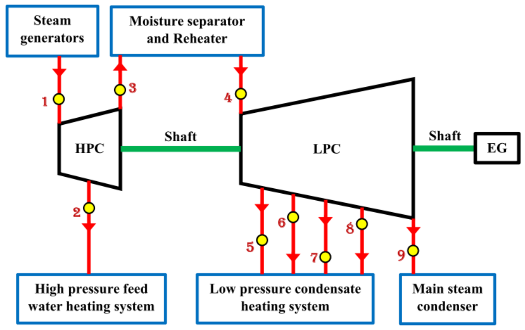

Fig. 1. *Scheme of the two-cylinder steam turbine from nuclear power plant and operating points necessary for the energy analysis*

3. Steam operating parameters required for the analysis and h-s diagram of the analyzed turbine

Steam operating parameters (pressure, temperature, mass flow rate and quality) in each operating point from Fig. 1 are found in [18] and presented in Table 1.

Table 1. *Steam operating parameters of the observed turbine for real (polytropic) expansion*

O.P.*	Temperature (°C)	Pressure (bar)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality	Mass flow rate (kg/s)
1	282.10	66.220	2771.4	5.832	0.9961	1943.04
2	219.22	22.850	2602.2	5.886	0.8933	161.49
3	186.62	11.650	2519.2	5.959	0.8676	1781.55
4	237.70	11.080	2911.3	6.820	Superheated	1456.71
5	164.30	4.960	2777.6	6.893	Superheated	66.96
6	125.77	2.378	2654.5	6.920	0.9727	83.36
7	96.41	0.891	2499.9	6.938	0.9250	116.34
8	55.05	0.158	2386.9	7.339	0.9100	69.92
9	40.61	0.0763	2325.5	7.450	0.8964	1120.13

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

Steam quality equal to 1 denotes dry saturated steam, while steam quality equal to 0 denotes condensate. Steam specific enthalpy and steam specific entropy in each operating point from Fig. 1 are also presented in Table 1 – they are calculated from known steam pressure, temperature and quality by using NIST REFPROP 9.0 software [19]. All the operating parameters presented in Table 1 are related to real (polytropic) steam expansion process.

Ideal (isentropic) steam expansion process of any cylinder (valid for any cylinder of any turbine, not only for the observed turbine) is the process which begins at the same operating point as the real (polytropic) expansion process. In ideal steam expansion process in each cylinder, steam expand between the same pressures with identical steam mass flow rates as in the real process, but assuming always the same steam specific entropy as at the beginning of the expansion. Therefore, steam operating parameters for the ideal (isentropic) expansion process are obtained mathematically and presented in Table 2. In Table 2 can be clearly seen that the pressures and mass flow rates are identical as in Table 1, while steam specific entropies are always the same for each cylinder. Operating points related to ideal (isentropic) steam expansion process are marked with the same numbers as in Table 1 and Fig. 1, but with an addition of abbreviation – is.

Table 2. *Steam operating parameters of the observed turbine for ideal (isentropic) expansion*

O.P.*	Pressure (bar)	Mass flow rate (kg/s)	Specific entropy (isentropic expansion) (kJ/kg·K)	Specific enthalpy (isentropic expansion) (kJ/kg)
1	66.220	1943.04	5.8317	2771.4
2is	22.850	161.49	5.8317	2575.2
3is	11.650	1781.55	5.8317	2460.7
4	11.080	1456.71	6.8195	2911.3
5is	4.960	66.96	6.8195	2746.1
6is	2.378	83.36	6.8195	2614.6
7is	0.891	116.34	6.8195	2456.2
8is	0.158	69.92	6.8195	2216.4
9is	0.0763	1120.13	6.8195	2127.6

* O.P. = Operating Point (according to Fig. 2)

According to data from Table 1 and Table 2 is drawn h-s diagram for the ideal (isentropic) and real (polytropic) steam expansion processes through both analyzed turbine cylinders, Fig. 2. Between the HPC and LPC occur moisture separation and steam reheating processes which resulted with an increase in steam specific enthalpy (between operating points 3 and 4). It also should be noted that almost entire steam expansion process in both observed turbine cylinders occurs under the saturation line (only operating points 4 and 5 are in the superheated steam area), Fig. 2. Almost the entire turbine operation under the saturation line is the characteristic not only for the observed, but also for any other steam turbine which operate in nuclear power plant [20].

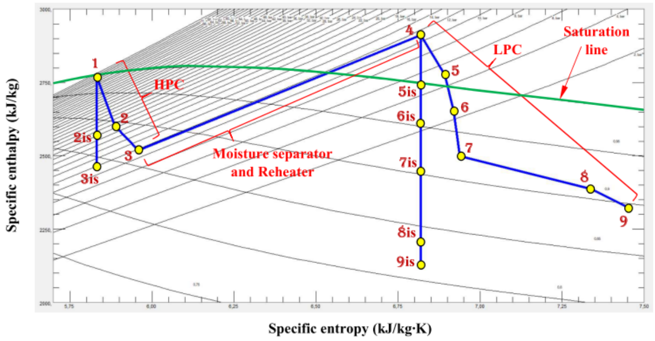

Fig. 2. *Ideal (isentropic) and real (polytropic) steam expansion processes in h-s diagram through both analyzed turbine cylinders (drawn according to data from Table 1 and Table 2, using [19])*

4. Energy analysis equations

4.1. General energy analysis equations and balances

The first law of thermodynamics defines energy analysis of any system or a control volume [21, 22]. While disregarding potential and kinetic energies, which have a low influence on the entire energy balance, energy balance equation of any system or a control volume can be written as [23]:

$$\left(\dot{Q} + P + \sum \dot{E}n\right)_{\text{inlet}} = \left(\dot{Q} + P + \sum \dot{E}n\right)_{\text{outlet}}. \tag{1}$$

In the above equation, P is mechanical power and $\dot{Q}$ is energy transfer by heat. $\dot{E}n$ is a total energy power of fluid flow, defined according to [24] as:

$$\dot{E}n = \dot{m} \cdot h. \tag{2}$$

In Eq. 2, $\dot{m}$ is a fluid mass flow rate and h is fluid specific enthalpy (fluid energy content). During any system or a control volume operation, fluid mass flow rate leakage usually did not occur, therefore the valid mass flow rate balance is [25]:

$$\sum \dot{m}_{\text{inlet}} = \sum \dot{m}_{\text{outlet}}. \tag{3}$$

The overall definition of any system or a control volume energy efficiency is [26]:

$$\eta_{\text{en}} = \frac{\text{cumulative energy outlet}}{\text{cumulative energy inlet}}. \tag{4}$$

Presented equations and balances will be used in energy analysis of the whole observed steam turbine and each of its cylinders.

4.2. Energy analysis equations of the observed steam turbine

Markings in all the equations presented in this section will be related to operating points from Fig. 1 and Fig. 2.

High Pressure Cylinder (HPC)

- Real (polytropic) and ideal (isentropic) mechanical power:

$$P_{\text{re,HPC}} = \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3), \tag{5}$$

$$P_{\text{id,HPC}} = \dot{m}_1 \cdot (h_1 - h_{2\text{is}}) + (\dot{m}_1 - \dot{m}_2) \cdot (h_{2\text{is}} - h_{3\text{is}}). \tag{6}$$

- Energy loss:

$$\dot{E}n_{\text{loss,HPC}} = P_{\text{id,HPC}} - P_{\text{re,HPC}}. \tag{7}$$

- Energy loss per unit of produced mechanical power:

$$\dot{E}n_{\text{loss,power,HPC}} = \frac{\dot{E}n_{\text{loss,HPC}}}{P_{\text{re,HPC}}} \cdot 100. \tag{8}$$

- Energy efficiency:

$$\eta_{\text{en,HPC}} = \frac{P_{\text{re,HPC}}}{P_{\text{id,HPC}}}. \tag{9}$$

Low Pressure Cylinder (LPC)

- Real (polytropic) and ideal (isentropic) mechanical power:

$$P_{\text{re,LPC}} = \dot{m}_4 \cdot (h_4 - h_5) + (\dot{m}_4 - \dot{m}_5) \cdot (h_5 - h_6) + (\dot{m}_4 - \dot{m}_5 - \dot{m}_6) \cdot (h_6 - h_7) + (\dot{m}_4 - \dot{m}_5 - \dot{m}_6 - \dot{m}_7) \cdot (h_7 - h_8) + \dot{m}_9 \cdot (h_8 - h_9), \tag{10}$$

$$P_{\text{id,LPC}} = \dot{m}_4 \cdot (h_4 - h_{5\text{is}}) + (\dot{m}_4 - \dot{m}_5) \cdot (h_{5\text{is}} - h_{6\text{is}}) + (\dot{m}_4 - \dot{m}_5 - \dot{m}_6) \cdot (h_{6\text{is}} - h_{7\text{is}}) + (\dot{m}_4 - \dot{m}_5 - \dot{m}_6 - \dot{m}_7) \cdot (h_{7\text{is}} - h_{8\text{is}}) + \dot{m}_9 \cdot (h_{8\text{is}} - h_{9\text{is}}). \tag{11}$$

- Energy loss:

$$\dot{E}n_{\text{loss,LPC}} = P_{\text{id,LPC}} - P_{\text{re,LPC}}. \tag{12}$$

- Energy loss per unit of produced mechanical power:

$$\dot{E}n_{\text{loss,power,LPC}} = \frac{\dot{E}n_{\text{loss,LPC}}}{P_{\text{re,LPC}}} \cdot 100. \tag{13}$$

- Energy efficiency:

$$\eta_{\mathrm{en,LPC}} = \frac{P_{\mathrm{re,LPC}}}{P_{\mathrm{id,LPC}}}. \tag{14}$$

Whole Turbine (WT)

- Real (polytropic) and ideal (isentropic) mechanical power:

$$P_{\mathrm{re,WT}} = P_{\mathrm{re,HPC}} + P_{\mathrm{re,LPC}}, \tag{15}$$

$$P_{\mathrm{id,WT}} = P_{\mathrm{id,HPC}} + P_{\mathrm{id,LPC}}. \tag{16}$$

- Energy loss:

$$\dot{E}n_{\mathrm{loss,WT}} = P_{\mathrm{id,WT}} - P_{\mathrm{re,WT}}. \tag{17}$$

- Energy loss per unit of produced mechanical power:

$$\dot{E}n_{\mathrm{loss,power,WT}} = \frac{\dot{E}n_{\mathrm{loss,WT}}}{P_{\mathrm{re,WT}}} \cdot 100. \tag{18}$$

- Energy efficiency:

$$\eta_{\mathrm{en,WT}} = \frac{P_{\mathrm{re,WT}}}{P_{\mathrm{id,WT}}}. \tag{19}$$

5. Results and discussion

Real (polytropic) steam expansion process involves several losses which did not occur in ideal (isentropic) steam expansion process. The expected result is that mechanical power of the whole turbine and each turbine cylinder is lower in the real in comparison to ideal expansion process, Fig. 3.

As can be seen from Fig. 3, the dominant mechanical power producer from the observed turbine is LPC which mechanical power is approximately two times higher (in both real and ideal expansion processes) in comparison to HPC.

The whole observed turbine develop 1247.69 MW of mechanical power (real steam expansion process), while in an ideal situation the whole turbine can develop 1600.39 MW of mechanical power. Therefore, the ideal (isentropic) steam expansion process shows maximum mechanical power potential of the whole turbine (or each cylinder) which can be developed if all the losses are neglected.

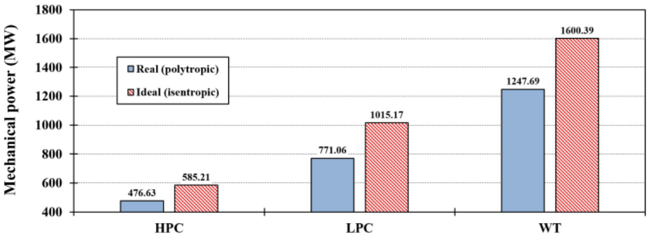

Fig. 3. *Real (polytropic) and ideal (isentropic) mechanical power of the whole analyzed turbine and each its cylinder*

The difference between ideal and real mechanical power of the whole analyzed steam turbine and each of its cylinders represents an energy loss. As shown in Fig. 4, the dominant mechanical power loss, if observing both cylinders, occurs in LPC (more than two times higher in comparison to HPC). Energy loss of the whole turbine is equal to 352.70 MW.

Energy loss per unit of produced mechanical power is the variable related to specific fuel consumption in internal combustion engines [27]. Specific fuel consumption allows comparison of, for example, high power slow speed marine two stroke diesel engines and low power automotive fast speed four stroke diesel or gasoline engines. Energy loss per unit of produced mechanical power allows comparison of different steam turbines (or its cylinders), regardless of steam operating parameters, developed power, size, or any other parameter related to each turbine.

Energy loss per unit of produced mechanical power equals 22.78%, 31.66% and 28.27% for the HPC, LPC and the whole observed steam turbine, respectively. Comparison of HPC and LPC shows that per unit of produced mechanical power LPC has a much higher energy loss. The energy loss per unit of produced mechanical power of the whole turbine is much closer to LPC than to HPC, which means that the dominant influence on this parameter for the whole turbine has LPC.

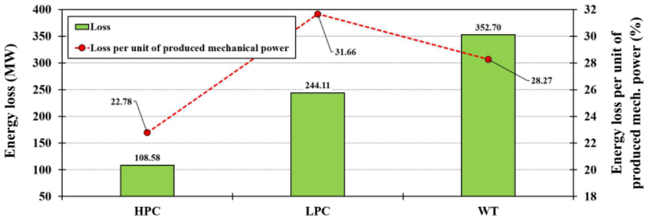

Fig. 4. *Energy loss and energy loss per unit of produced mechanical power for the whole analyzed turbine and each its cylinder*

Considering both cylinders of the analyzed steam turbine, LPC which is the dominant mechanical power producer and which has higher energy loss, also has much lower energy efficiency in comparison to HPC, Fig. 5. The energy efficiency of the HPC is 81.45%, while of the LPC is 75.95%. Whole turbine energy efficiency is equal to 77.96% what again confirms that LPC has the dominant influence on the whole turbine energy analysis parameters.

According to obtained energy efficiency of the whole analyzed steam turbine from nuclear power plant, it can be concluded that such energy efficiency is comparable to the energy efficiency of main marine steam turbines at the highest loads [28]. Also, it is expected that such turbine from nuclear power plant has much lower energy efficiency in comparison to steam turbines from conventional steam power plants [29] because in nuclear power plant steam turbine operates dominantly by using wet steam. Operation with wet steam (steam under the saturation line) brings several additional losses in the turbine operation (inner turbine losses) [30].

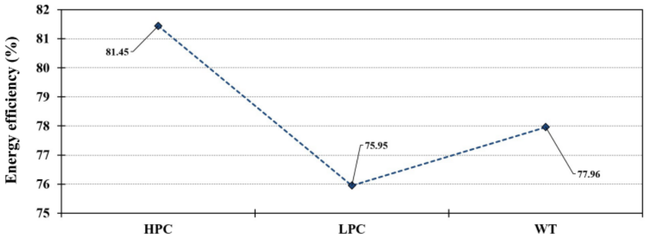

Fig. 5. *The energy efficiency of the whole analyzed turbine and each its cylinder*

Further research of the observed steam turbine from nuclear power plant will be performed by using various artificial intelligence approaches [31-33]. If possible, it will be performed optimization. Low pressure cylinder of the observed turbine, which has a much higher energy loss and much lower energy efficiency in comparison to the high pressure cylinder will be the baseline for any further research and improvement.

6. Conclusions

In this paper is performed energy analysis of the two-cylinder steam turbine, which operates in nuclear power plant. Mechanical power, energy loss, energy loss per unit of produced mechanical power as well as energy efficiency are calculated for each cylinder and the whole observed turbine. The most important conclusions from the performed analysis are:

- The dominant mechanical power producer from the observed turbine is LPC which mechanical power is approximately two times higher in comparison to HPC. The whole observed turbine develop 1247.69 MW of mechanical power in the real (polytropic) steam expansion process.
- Comparison of both turbine cylinders shows that LPC has much higher energy loss and energy loss per unit of produced mechanical power in comparison to HPC. Energy loss of the whole turbine is

352.70 MW, while energy loss per unit of produced mechanical power of the whole turbine is 28.27%.

- Energy efficiency of the whole turbine is 77.96%, which makes it comparable to main marine steam turbines at the highest loads. Such energy efficiency is notably lower in comparison to steam turbines from conventional steam power plants, what is an expected occurrence because steam turbine in nuclear power plant operates with wet, not superheated steam.
- LPC has much lower energy efficiency in comparison to HPC (75.95% in comparison to 81.45%), so any possible improvement of this turbine should be based firstly on the LPC.

7. Acknowledgment

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