Energy evaluation of a three-cylinder steam turbine which operates in combined cycle power plant

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Abstract: *This paper presents an energy analysis of a three-cylinder steam turbine from a combined cycle power plant. Observing all the cylinders from the analyzed turbine, it is found that the dominant mechanical power producer is Low Pressure Cylinder (LPC), followed by the Intermediate Pressure Cylinder (IPC), while High Pressure Cylinder (HPC) is the cylinder which produces the lowest mechanical power. Whole observed steam turbine develop 119.41 MW of useful mechanical power. Energy loss and energy efficiency of all cylinders are reverse proportional – higher energy efficiency will result with lower energy loss and vice versa. IPC is the cylinder which has the lowest energy loss (equal to 2.59 MW) and the highest energy efficiency of 93.32%. Whole observed steam turbine has energy loss equal to 23.43 MW, while its energy efficiency is equal to 83.60%, what falls in the expected range of such low power steam turbines. Steam mass flow rate through each cylinder is the main element which defines produced mechanical power and energy flows.*
KEYWORDS: *THREE-CYLINDER STEAM TURBINE, COMBINED CYCLE POWER PLANT, ENERGY FLOW STREAMS, ENERGY EVALUATION*

1. Introduction

Considering energy systems worldwide, it can be concluded that in many of them exists heat turbines in various combinations [1, 2]. In conventional steam power plants and nuclear power plants, steam turbines are essential components [3-5]. Steam turbines can also be often found in various cogeneration power plants and systems which simultaneously produces and delivers two types of energy – heat and electrical [6, 7].

Power plants which have one of the highest overall efficiencies are combined cycle power plants [8]. Combined cycle power plants consist of at least one gas turbine and at least one steam turbine [9]. In such power plants, combustion gases after expansion in gas turbine are not released to the atmosphere – heat from combustion gases is utilized in Heat Recovery Steam Generator (HRSG) and used for superheated steam production [10, 11]. Steam from HRSG is delivered to steam turbine which produces an additional amount of useful mechanical power, dominantly used for electrical generator drive [12]. As HRSG in combined cycle power plant did not use additional fuel (or use a small amount of additional fuel), the entire steam mass flow rate is produced by using waste heat from gas turbine [13]. Heat utilization in combined cycle power plants results with notable fuel savings, which increases plant efficiency and have many economic benefits [14].

In combined cycle power plants can be used various types of steam turbines, what mostly depends on the HRSG composition and operation characteristics [15]. In this paper is analyzed (from the energy aspect) three-cylinder steam turbine, as well as its cylinders, which operate in the commercial combined cycle power plant. It is investigated which cylinder of this turbine shows the best performance, the characteristics and operation parameters of the whole steam turbine are also analyzed and the steam turbine dependence on HRSG is discussed. This analysis can and should be used as a baseline for further improvements of this and many similar steam turbines which operate in combined cycle power plants.

2. Description and operation characteristics of the analyzed turbine

Steam turbine analyzed in this paper operates in a steam part of complex combined cycle power plant [16]. The turbine is composed of three cylinders connected to the same shaft which drives an electric generator, Fig. 1.

The steam mass flow rate used in the steam turbine cylinders is produced in HRSG which uses combustion gases from a gas turbine to produce steam. If required, an additional amount of fuel can be used in a secondary burner before HRSG for the combustion gases temperature increase, but the dominant heating medium is combustion gases from gas turbine [17]. In such way, HRSG utilizes heat released from the gas turbine and produces superheated steam which will expand in the steam turbine cylinders. Due to the high heat utilization, combined cycle power plants have extremely high efficiencies, one of the highest in the overall energy sector [18].

Observation of the steam turbine analyzed in this paper shows that superheated steam produced in HRSG is delivered firstly to High Pressure Cylinder (HPC), expands through it and is returned back to HRSG. Again, from HRSG steam is delivered to Intermediate Pressure Cylinder (IPC), expands through it and is again returned back to HRSG. The last cylinder which gets steam from HRSG is Low Pressure Cylinder (LPC). After expansion in LPC steam has a very low temperature and pressure, it cannot be used anywhere else in the power plant, so from the LPC outlet steam is delivered to steam condenser for condensation [19]. Condensate obtained in steam condenser will be returned back to HRSG and from that condensate will be produced superheated steam for the HPC again. This circulation is continuous during power plant operation.

From the general and simplified steam turbine scheme, Fig. 1, can be observed that neither one cylinder did not possess steam extraction, so the steam mass flow rate which enters in each cylinder will expand through entire cylinder until its outlet. HRSG in this power plant is a highly complex device, so in Fig. 1 are presented only some HRSG parts essential for the turbine operation.

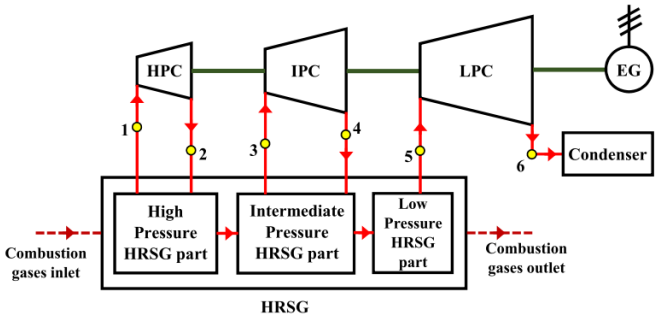

Fig. 1. *General scheme of the observed three-cylinder steam turbine from combined cycle power plant along with operating points necessary for the energy analysis*

Steam expansion processes (both ideal and real) through each cylinder of the observed steam turbine are presented in specific enthalpy-specific entropy (*h*-*s*) diagram in Fig. 2.

Real (polytropic) steam expansion process through each cylinder is marked in accordance to operating points from Fig. 1. From Fig. 2 is clear that real (polytropic) steam expansion process involves losses which occur during steam expansion due to increase in steam specific entropy.

In comparison to real (polytropic) steam expansion, ideal (isentropic) steam expansion process did not consider any losses which occur during expansion, therefore in an ideal process steam specific entropy remains always the same. The ideal steam expansion process is actually the process between the same pressures and with same mass flow rates as real process, but in ideal

process steam specific entropy remains unchanged from the inlet until the outlet of each cylinder. Due to losses neglecting, ideal (isentropic) steam expansion process will result with the highest theoretical power which can be developed by each cylinder and the whole turbine. Real expansion processes should have intention to be as close as possible to the ideal ones, but ideal processes cannot be achieved in real exploitation conditions. However, the ideal expansion process can be a proper guideline for losses decreasing in any cylinder and whole turbine. The operating points of the ideal (isentropic) steam expansion processes are numerated in a same manner as presented in Fig. 1, but with "is" as an addition along with the number.

In Fig. 2, ideal expansion process in HPC is marked with operating points 1 and 2is, in the IPC ideal process is marked with operating points 3 and 4is and in LPC ideal steam expansion process is the process between operating points 5 and 6is.

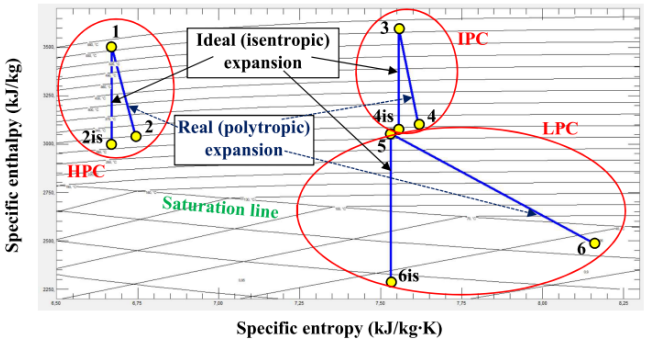

Fig. 2. *Steam expansion process (ideal and real) in h-s diagram throughout all the cylinders of the analyzed three-cylinder steam turbine from combined cycle power plant*

3. Equations required for the analysis

The first law of thermodynamics defines energy analysis. Such kind of analysis did not consider the parameters of the ambient inside which observed system or a component operates [20].

However, in the energy analysis exists a few overall equations and balances which should always be satisfied, in any operating conditions of the observed system or a component. These equations will be presented in the first part of this section, after which will be presented exact equations for the energy analysis of the observed three-cylinder steam turbine from a combined cycle power plant.

3.1. Overall energy analysis equations and balances

For any system or a component, always valid energy balance equation is [21]:

$$\dot{Q}_{\mathrm{IN}} + P_{\mathrm{IN}} + \sum \dot{E}n_{\mathrm{IN}} = \dot{Q}_{\mathrm{OUT}} + P_{\mathrm{OUT}} + \sum \dot{E}n_{\mathrm{OUT}} + \dot{E}n_{\mathrm{L}}, \quad (1)$$

where $\dot{Q}$ is an energy transfer by heat, P is mechanical power, index IN is related to the inlet (input), index OUT is related to outlet (output) and index L is related to the loss (destruction). $\dot{E}n$ is a total energy flow of any fluid stream, which definition can be found in [22] and presented by an equation:

$$\dot{E}n = \dot{m} \cdot h, \quad (2)$$

where $\dot{m}$ is a fluid mass flow rate and h is fluid specific enthalpy. Standard fluid mass flow rate balance (for a system or component without leakages) is [23]:

$$\sum \dot{m}_{\mathrm{IN}} = \sum \dot{m}_{\mathrm{OUT}}. \quad (3)$$

The overall energy efficiency equation is [24]:

$$\eta_{\mathrm{EN}} = \frac{\mathrm{CUMULATIVE\ \ ENERGY\ \ OUTPUT}}{\mathrm{CUMULATIVE\ \ ENERGY\ \ INPUT}}. \quad (4)$$

It should be highlighted that overall energy efficiency equation (Eq. 4) can significantly vary from the presented one, what depends on the observed system or component operation characteristics.

3.2. Equations for the energy analysis of whole three-cylinder steam turbine and its cylinders

Equations for the energy analysis of each cylinder and whole observed turbine (WT) are composed according to recommendations from the literature [25]. Markings in the equations are placed in accordance with operating points presented in Fig. 1 and Fig. 2 for both ideal and real expansion processes. Real (polytropic) mechanical power of each cylinder from the observed turbine is:

$$P_{\mathrm{RE,HPC}} = \dot{m}_1 \cdot (h_1 - h_2), \quad (5)$$

$$P_{\mathrm{RE,IPC}} = \dot{m}_3 \cdot (h_3 - h_4), \quad (6)$$

$$P_{\mathrm{RE,LPC}} = \dot{m}_5 \cdot (h_5 - h_6). \quad (7)$$

Ideal (isentropic) mechanical power of each cylinder from the observed turbine (according to Fig. 2) is:

$$P_{\mathrm{ID,HPC}} = \dot{m}_1 \cdot (h_1 - h_{2\mathrm{is}}), \quad (8)$$

$$P_{\mathrm{ID,IPC}} = \dot{m}_3 \cdot (h_3 - h_{4\mathrm{is}}), \quad (9)$$

$$P_{\mathrm{ID,LPC}} = \dot{m}_5 \cdot (h_5 - h_{6\mathrm{is}}). \quad (10)$$

The energy loss of each cylinder from the observed turbine is:

$$\dot{E}n_{\mathrm{L,HPC}} = P_{\mathrm{ID,HPC}} - P_{\mathrm{RE,HPC}}, \quad (11)$$

$$\dot{E}n_{\mathrm{L,IPC}} = P_{\mathrm{ID,IPC}} - P_{\mathrm{RE,IPC}}, \quad (12)$$

$$\dot{E}n_{\mathrm{L,LPC}} = P_{\mathrm{ID,LPC}} - P_{\mathrm{RE,LPC}}. \quad (13)$$

The energy efficiency of each cylinder is:

$$\eta_{\mathrm{EN,HPC}} = \frac{P_{\mathrm{RE,HPC}}}{P_{\mathrm{ID,HPC}}}, \quad (14)$$

$$\eta_{\mathrm{EN,IPC}} = \frac{P_{\mathrm{RE,IPC}}}{P_{\mathrm{ID,IPC}}}, \quad (15)$$

$$\eta_{\mathrm{EN,LPC}} = \frac{P_{\mathrm{RE,LPC}}}{P_{\mathrm{ID,LPC}}}. \quad (16)$$

For the whole turbine, real (polytropic) mechanical power is:

$$P_{\mathrm{RE,WT}} = P_{\mathrm{RE,HPC}} + P_{\mathrm{RE,IPC}} + P_{\mathrm{RE,LPC}}, \quad (17)$$

ideal (isentropic) mechanical power is:

$$P_{\mathrm{ID,WT}} = P_{\mathrm{ID,HPC}} + P_{\mathrm{ID,IPC}} + P_{\mathrm{ID,LPC}}, \quad (18)$$

while energy loss and energy efficiency of the whole observed three-cylinder steam turbine are:

$$\dot{E}n_{\mathrm{L,WT}} = P_{\mathrm{ID,WT}} - P_{\mathrm{RE,WT}}, \quad (19)$$

$$\eta_{\mathrm{EN,WT}} = \frac{P_{\mathrm{RE,WT}}}{P_{\mathrm{ID,WT}}}. \quad (20)$$

4. Steam operating parameters necessary for the analysis

Essential steam operating parameters (steam pressure, temperature and mass flow rate) in each operating point of the real (polytropic) expansion process from Fig. 1 and Fig. 2 are found in [16] and presented in Table 1.

Table 1. *Steam operating parameters at each cylinder inlet and outlet of the observed three-cylinder turbine – real expansion*

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)
1	560.6	124.00	65.21	3505.0	6.6695
2	313.2	23.16	65.21	3046.2	6.7423
3	560.6	22.00	72.43	3600.8	7.5554
4	317.2	4.10	72.43	3102.2	7.6168
5	293.0	4.10	94.58	3052.4	7.5307
6	32.9	0.05	94.58	2488.0	8.1563

* O.P. = Operating Point (in accordance to Fig. 1 and Fig. 2)

For the ideal (isentropic) steam expansion process, steam operating parameters are presented in Table 2 (ideal process is the process between the same pressures and with same mass flow rates as ideal one, but it assumes always the same steam specific entropy from each turbine cylinder inlet until the outlet).

Other steam operating parameters presented in Table 1 and Table 2 are calculated by using NIST-Refprop 9.0 software [26] from essential steam parameters.

Table 2. *Steam operating parameters at each cylinder inlet and outlet of the observed three-cylinder turbine – ideal expansion*

O.P.*	Pressure (bar)	Mass flow rate (kg/s)	Specific entropy (kJ/kg·K)	Isentropic specific enthalpy (kJ/kg)
1	124.00	65.21	6.6695	3505.0
2is	23.16	65.21	6.6695	3004.2
3	22.00	72.43	7.5554	3600.8
4is	4.10	72.43	7.5554	3066.5
5	4.10	94.58	7.5307	3052.4
6is	0.05	94.58	7.5307	2296.6

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

5. Results and discussion

Ideal (isentropic) as well as real (polytropic) mechanical power of each cylinder and whole observed three-cylinder steam turbine from a combined cycle power plant are presented in Fig. 3.

Observing all the cylinders from the analyzed turbine, it can easily be seen that the dominant mechanical power producer (both ideal and real) is LPC. IPC produces approximately two times lower mechanical power than LPC in both ideal and real cases, while HPC is the cylinder which produces the lowest mechanical power.

Produced mechanical power in turbine cylinders is directly proportional to mass flow rate of steam which expands through each cylinder. From Table 1 and Table 2 can be seen that the complex arrangement of the HRSG results with an increase in the steam mass flow rate from the highest pressures up to the lowest pressures. A complex HRSG arrangement allows that all steam mass flow rates which exist in the steam part of combined cycle power plant (main and auxiliary steam mass flow rates) can be effectively used in the steam turbine. Therefore, through HPC expands the lowest steam mass flow rate what results with the lowest produced mechanical power of all cylinders, while through LPC expands the highest steam mass flow rate what results with the highest produced mechanical power of all cylinders.

Whole observed steam turbine from combined cycle power plant develop 119.41 MW of useful mechanical power in real process which involves all losses during the expansion, while in an ideal situation, whole turbine will be capable to develop 142.84 MW of mechanical power.

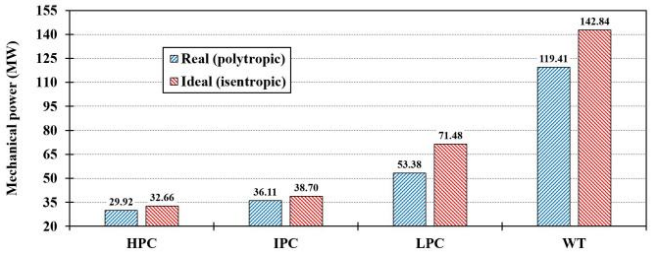

Fig. 3. *Ideal (isentropic) and real (polytropic) mechanical power of each cylinder and whole observed three-cylinder steam turbine from combined cycle power plant*

Energy loss and energy efficiency of each cylinder and whole observed three-cylinder steam turbine from a combined cycle power plant are presented in Fig. 4.

From Fig. 4 is clear that energy loss and energy efficiency of all cylinders are reverse proportional – higher energy efficiency will result with lower energy loss and vice versa. IPC is the cylinder which has the lowest energy loss (equal to 2.59 MW) and the highest energy efficiency of 93.32% in comparison to the other cylinders. Such high energy efficiency and low energy loss of IPC can be explained with the fact that IPC avoids the dominant losses which occur in the turbine. In HPC can be expected increased losses due to its operation with a steam of the highest temperature and pressure, while in LPC can be expected increased losses due to its operation with the wet steam at least in last few LPC stages. As the IPC avoids all mentioned losses, its performance and operating conditions are almost optimal. From the energy aspect, wet steam losses are more influential than losses of steam which has high temperature and pressure, therefore, LPC has much higher energy loss (equal to 18.10 MW) and much lower energy efficiency (equal to 74.68%) in comparison to both HPC and IPC. It is interesting to note that HPC energy loss is only slightly higher and its energy efficiency is only slightly lower in comparison to IPC.

Whole observed steam turbine from a combined cycle power plant has energy loss equal to 23.43 MW, while its energy efficiency is equal to 83.60%. As the whole presented and analyzed turbine develops 119.41 MW of useful mechanical power (real expansion), this turbine can be considered as a low power steam turbine, so obtained energy loss and energy efficiency are in the expected range of such steam turbines [27].

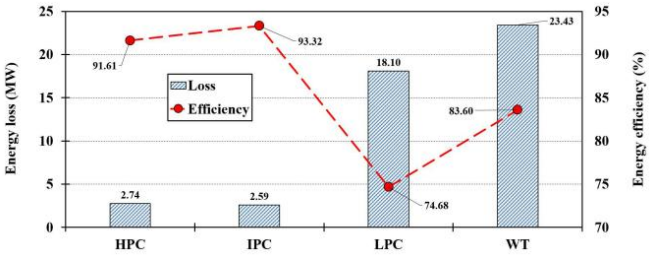

Fig. 4. *Energy loss and energy efficiency of each cylinder and whole observed three-cylinder steam turbine from a combined cycle power plant*

Total energy flows at each cylinder inlet and outlet (calculated by using Eq. 2) for the observed three-cylinder steam turbine are presented in Fig. 5 in relation to fluid (steam) mass flow rate.

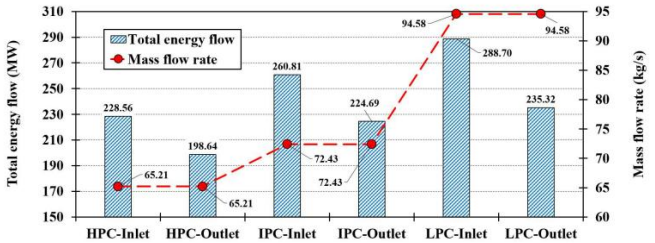

Fig. 5. *Total energy flow in relation to steam mass flow rate at each cylinder inlet and outlet for the observed three-cylinder steam turbine from combined cycle power plant*

From Fig. 5 can be clearly seen that increase in steam mass flow rate increases total energy flows at each cylinder inlet and outlet and vice versa. If comparing cylinders of the observed turbine, it can be concluded that total energy flows of LPC (at both LPC inlet and outlet) are higher in comparison to any total energy flow of the HPC. This fact can be explained with notably higher steam mass flow rate through LPC (equal to 94.58 kg/s) in comparison to steam mass flow rate through HPC (equal to 65.21 kg/s).

In the observed turbine, steam mass flow rate through each cylinder is the main element which defines produced mechanical power and energy flows, while it did not have an obvious and direct impact on cylinder energy efficiency and energy loss.

6. Conclusions

In this paper is presented an energy analysis of a three-cylinder steam turbine which operates in a combined cycle power plant. Using measured steam operating parameters during turbine exploitation, for each cylinder and whole turbine is calculated real and ideal mechanical power, energy loss and energy efficiency. At each cylinder inlet and outlet are calculated total energy flows and

their relation to steam mass flow rate through each cylinder is described. The most important conclusions of this paper are:

- Observing all the cylinders from the analyzed turbine, it is found that the dominant mechanical power producer is LPC, followed by the IPC, while HPC is the cylinder which produces the lowest mechanical power.
- Whole observed steam turbine from combined cycle power plant develop 119.41 MW of useful mechanical power.
- Energy loss and energy efficiency of all cylinders are reverse proportional – higher energy efficiency will result with lower energy loss and vice versa.
- IPC is the cylinder which has the lowest energy loss (equal to 2.59 MW) and the highest energy efficiency of 93.32%, while the highest energy loss (equal to 18.10 MW) and the lowest energy efficiency of 74.68% has LPC.
- Whole observed steam turbine from a combined cycle power plant has energy loss equal to 23.43 MW, while its energy efficiency is equal to 83.60%. The observed steam turbine can be considered as a low power steam turbine, so obtained energy loss and energy efficiency are in the expected range of such steam turbines.
- Steam mass flow rate through each cylinder is the main element which defines produced mechanical power and energy flows, while it did not have an obvious and direct impact on cylinder energy efficiency and energy loss.

7. Acknowledgment

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