Isentropic analysis of 320 MW steam turbine cylinders and segments

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Abstract: *In this paper are presented results of the isentropic analysis related to the cylinders, segments and whole three cylinder steam turbine from the conventional power plant. In the analyzed steam turbine Low Pressure Cylinder (LPC) is the dominant mechanical power producer of all cylinders – it produces 130.16 MW of mechanical power in the real expansion process and it can produce 142.80 MW of mechanical power if the expansion conditions are ideal. The satisfactory isentropic performance of the whole High Pressure Cylinder (HPC) is a combination of two segment's isentropic performance – one of these segments show extremely good isentropic performance (Seg2), but another segment (Seg1) shows very poor isentropic performance. Both Intermediate Pressure Cylinder (IPC) segments (Seg3 and Seg4) show similar isentropic performance, what result with the balanced IPC operation. LPC has an isentropic efficiency of 91.15%, what is the highest isentropic efficiency of all cylinders from the observed steam turbine. Whole observed steam turbine has an isentropic efficiency of 88.42% what is better isentropic performance in comparison to similar steam turbines from conventional power plants.*

KEYWORDS*: ISENTROPIC ANALYSIS, STEAM TURBINE, TURBINE CYLINDERS, CYLINDER SEGEMENTS*

1. Introduction

Steam turbines are the dominant mechanical power producers worldwide [1]. Produced mechanical power is dominantly used for the electric generators drive and electricity production [2]. However, steam turbines can be used for many other purposes in all processes which require mechanical power production [3, 4].

In relation to produced mechanical power, steam turbines can be divided into low power, medium power and high power steam turbines [5]. Medium and low power steam turbines can be composed of one cylinder only, while high power steam turbines are composed of several cylinders, usually connected to the same shaft [6, 7]. In the most of the cases, each cylinder of high power steam turbines has one or more steam extractions which are used for steam mass flow rate delivery to the components of condensate/feedwater heating system [8]. To improve efficiency of the whole turbine, high power steam turbines nowadays have a steam re-heater between high pressure and intermediate pressure cylinders [9].

In this paper is performed isentropic analysis of a complex three cylinder steam turbine from conventional power plant. The analysis considers not the turbine cylinders and whole turbine only, analysis is also performed for each segment of each turbine cylinder. Isentropic analysis of cylinder segments must carefully be performed and ideal (isentropic) expansion process in each segment must properly be defined. Isentropic analysis of each cylinder segment shows some interesting results which cannot be obtained if the turbine cylinder is observed as a whole.

2. Description of the analyzed steam turbine, turbine cylinders and cylinder segments

General and simplified scheme of the steam turbine analyzed in this paper is presented in Fig. 1.

The analyzed steam 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). In Fig. 1 are also marked operating points in which are performed measurements of steam operating parameters during the plant operation. Measured steam operating parameters in each operating point define real (polytropic) steam expansion process of each cylinder, cylinder segment and whole turbine. Ideal (isentropic) steam expansion processes of each cylinder and segment is obtained mathematically, and it represent the best possible expansion process (without losses) which can occur in ideal circumstances.

From Fig. 1 is visible that HPC has two steam extractions (operating points 2 and 3) – both of them deliver certain steam mass flow rate to the components of high pressure feedwater heating system [10]. As HPC, also IPC possess two steam extractions – first IPC extraction (operating point 6, Fig. 1) delivery certain steam mass flow rate to the components of high pressure feedwater heating system, while second IPC extraction (operating point 7, Fig. 1) deliver certain steam mass flow rate to the deaerator which divides condensate/feedwater heating system on the low pressure and high pressure part [11]. LPC has three steam extractions (operating points 9, 10 and 11, Fig. 1) – all LPC extractions deliver certain steam mass flow rate to the components of low pressure condensate heating system [12]. In addition, from Fig. 1 is visible that HPC get steam from the steam generator, between HPC and IPC steam is reheated in re-heater (re-heater is mounted in the steam generator), while after expansion in the LPC remaining steam mass flow rate is delivered to the main condenser for condensation.

Segments of each cylinder are defined between the cylinder inlet (input), outlet (output) and each steam extraction. Therefore, HPC has two segments – Seg1 between HPC inlet and first HPC extraction and Seg2 between first HPC extraction and HPC outlet. Second HPC extraction (operating point 3, Fig. 1) is mounted at the HPC outlet, and this extraction did not define an additional segment. IPC also possesses two segments (as HPC) – Seg3 between IPC inlet and first IPC extraction and Seg4 between first IPC extraction and IPC outlet. LPC has three segments – Seg5 between LPC inlet and first LPC extraction, Seg6 between first and second LPC extractions (between operating points 9 and 10, Fig. 1), and Seg7 between second LPC extraction and LPC outlet.

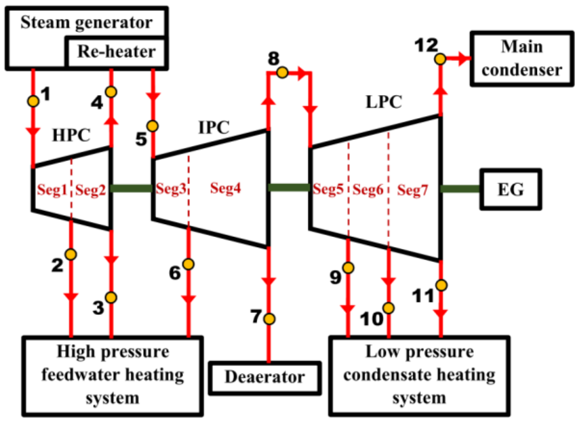

Fig. 1. *General scheme of the analyzed steam turbine (nominal power 320 MW) along with operating points in which are performed steam operating parameters measurements*

Isentropic analysis performed in this paper is related to all turbine cylinders, each segment of each cylinder as well as whole turbine. Isentropic analysis represents a comparison of real (polytropic) and ideal (isentropic) steam expansion process in each turbine cylinder and segment.

Real (polytropic) steam expansion of each cylinder and segment involves all the losses which occur during the expansion process (these losses are represented in a continuous steam specific entropy increase) [13]. In Fig. 2 real (polytropic) steam expansion process in each turbine cylinder and segment is marked with the numbers only. Steam operating parameters of the real (polytropic) expansion process can be obtained from the measurements during turbine exploitation.

Ideal (isentropic) steam expansion process is characterized with a fact that steam pressures and mass flow rates remain the same as in the real (polytropic) process, but in the ideal process steam specific entropy remains constant during the expansion [14]. Steam operating parameters in each ideal (isentropic) expansion process are obtained by mathematical calculations using previously described facts.

For each turbine cylinder and segment, in ideal (isentropic) steam expansion process steam specific entropy remains constant from the cylinder (or segment) inlet up to cylinder (or segment) outlet. Therefore, ideal (isentropic) steam expansion processes will not be identical for turbine cylinders and segments.

From Fig. 2 is clearly visible that ideal expansion in the HPC is represented with operating points 1, 2IS,HPC and 3IS,HPC, while for both HPC segments ideal expansion is represented with operating points 1 and 2IS,Seg1 for the first HPC segment (Seg1) and with operating points 2 and 3IS,Seg2 for the second HPC segment (Seg2). The same principle is visible for IPC and LPC from Fig. 2. Along with an operating point number, in the ideal (isentropic) expansion process for each operating point is used additional index IS (for both cylinders and segments). With an aim to make a difference between isentropic expansions related to the cylinders and segments, operating points related to the isentropic expansion in the cylinders have an additional index of the cylinder (HPC, IPC and LPC), while operating points related to the isentropic expansion in the segments have an additional index of the segment (Seg1, Seg2, Seg3, Seg4, Seg5, Seg6 and Seg7), Fig. 2.

Isentropic expansion in any turbine cylinder or segment did not involve any losses, therefore the mechanical power which will be produced in each cylinder and segment during ideal (isentropic) expansion will be the highest possible.

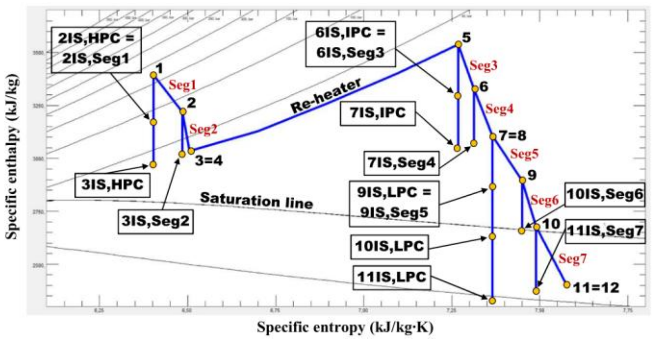

Fig. 2. *Specific enthalpy/Specific entropy (h/s) diagram of real (polytropic) and ideal (isentropic) steam expansion process through analyzed turbine cylinders and segments*

3. Isentropic analysis equations of the turbine cylinders and cylinder segments

The equations used in the isentropic analysis of each cylinder, segment and whole observed steam turbine are defined according to recommendations from the literature [14, 15]. It should be highlighted that isentropic analysis is actually a “black box” method because it did not consider the inner structure of neither one observed component (in this analysis observed components are turbine cylinders, cylinder segments and whole turbine) [16]. All isentropic analysis equations are defined according to operating points presented in Fig. 1 and Fig. 2. Equations for real (polytropic) and ideal (isentropic) mechanical power calculation of the cylinders and whole turbine are presented in Table 1, while equations for real (polytropic) and ideal (isentropic) mechanical power calculation of all cylinder segments are presented in Table 2.

Table 1. *Equations for real (polytropic) and ideal (isentropic) mechanical power calculation of the cylinders and whole turbine*

Comp.*	Real and ideal mechanical power**	Eq.
HPC	$P_{\text{re,HPC}}=\dot{m}_1\cdot(h_1-h_2)+(\dot{m}_1-\dot{m}_2)\cdot(h_2-h_3)$	(1)
	$P_{\text{id,HPC}}=\dot{m}_1\cdot\left(h_1-h_{2\text{IS,HPC}}\right)+(\dot{m}_1-\dot{m}_2)\cdot\left(h_{2\text{IS,HPC}}-h_{3\text{IS,HPC}}\right)$	(2)
IPC	$P_{\text{re,IPC}}=\dot{m}_5\cdot(h_5-h_6)+(\dot{m}_5-\dot{m}_6)\cdot(h_6-h_7)$	(3)
	$P_{\text{id,IPC}}=\dot{m}_5\cdot\left(h_5-h_{6\text{IS,IPC}}\right)+(\dot{m}_5-\dot{m}_6)\cdot\left(h_{6\text{IS,IPC}}-h_{7\text{IS,IPC}}\right)$	(4)
LPC	$P_{\text{re,LPC}}=\dot{m}_8\cdot(h_8-h_9)+(\dot{m}_8-\dot{m}_9)\cdot(h_9-h_{10})+(\dot{m}_8-\dot{m}_9-\dot{m}_{10})\cdot(h_{10}-h_{11})$	(5)
	$P_{\text{id,LPC}}=\dot{m}_8\cdot\left(h_8-h_{9\text{IS,LPC}}\right)+(\dot{m}_8-\dot{m}_9)\cdot\left(h_{9\text{IS,LPC}}-h_{10\text{IS,LPC}}\right)+\left(\dot{m}_8-\dot{m}_9-\dot{m}_{10}\right)\cdot\left(h_{10\text{IS,LPC}}-h_{11\text{IS,LPC}}\right)$	(6)
Whole turbine	$P_{\text{re,Whole turbine}}=P_{\text{re,HPC}}+P_{\text{re,IPC}}+P_{\text{re,LPC}}$	(7)
	$P_{\text{id,Whole turbine}}=P_{\text{id,HPC}}+P_{\text{id,IPC}}+P_{\text{id,LPC}}$	(8)

* Comp. = Component (Cylinders and Whole turbine)
** Indexes: re = real (polytropic); id = ideal (isentropic)

Table 2. *Equations for real (polytropic) and ideal (isentropic) mechanical power calculation of all cylinder segments*

Comp.*	Real and ideal mechanical power**	Eq.
Seg1	$P_{\text{re,Seg1}}=\dot{m}_1\cdot(h_1-h_2)$	(9)
	$P_{\text{id,Seg1}}=\dot{m}_1\cdot\left(h_1-h_{2\text{IS,Seg1}}\right)$	(10)
Seg2	$P_{\text{re,Seg2}}=(\dot{m}_1-\dot{m}_2)\cdot(h_2-h_3)$	(11)
	$P_{\text{id,Seg2}}=(\dot{m}_1-\dot{m}_2)\cdot\left(h_2-h_{3\text{IS,Seg2}}\right)$	(12)
Seg3	$P_{\text{re,Seg3}}=\dot{m}_5\cdot(h_5-h_6)$	(13)
	$P_{\text{id,Seg3}}=\dot{m}_5\cdot\left(h_5-h_{6\text{IS,Seg3}}\right)$	(14)
Seg4	$P_{\text{re,Seg4}}=(\dot{m}_5-\dot{m}_6)\cdot(h_6-h_7)$	(15)
	$P_{\text{id,Seg4}}=(\dot{m}_5-\dot{m}_6)\cdot\left(h_6-h_{7\text{IS,Seg4}}\right)$	(16)
Seg5	$P_{\text{re,Seg5}}=\dot{m}_8\cdot(h_8-h_9)$	(17)
	$P_{\text{id,Seg5}}=\dot{m}_8\cdot\left(h_8-h_{9\text{IS,Seg5}}\right)$	(18)
Seg6	$P_{\text{re,Seg6}}=(\dot{m}_8-\dot{m}_9)\cdot(h_9-h_{10})$	(19)
	$P_{\text{id,Seg6}}=(\dot{m}_8-\dot{m}_9)\cdot\left(h_9-h_{10\text{IS,Seg6}}\right)$	(20)
Seg7	$P_{\text{re,Seg7}}=(\dot{m}_8-\dot{m}_9-\dot{m}_{10})\cdot(h_{10}-h_{11})$	(21)
	$P_{\text{id,Seg7}}=(\dot{m}_8-\dot{m}_9-\dot{m}_{10})\cdot\left(h_{10}-h_{11\text{IS,Seg7}}\right)$	(22)

* Comp. = Component (Segments)
** Indexes: re = real (polytropic); id = ideal (isentropic)

Isentropic loss of all observed components (cylinders, segments and whole turbine) is calculated as:

$$IS_{\text{Loss,(i)}}=P_{\text{id,(i)}}-P_{\text{re,(i)}}, \tag{23}$$

while isentropic efficiency of all observed components (cylinders, segments and whole turbine) is calculated as:

$$\eta_{\text{IS,(i)}}=\frac{P_{\text{re,(i)}}}{P_{\text{id,(i)}}}. \tag{24}$$

In Eq. 23 and Eq. 24, index i is related to each observed cylinder, segment and whole turbine (i = HPC; IPC; LPC; Seg1; Seg2; Seg3; Seg4; Seg5; Seg6; Seg7 and Whole turbine).

4. Steam operating parameters required in the isentropic analysis of turbine cylinders and segments

Steam operating parameters for the real (polytropic) expansion process in turbine exploitation are found in [17] and presented in Table 3. Mentioned parameters in each operating point are steam temperature, pressure and mass flow rate. Other steam operating parameters from Table 3 are calculated by using NIST-REFPROP 9.0 software [18].

Every isentrope (related to each cylinder or segment) is obtained by mathematical calculations following previously described procedure. From Fig. 2 is clear that isentrope related to each turbine cylinder is not the same as isentrope related to each segment of each turbine cylinder. Therefore, steam operating parameters on the isentrope of each cylinder and each segment are presented independently. In Table 4 are presented steam operating parameters for the ideal (isentropic) expansion process related to each cylinder, while in Table 5 are presented steam operating parameters for the ideal (isentropic) expansion process related to each cylinder segment.

Table 3. *Steam operating parameters for the real (polytropic) expansion process*

O. P. *	Temp. (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality **
1	537.85	170.00	285.59	3394.7	6.4031	Sh.
2	428.95	79.53	32.39	3219.0	6.4841	Sh.
3	325.70	38.54	29.35	3035.3	6.5051	Sh.
4	325.70	38.54	223.85	3035.3	6.5051	Sh.
5	537.85	34.92	223.85	3537.5	7.2688	Sh.
6	434.35	17.17	13.82	3327.8	7.3132	Sh.
7	322.85	7.23	13.73	3106.8	7.3658	Sh.
8	322.85	7.23	196.30	3106.8	7.3658	Sh.
9	213.15	2.54	12.82	2894.8	7.4492	Sh.
10	100.15	0.77	7.34	2679.2	7.4892	Sh.
11	45.81	0.10	8.31	2401.1	7.5758	0.924
12	45.81	0.10	167.83	2401.1	7.5758	0.924

* O. P. = Operating Point (in accordance to Fig. 1 and Fig. 2)
** Sh. = Superheated steam; 1 = Dry saturated steam; 0 = Water

Table 4. *Steam operating parameters for the ideal (isentropic) expansion process related to each observed turbine cylinder*

Comp. *	O. P. **	Pressure (bar)	Specific entropy (kJ/kg·K)	Isentropic specific enthalpy (kJ/kg)
HPC	1	170.00	6.4031	3394.7
	2IS,HPC	79.53	6.4031	3163.0
	3IS,HPC	38.54	6.4031	2975.4
IPC	5	34.92	7.2688	3537.5
	6IS,IPC	17.17	7.2688	3296.7
	7IS,IPC	7.23	7.2688	3050.3
LPC	8	7.23	7.3658	3106.8
	9IS,LPC	2.54	7.3658	2855.1
	10IS,LPC	0.77	7.3658	2633.9
	11IS,LPC	0.10	7.3658	2334.1

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

Table 5. *Steam operating parameters for the ideal (isentropic) expansion process related to each cylinder segment*

Comp. *	O. P. **	Pressure (bar)	Specific entropy (kJ/kg·K)	Isentropic specific enthalpy (kJ/kg)
Seg1	1	170.00	6.4031	3394.7
	2IS,Seg1	79.53	6.4031	3163.0
Seg2	2	79.53	6.4841	3219.0
	3IS,Seg2	38.54	6.4841	3022.8
Seg3	5	34.92	7.2688	3537.5
	6IS,Seg3	17.17	7.2688	3296.7
Seg4	6	17.17	7.3132	3327.8
	7IS,Seg4	7.23	7.3132	3075.8
Seg5	8	7.23	7.3658	3106.8
	9IS,Seg5	2.54	7.3658	2855.1
Seg6	9	2.54	7.4492	2894.8
	10IS,Seg6	0.77	7.4492	2664.4
Seg7	10	0.77	7.4892	2679.2
	11IS,Seg7	0.1	7.4892	2373.5

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

5. Results and discussion

Real (polytropic) and ideal (isentropic) mechanical power of each cylinder and whole observed turbine are presented in Fig. 3.

From Fig. 3 is clear that LPC is the dominant mechanical power producer in the observed turbine – it produces 130.16 MW of mechanical power in the real expansion process and it can produce 142.80 MW of mechanical power if the expansion conditions are ideal. In any cylinder and whole turbine ideal (isentropic) mechanical power must be higher than real (polytropic) one because the ideal mechanical power did not consider any losses.

Whole observed turbine produces 320.21 MW of real mechanical power, and she can produce 362.13 MW of mechanical power in ideal expansion conditions.

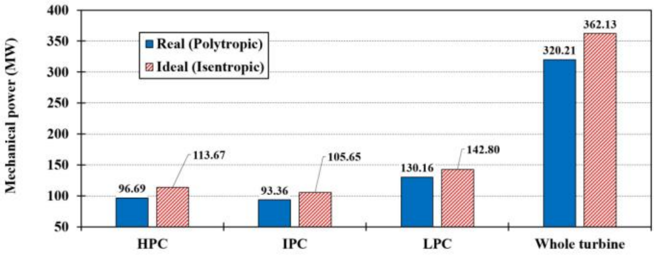

Fig. 3. *Mechanical power (real and ideal) for the whole observed turbine and each cylinder*

Isentropic loss and isentropic efficiency of the HPC and each HPC segment is presented in Fig. 4.

HPC is a good example of a cylinder which segments show much different performance and offer additional interesting information that cannot be obtained if the HPC is observed as a whole. Observing whole HPC, its isentropic efficiency is equal to 85.06% and isentropic loss is 16.98 MW, therefore the whole HPC shows satisfactory isentropic performance. However, Seg1 of the HPC has a very low isentropic efficiency (75.83%) and very high isentropic loss (15.99 MW). Such low isentropic efficiency and high isentropic loss of the Seg1 can be explained by a fact that through Seg1 expands steam of the highest pressure and temperature in the plant, what leads to increased losses and low efficiency. After expansion in Seg1, steam pressure and temperature notably drops, so Seg2 of the HPC has very low isentropic loss (3.17 MW) and very high isentropic efficiency (93.63%) in comparison to Seg1.

Finally, it can be concluded that the satisfactory isentropic performance of the whole HPC is a combination of two segment's isentropic performance – one of these segments show extremely good isentropic performance (Seg2), but another segment (Seg1) shows very poor isentropic performance.

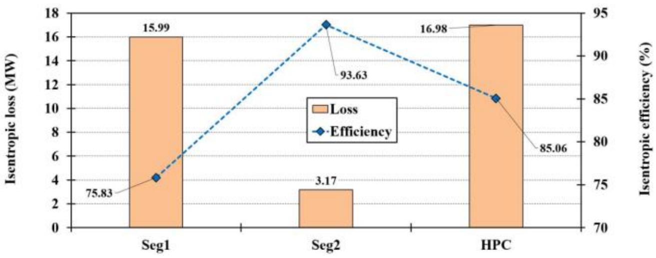

Fig. 4. *Isentropic loss and isentropic efficiency of the HPC and each HPC segment*

Isentropic loss and isentropic efficiency of the IPC and each IPC segment is presented in Fig. 5.

Whole IPC has satisfactory isentropic performance – isentropic efficiency of 88.36% and isentropic loss of 12.30 MW. Both IPC segments show similar isentropic performance – Seg3 has a slightly higher isentropic loss in comparison to Seg4, while Seg4 has slightly higher isentropic efficiency in comparison to Seg3. Such balanced isentropic performance of both IPC segments can be explained by a fact that IPC operates in optimal operating conditions (it is not influenced by the steam of the highest pressure as HPC and is not influenced by wet steam which occur at least in a last few LPC stages). Moreover, steam re-heater mounted between HPC and IPC surely has beneficial influence on the balanced isentropic performance of both IPC segments (Seg3 and Seg4).

Isentropic loss and isentropic efficiency of the LPC and each LPC segment is presented in Fig. 6.

From Fig. 6 is clear that the first LPC segment (Seg5) shows the worst isentropic performance (the highest isentropic loss of 7.79 MW and the lowest isentropic efficiency of 84.23%) in comparison to all other LPC segments. Seg6 has a very high isentropic efficiency of 93.58% and a low isentropic loss of 2.72 MW only. As the last LPC segment (Seg7) also has very high isentropic efficiency of 90.97%, regardless of that fact that at least last few stages of Seg7 operate with wet steam which increase losses, the whole LPC shows excellent isentropic performance. Whole LPC has an isentropic efficiency of 91.15% and isentropic loss of 12.64 MW. In comparison to other analyzed turbine cylinders, LPC has the highest isentropic efficiency.

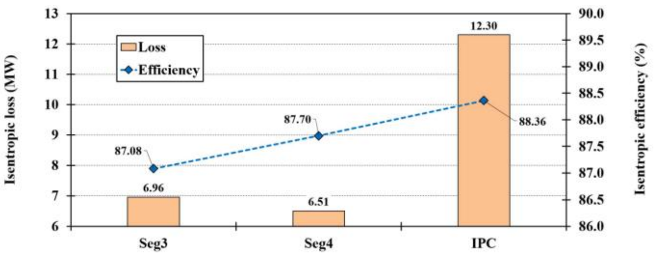

Fig. 5. Isentropic loss and isentropic efficiency of the IPC and each IPC segment

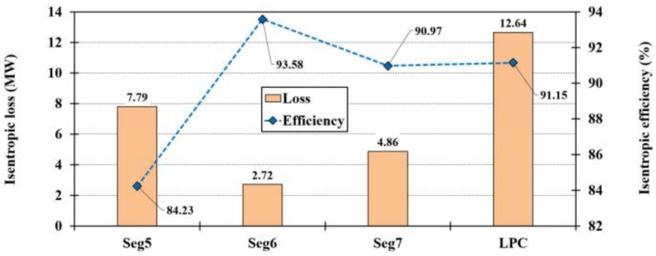

Fig. 6. Isentropic loss and isentropic efficiency of the LPC and each LPC segment

Whole observed steam turbine has an isentropic loss of 41.92 MW and isentropic efficiency of 88.42% what is better isentropic performance in comparison to similar steam turbines from conventional power plants [19].

6. Conclusions

In this paper are presented results of the isentropic analysis related to the cylinders, segments and whole three cylinder steam turbine from the conventional power plant. The most important conclusions obtained in the performed analysis are:

- LPC is the dominant mechanical power producer in the observed turbine of all cylinders – it produces 130.16 MW of mechanical power in the real expansion process and it can produce 142.80 MW of mechanical power if the expansion conditions are ideal.
- Satisfactory isentropic performance of the whole HPC is a combination of two segments isentropic performance – one of these segments show extremely good isentropic performance (Seg2), but another segment (Seg1) shows very poor isentropic performance.
- Both IPC segments (Seg3 and Seg4) show very similar isentropic performance, what result with the balanced IPC operation.
- The first LPC segment (Seg5) shows the worst isentropic performance (the highest isentropic loss of 7.79 MW and the lowest isentropic efficiency of 84.23%) in comparison to all other LPC segments.
- Whole LPC has an isentropic efficiency of 91.15% and the isentropic loss of 12.64 MW. In comparison to other analyzed turbine cylinders, LPC has the highest isentropic efficiency.
- Whole observed steam turbine has an isentropic loss of 41.92 MW and isentropic efficiency of 88.42% what is better isentropic performance in comparison to similar steam turbines from conventional power plants.

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8. References

[1] Leyzerovich, A. S. (2021). Steam turbines for modern fossil-fuel power plants. River Publishers.
[2] Elhelw, M., Al Dahma, K. S., & el Hamid Attia, A. (2019). Utilizing exergy analysis in studying the performance of steam power plant at two different operation mode. Applied Thermal Engineering, 150, 285-293. (doi:10.1016/j.applthermaleng.2019.01.003)
[3] Poljak, I., & Mrzljak, V. (2023). Thermodynamic Analysis and Comparison of Two Marine Steam Propulsion Turbines. NAŠE MORE: znanstveni časopis za more i pomorstvo, 70(2), 0-0. (doi:10.17818/NM/2023/2.2)
[4] Mrzljak, V., Prpić-Oršić, J., & Poljak, I. (2018). Energy power losses and efficiency of low power steam turbine for the main feed water pump drive in the marine steam propulsion system. Pomorski zbornik, 54(1), 37-51. (doi:10.18048/2018.54.03)
[5] Kostyuk, A., & Frolov, V. (1988). Steam and gas turbines. Mir Publishers.
[6] Mrzljak, V., Poljak, I., & Mrakovčić, T. (2017). Energy and exergy analysis of the turbo-generators and steam turbine for the main feed water pump drive on LNG carrier. Energy conversion and management, 140, 307-323. (doi:10.1016/j.enconman.2017.03.007)
[7] Mrzljak, V., Anđelić, N., Lorencin, I., & Sandi Baressi Šegota, S. (2021). The influence of various optimization algorithms on nuclear power plant steam turbine exergy efficiency and destruction. Pomorstvo, 35(1), 69-86. (doi:10.31217/p.35.1.8)
[8] Tanuma, T. (Ed.). (2022). Advances in steam turbines for modern power plants. Woodhead Publishing.
[9] Elčić, Z. (1995). Steam turbines. ABB, Karlovac, National and University Library Zagreb.
[10] Mrzljak, V., Poljak, I., & Medica-Viola, V. (2017). Thermodynamical analysis of high-pressure feed water heater in steam propulsion system during exploitation. Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike, 68(2), 45-61. (doi:10.21278/brod68204)
[11] Mrzljak, V., Prpić-Oršić, J., Musulin, J., & Štifanić, D. (2020). Energy and exergy analysis of deaerator from combined-cycle power plant. Trans Motauto World, 5(2), 64-67.
[12] Mrzljak, V., Poljak, I., & Medica-Viola, V. (2016). Efficiency and losses analysis of low-pressure feed water heater in steam propulsion system during ship maneuvering period. Pomorstvo, 30(2), 133-140. (doi:10.31217/p.30.2.6)
[13] Kanoğlu, M., Çengel, Y. A. & Dincer, I. (2012). Efficiency Evaluation of Energy Systems. Springer Briefs in Energy. (doi:10.1007/978-1-4614-2242-6)
[14] Medica-Viola, V., Baressi Šegota, S., Mrzljak, V., & Štifanić, D. (2020). Comparison of conventional and heat balance based energy analyses of steam turbine. Pomorstvo, 34(1), 74-85. (doi:10.31217/p.34.1.9)
[15] Mrzljak, V., Poljak, I., Jelić, M., & Prpić-Oršić, J. (2023). Thermodynamic Analysis and Improvement Potential of Helium Closed Cycle Gas Turbine Power Plant at Four Loads. Energies, 16(15), 5589. (doi:10.3390/en16155589)
[16] Dincer, I., & Rosen, M. A. (2012). Exergy: energy, environment and sustainable development. Newnes.
[17] Kabiri, S., Khoshgoftar Manesh, M. H., & Amidpour, M. (2020). 4E analysis and evaluation of a steam power plant full repowering in various operations. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-21. (doi:10.1080/15567036.2020.1761484)
[18] Lemmon, E. W., Huber, M. L., & McLinden, M. O. (2010). NIST Standard Reference Database 23, Reference Fluid Thermodynamic and Transport Properties (REFPROP), version 9.0, National Institute of Standards and Technology. R1234yf. fld file dated December, 22, 2010.
[19] Mrzljak, V., Jelić, M., Poljak, I., & Prpić-Oršić, J. (2023). Analysis and Comparison of Main Steam Turbines from Four Different Thermal Power Plants. Pomorstvo, 37(1), 58-74. (doi:10.31217/p.37.1.6)