Thermodynamic evaluation of a 250 mw three-cylinder steam turbine from ccpp

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Abstract: *In this paper are presented isentropic analysis results of a steam turbine, their cylinders and cylinder parts which nominal power is equal to 250 MW. The analyzed steam turbine is a complex three-cylinder turbine which operates in a CCPP (Combined Cycle Power Plant). Considering all cylinders, the dominant mechanical power producer in the observed turbine is LPC (Low Pressure Cylinder) which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process (almost half of the real mechanical power produced in the whole turbine). Developed mechanical power in turbine cylinders and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa. Whole analyzed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%. The isentropic performance of the whole analyzed steam turbine, their cylinders and cylinder parts is in the range of the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants which are proven to be the best steam turbines from isentropic point of view.*

KEYWORDS*: THERMODYNAMIC (ISENTROPIC) EVALUATION, THREE-CYLINDER STEAM TURBINE, CCPP (COMBINED CYCLE POWER PLANT)*

1. Introduction

The majority of electrical power worldwide today is produced by steam turbines [1, 2]. Steam turbines can operate in various kinds of power plants: conventional, nuclear, cogeneration, marine, etc. [3-7]. Steam turbines are also constitutive components of the combined cycle power plants where steam is produced by using combustion gases from gas turbine [8, 9]. Heat utilization in combined cycle power plants, along with mechanical power production in both gas and steam turbines, results in very high plant efficiency [10].

Steam turbines are usually composed of several cylinders connected to the same shaft which drives an electric generator [11, 12]. However, in many power plants and systems can be found low power steam turbines composed of one cylinder only [13, 14]. One cylinder steam turbines are usually auxiliary steam turbines which can be used for the drive of various mechanical power consumers [15]. Each turbine cylinder is dominantly composed of several turbine stages [16], but exceptions can be found in, for example, marine steam power plants where one-cylinder one stage steam turbine (Curtis stage) is used for the main feedwater pump drive [17].

Steam turbine cylinders can be single flow and dual flow cylinders, while dual flow cylinders can be symmetrical and dissymmetrical [18]. In a single flow cylinder, steam expands in one direction from the inlet until the outlet, while in dual flow cylinders steam enters in the cylinder and simultaneously expands in two opposite directions. Symmetrical dual flow steam turbine cylinder has identical left and right part, while dissymmetrical cylinder did not have identical both its parts (left and right parts) [19-21].

In this paper is analyzed one complex steam turbine composed of three cylinders which operates in CCPP (Combined Cycle Power Plant) and has a nominal power equal to 250 MW. Two cylinders of the observed turbine are single flow, while one cylinder is a symmetrical dual flow cylinder. The whole turbine is used for the electric generator drive. It is very interesting that analyzed steam turbine, their cylinders and cylinder parts show very high isentropic performance, comparable to the turbines (and their cylinders) from supercritical and ultra-supercritical steam power plants which are proven to be the best from isentropic point of view.

2. Description and characteristics of the analyzed turbine and their cylinders

As presented in Fig. 1, the turbine is composed of three cylinders – High Pressure Cylinder (HPC), Intermediate Pressure Cylinder (IPC) and Low Pressure Cylinder (LPC). All cylinders are connected to the same shaft which drives an electric generator (EG). Neither one cylinder from the observed turbine did not possess steam extraction [22], therefore the entire produced steam mass flow rate is used for mechanical power production only. Also, all cylinders get a steam mass flow rate produced in the Heat Recovery Steam Generator (HRSG). HRSG uses heat contained in combustion gases from the gas turbine for producing steam at several pressure levels. Produced steam in HRSG is delivered to each steam turbine cylinder by using complex pipeline network. The nominal power of this steam turbine is equal to 250 MW [23].

HPC get steam of the highest possible pressure and temperature from High Pressure SuperHeater (HPSH). The steam expands through HPC after which is returned back to HRSG and passes through ReHeater (RH). RH increases steam temperature before its expansion in IPC. In RH, additional intermediate pressure steam mass flow rate is added from Intermediate Pressure SuperHeater (IPSH) and cumulative steam mass flow rate from RH expands through IPC. After IPC, steam is not returned back to HRSG, but a certain mass flow rate of low pressure steam is added from Low Pressure SuperHeater (LPSH) – operating point 5, Fig. 1, before expansion in LPC. Cumulative low pressure steam mass flow rate expands through LPC which is a symmetrical dual flow cylinder (HPC and IPC are single flow cylinders). In dual flow cylinders cumulative steam mass flow rate at the cylinder inlet (operating point 6, Fig. 1) is divided into two identical parts – the first part of inlet steam mass flow rate expands through left cylinder part (LPC-L), while the second part of inlet steam mass flow rate expands through right cylinder part (LPC-R). LPC of the analyzed turbine is also a symmetrical cylinder because both LPC parts (left and right) are identical with identical steam operating parameters at the inlet and outlet. After expansion through both LPC parts, steam mass flow rate from each LPC part is delivered to the deaerating condenser for condensation. The analyzed steam turbine arrangement is identical to many steam turbines from various conventional steam power plants [24]. This steam turbine arrangement, among other benefits, ensures the best possible steam axial force self-balancing [25].

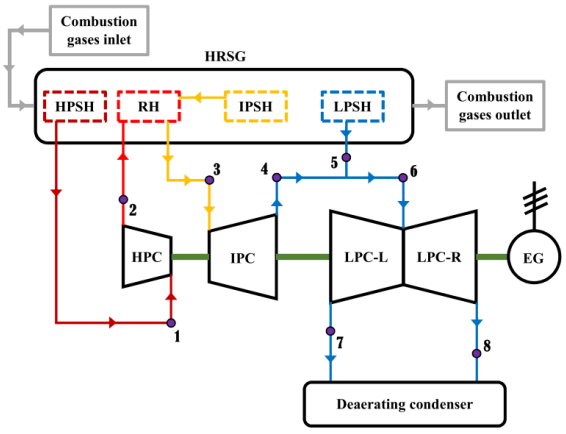

Fig. 1. *General scheme and operating points required for the isentropic analysis of the whole turbine and their cylinders*

Real (polytropic) and ideal (isentropic) steam expansion processes through each cylinder of the observed steam turbine are presented in specific enthalpy/specific entropy (*h/s*) diagram in Fig. 2.

In real (polytropic) steam expansion process through each cylinder is visible increase in steam specific entropy which is related to losses during expansion. Operating point's for real (polytropic) steam expansion process in each cylinder of the observed turbine are marked in Fig. 2 identically to operating points from Fig. 1.

Ideal (isentropic) steam expansion process is the best possible process which can occur in each turbine cylinder, and it did not consider any losses during the expansion (in ideal steam expansion process losses are equal to zero). Neglecting all the losses during expansion results with a fact that in ideal process steam specific entropy remains constant in each cylinder (and identical as at the cylinder inlet). Therefore, in ideal (isentropic) steam expansion process in each cylinder or cylinder part steam pressures and mass flow rates remain the same as in real (polytropic) process – the only difference in comparison to real process is retaining always the same steam specific entropy. In ideal expansion will always be developed the highest possible mechanical power (necessarily higher than in the real expansion process). Mechanical power developed in an ideal expansion process through each turbine cylinder cannot be obtained in real exploitation conditions, but it can be a guideline for losses reduction [26]. In ideal (isentropic) steam expansion processes operating points are marked in a same manner as presented in Fig. 1, but with the addition of index "is" 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, while in each part of the LPC ideal steam expansion process occur between operating points 6 and 7is or between operating points 6 and 8is.

As noted before, LPC is composed of two identical parts with identical steam operating parameters – so steam expansion processes through both LPC parts (LPC-L and LPC-R) are identical.

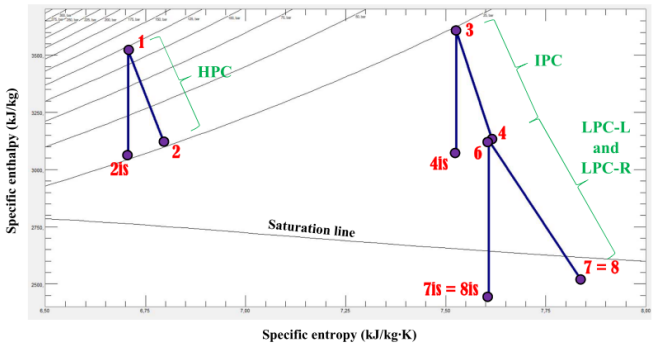

Fig. 2. *Specific enthalpy/specific entropy diagram of steam expansion process (both ideal and real) through all three steam turbine cylinders*

3. Isentropic analysis equations

Isentropic analysis is based on a comparison of ideal (isentropic) and real (polytropic) steam expansion processes. The essential element of comparison is produced ideal and real mechanical power in each cylinder, cylinder part and whole observed turbine [27]. Isentropic analysis equations presented in this paper part are based on the recommendations from available literature [28-30]. Also, it should be highlighted that isentropic analysis is a "black box" method because it did not require knowledge of the internal structure of any cylinder or cylinder part [31]. Markings in the following equations will be related to operating points from Fig. 1 and Fig. 2.

Real (polytropic) mechanical power of each cylinder, cylinder part and whole turbine is calculated according to the equations:

$$P_{\mathrm{re,HPC}} = \dot{m}_1 \cdot (h_1 - h_2), \quad (1)$$

$$P_{\mathrm{re,IPC}} = \dot{m}_3 \cdot (h_3 - h_4), \quad (2)$$

$$P_{\mathrm{re,LPC-L}} = P_{\mathrm{re,LPC-R}} = \frac{\dot{m}_6}{2} \cdot (h_6 - h_7), \text{ where } h_7 = h_8, \quad (3)$$

$$P_{\mathrm{re,Whole\ LPC}} = P_{\mathrm{re,LPC-L}} + P_{\mathrm{re,LPC-R}} = 2 \cdot P_{\mathrm{re,LPC-L}}, \quad (4)$$

$$P_{\mathrm{re,Whole\ Turbine}} = P_{\mathrm{re,HPC}} + P_{\mathrm{re,IPC}} + P_{\mathrm{re,Whole\ LPC}}. \quad (5)$$

Ideal (isentropic) mechanical power of each cylinder, cylinder part and whole turbine is calculated according to the equations:

$$P_{\mathrm{id,HPC}} = \dot{m}_1 \cdot (h_1 - h_{2\mathrm{is}}), \quad (6)$$

$$P_{\mathrm{id,IPC}} = \dot{m}_3 \cdot (h_3 - h_{4\mathrm{is}}), \quad (7)$$

$$P_{\mathrm{id,LPC-L}} = P_{\mathrm{id,LPC-R}} = \frac{\dot{m}_6}{2} \cdot (h_6 - h_{7\mathrm{is}}), \text{ where } h_{7\mathrm{is}} = h_{8\mathrm{is}}, \quad (8)$$

$$P_{\mathrm{id,Whole\ LPC}} = P_{\mathrm{id,LPC-L}} + P_{\mathrm{id,LPC-R}} = 2 \cdot P_{\mathrm{id,LPC-L}}, \quad (9)$$

$$P_{\mathrm{id,Whole\ Turbine}} = P_{\mathrm{id,HPC}} + P_{\mathrm{id,IPC}} + P_{\mathrm{id,Whole\ LPC}}. \quad (10)$$

Isentropic loss is calculated according to the equation:

$$IS_{\mathrm{Loss,(i)}} = P_{\mathrm{id,(i)}} - P_{\mathrm{re,(i)}}, \quad (11)$$

while isentropic efficiency is:

$$\eta_{\mathrm{IS,(i)}} = \frac{P_{\mathrm{re,(i)}}}{P_{\mathrm{id,(i)}}}. \quad (12)$$

In Eq. 11 and Eq. 12 i is the index related to any cylinder, cylinder part and whole turbine (i = HPC; IPC; LPC-L; LPC-R; Whole LPC; Whole Turbine).

4. Steam operating parameters required for the isentropic analysis

Steam operating parameters of the real (polytropic) expansion process in each operating point from Fig. 1 are found in [23] and presented in Table 1. For the ideal (isentropic) steam expansion process, operating parameters in each operating point from Fig. 2 are calculated according to the previously described procedure by using NIST-Refprop 9.0 software [32] and they are presented in Table 2.

Table 1. *Steam operating parameters of the real (polytropic) steam expansion process*

O. P.*	Temp. (K)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality**
1	838.06	118.90	149.65	3521.0	6.7067	Superh.
2	625.82	27.89	149.65	3126.9	6.7942	Superh.
3	837.74	23.89	166.36	3608.0	7.5265	Superh.
4	605.76	4.60	166.36	3132.9	7.6154	Superh.
5	583.28	4.75	17.95	3086.1	7.5221	Superh.
6	603.55	4.60	184.31	3128.3	7.6079	Superh.
7	324.18	0.13	92.16	2521.7	7.8368	0.97
8	324.18	0.13	92.16	2521.7	7.8368	0.97

* O. P. = Operating Point (in accordance to Fig. 1)
** Quality equal to 1 denotes saturated steam, while quality equal to 0 denotes water

Table 2. *Steam operating parameters of the ideal (isentropic) steam expansion process*

O. P.*	Pressure (bar)	Mass flow rate (kg/s)	Isentropic specific enthalpy (kJ/kg)
1	118.90	149.65	3521.0
2is	27.89	149.65	3073.2
3	23.89	166.36	3608.0
4is	4.60	166.36	3080.1
6	4.60	184.31	3128.3
7is = 8is	0.13	92.16	2447.5

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

5. Isentropic analysis results and discussion

Mechanical power of each cylinder, cylinder part and whole turbine developed in real (polytropic) and ideal (isentropic) steam expansion processes is presented in Fig. 3. Due to neglecting all losses during expansion, mechanical power developed in the ideal process must always be higher than mechanical power developed in the real process, what can clearly be seen in Fig. 3.

According to the results presented in Fig. 3, considering all cylinders, the dominant mechanical power producer in the observed turbine is LPC which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process. HPC is the cylinder which produces the lowest mechanical power (both ideal and real). Fig. 3 also confirms that LPC is a symmetrical cylinder because both of its parts (LPC-L and LPC-R) develop identical mechanical power equal to 55.90 MW in real and 62.74 MW in the ideal expansion process.

Whole observed steam turbine produces mechanical power equal to 249.82 MW in real (polytropic) steam expansion process what means that steam operating parameters presented in Table 1 are nominal load parameters. In ideal (isentropic) steam expansion process whole turbine can produce mechanical power equal to 280.31 MW what can be used as a guideline for the improvements and losses reduction.

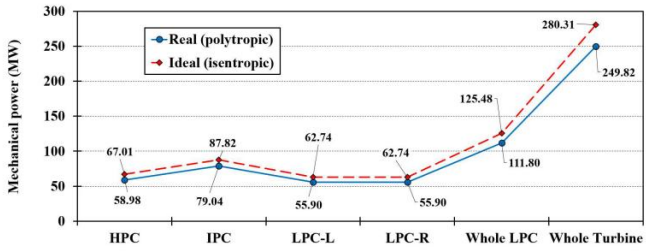

Fig. 3. *Mechanical power (real and ideal) of each cylinder and whole observed turbine*

Isentropic losses of each cylinder, cylinder part and whole analyzed turbine are presented in Fig. 4.

Comparison of Fig. 3 and Fig. 4 related to the turbine cylinders shows that developed mechanical power (both ideal and real) and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa. Therefore, the highest isentropic loss of all cylinders can be seen in LPC (equal to 13.68 MW), while the lowest isentropic loss of all cylinders has HPC (equal to 8.04 MW).

Whole observed steam turbine has isentropic loss equal to 30.50 MW. Any reducing the whole turbine isentropic loss will result with an increase in produced mechanical power and overall efficiency.

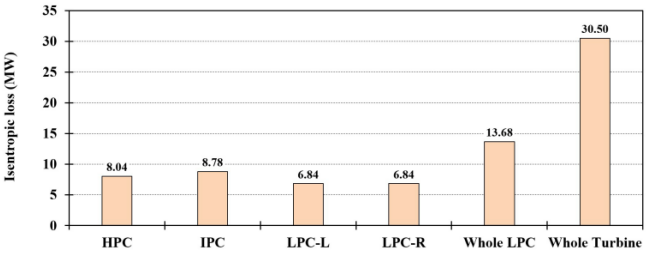

Fig. 4. *Isentropic loss of each cylinder and whole observed turbine*

Isentropic efficiency of each cylinder, cylinder part and whole observed turbine can clearly be seen in Fig. 5.

From Fig. 5 can easily be concluded that whole observed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%. Observation of all cylinders leads to conclusion that HPC has the lowest isentropic efficiency (equal to 88.01%), while IPC has the highest isentropic efficiency (equal to 90.00%). Whole LPC as well as both of its parts (LPC-L and LPC-R) have identical isentropic efficiencies equal to 89.10%. The highest isentropic efficiency of IPC can be explained with optimal operating conditions in which this cylinder operates. IPC is not influenced with a steam of the highest pressure and temperature in the plant (as HPC) and, simultaneously, what can clearly be seen in Fig. 2, neither one IPC stage did not operate by using wet steam as LPC (wet steam contains water droplets which increases losses). Therefore, as concluded for many other similar steam turbines, IPC performance is in the most of the cases better than the performance of any other cylinder inside the same steam turbine [33]. Whole observed steam turbine has a very high isentropic efficiency equal to 89.12%.

In comparison to isentropic efficiencies (for each cylinder and whole turbine) of various similar steam turbines from other power plants which can be found in the literature [34], it can be concluded that analyzed steam turbine and their cylinders have very high isentropic efficiencies. In the literature can be found that steam turbines from supercritical and ultra-supercritical steam power plants shows the best performance and the highest efficiencies (for each cylinder and whole turbine) [34]. It should be highlighted that an isentropic performance of the whole steam turbine and their cylinders analyzed in this paper is in the range of the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants.

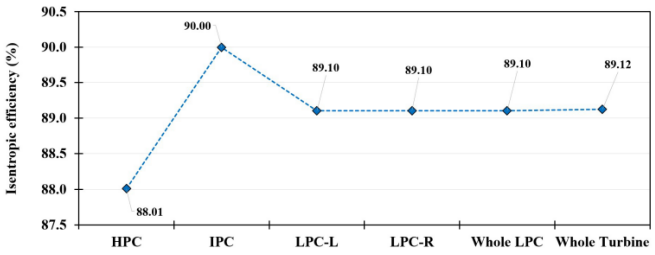

Fig. 5. *Isentropic efficiency of each cylinder and whole observed turbine*

Further analysis and possible optimization of the observed steam turbine will be based on the results obtained in this analysis. For that purpose, many conventional and artificial intelligence [35, 36] methods and processes can and will be used.

6. Conclusions

This paper presents isentropic analysis results of the complex three-cylinder steam turbine which operates in a CCPP. The nominal power of the observed steam turbine is equal to 250 MW, while entire steam mass flow rate used in the observed turbine is produced in HRSG which uses combustion gases from the gas turbine. The most important conclusions of the performed analysis are:

- The dominant mechanical power producer in the observed turbine is LPC which produces 111.80 MW of mechanical power in real (polytropic) steam expansion process. Real mechanical power produced in the LPC represents almost half of cumulative produced real mechanical power in the whole turbine.
- Developed mechanical power in turbine cylinders and isentropic losses are directly proportional – higher produced mechanical power will result in higher isentropic losses and vice versa.
- Whole observed steam turbine has isentropic loss equal to 30.50 MW. Any reducing the whole turbine isentropic loss will result with an increase in produced mechanical power and overall efficiency.
- Whole observed steam turbine, their cylinders and cylinder parts show very good isentropic performance and high isentropic efficiencies of around 90%.
- IPC of all cylinders has the highest isentropic efficiency (equal to 90.00%). The highest isentropic efficiency of IPC can be explained with optimal operating conditions in which this cylinder operates. IPC is not influenced with a steam of the highest pressure and temperature in the plant (as HPC) and, simultaneously, neither one IPC stage did not operate by using wet steam as LPC (wet steam contains water droplets which increases losses).
- It should be highlighted that an isentropic performance of the whole analyzed steam turbine and their cylinders is in the range of

the steam turbines (and their cylinders) from supercritical and ultra-supercritical power plants which are proven to be the best turbines from isentropic point of view.

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