Energy (isentropic) analysis of three-cylinder steam turbine with re-heating

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Abstract: *In this paper is presented energy (isentropic) analysis of high power, three-cylinder steam turbine with steam re-heating. A comparison of real (polytropic) and ideal (isentropic) steam expansion processes at nominal load show that observed turbine develops real power of 655.35 MW, while in ideal situation it can develop 716.18 MW. The highest energy loss and the lowest energy efficiency occur in the high pressure turbine cylinder (25.67 MW and 89.14%), while intermediate pressure cylinder has the highest energy efficiency and the lowest energy loss. The energy efficiency of the whole observed turbine is 91.51%, what is in the expected range for such high power steam turbines at nominal load. Further optimization of this steam turbine will be primarily based on the high pressure cylinder.*

KEYWORDS: ENERGY (ISENTROPIC) ANALYSIS, STEAM TURBINE, ENERGY EFFICIENCY, ENERGY LOSS

1. Introduction

Steam turbines are the dominant power producers which drive electric generators for the electricity production worldwide [1]. Steam turbines can operate in conventional power plants [2], combined power plants (where steam is produced from flue gases of gas turbine) [3], marine power plants [4] and many others.

Steam turbines are complex power producers which consist of many stages, elements and sub-systems. In various power plants can be found steam turbines which consist of several cylinders (single-flow or dual-flow) as well as steam re-heater due to many benefits which it brings in entire power plant operation [5]. However, many low power steam turbines usually consist of only one single-flow cylinder (in some situations it can also be only one Curtis stage) for the drive of auxiliary components (pumps, compressors, etc.) [6].

In this paper is performed energy (isentropic) analysis of high power steam turbine, which consists of three cylinders and has a re-heater between high pressure and intermediate pressure cylinders. The analysis is performed for each turbine cylinder as well as for the whole steam turbine. Calculated power distribution, energy efficiencies and losses for the whole turbine and each of its cylinders at nominal load present interesting overview of turbine operation, while the obtained conclusions can be used as a guideline in future research and improvements.

2. Description and operating process of the analyzed three-cylinder steam turbine with re-heating

Analyzed steam turbine consists of three cylinders: High Pressure Cylinder (HPC), Intermediate Pressure Cylinder (IPC) and Low Pressure Cylinder (LPC). All the cylinders are connected to the same shaft which drives an electric generator, as presented in Fig. 1.

Steam produced in steam generator [7] is delivered to HPC which has two steam extractions - both of them lead steam to high pressure feed water heaters [8]. After expansion in HPC, remaining steam mass flow rate is lead to steam re-heater, which increases steam temperature (along with pressure drop due to losses which occurs in re-heater). After re-heater steam enters into IPC which also has two steam extractions - first extraction leads steam to high pressure heater while second extraction leads steam to the deaerator. Remaining steam mass flow rate which exits IPC enters in LPC. LPC has three steam extractions - all of them lead steam to low pressure feed water heaters [9]. After expansion in LPC, remaining steam mass flow rate is lead to steam condenser for condensation [10].

It should be noted that steam mass flow rates leaked through the front and rear gland seals of each cylinder [11] are neglected in this analysis due to lack of such data. However, in real operation, steam mass flow rate leaked through both gland seals of each turbine cylinder will be led to gland steam condenser [12].

Fig. 1 also presents operating points required for the observed turbine and all of its cylinders energy (isentropic) analysis.

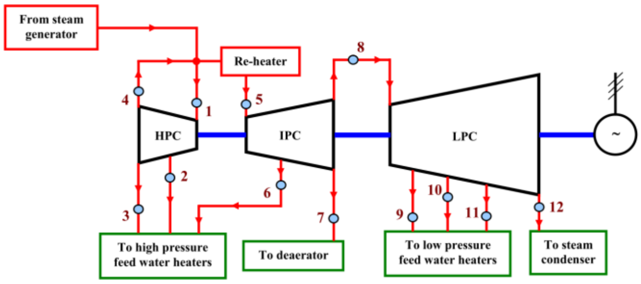

Fig. 1. *General scheme of steam turbine along with operating points required for the analysis*

Steam expansion processes of each analyzed turbine cylinder (real and ideal) in *h-s* diagram are presented in Fig. 2. Real (polytropic) expansion processes are: for the HPC - 1-2-3; for the IPC - 5-6-7 and for the LPC - 8-9-10-11-12, while ideal (isentropic) expansion processes are: for the HPC - 1-2is-3is; for the IPC - 5-6is-7is and for the LPC - 8-9is-10is-11is-12is. According to those operating points for both expansion processes in each turbine cylinder, presented in Fig. 2, will be shown operating parameters obtained during the turbine exploitation (real process at nominal turbine load), as well as operating parameters of ideal expansion (obtained by retaining constant steam specific entropy in each turbine cylinder).

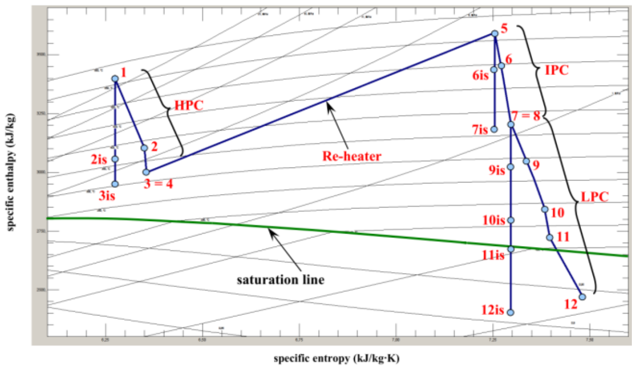

Fig. 2. *h-s diagram of the real (polytropic) and ideal (isentropic) expansion processes inside each cylinder of the analyzed steam turbine*

3. Energy analysis equations

3.1. Overall energy analysis equations

Energy analysis is defined by the first law of thermodynamics [13] and is independent of the ambient conditions in which control volume or a system operates. Mass and energy balance equations for a control volume or a system in steady state, disregarding potential and kinetic energy, can be expressed according to [14] as:

$$\sum \dot{m}_{\mathrm{IN}} = \sum \dot{m}_{\mathrm{OUT}} , \tag{1}$$

$$\dot{Q}_{IN} + P_{IN} + \sum(\dot{m}_{IN} \cdot h_{IN}) = \\ = \dot{Q}_{OUT} + P_{OUT} + \sum(\dot{m}_{OUT} \cdot h_{OUT}), \quad (2)$$

where $\dot{m}$ is mass flow rate (kg/s), $\dot{Q}$ is heat transfer (kW), P is power (kW), h is operating medium specific enthalpy (kJ/kg), IN denotes input (inlet) and OUT denotes output (outlet).

Operating medium energy flow [15] is calculated as:

$$\dot{E} = \dot{m} \cdot h, \quad (3)$$

where $\dot{E}$ is energy flow of operating medium (kW).

General definition of control volume or system energy efficiency is [16]:

$$\eta = \frac{\text{energy output}}{\text{energy input}}, \quad (4)$$

where η is energy efficiency (%).

Mentioned overall equations are used in the energy (isentropic) analysis of observed steam turbine and each of its cylinders.

3.2. Energy (isentropic) analysis of the observed steam turbine

Energy (isentropic) analysis of entire observed steam turbine and each of its cylinders is based on the comparison of real (polytropic) and ideal (isentropic) steam expansion processes.

Equations for the calculation of all required variables in energy (isentropic) analysis of the observed turbine and its cylinders are presented in Table 1 and Table 2. In Table 1 are presented equations for HPC and IPC, while in Table 2 are presented equations for LPC and whole turbine. Markings in all the equations from Table 1 and Table 2 are defined in accordance to Fig. 2.

Table 1. *Equations for the energy (isentropic) analysis of steam turbine HPC and IPC*

	HPC	Eq.	IPC	Eq.
Real (polytropic) power (kW)	$P_{HPC,re} = \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3)$	(5)	$P_{IPC,re} = \dot{m}_5 \cdot (h_5 - h_6) + (\dot{m}_5 - \dot{m}_6) \cdot (h_6 - h_7)$	(10)
Ideal (isentropic) power (kW)	$P_{HPC,is} = \dot{m}_1 \cdot (h_1 - h_{2is}) + (\dot{m}_1 - \dot{m}_2) \cdot (h_{2is} - h_{3is})$	(6)	$P_{IPC,is} = \dot{m}_5 \cdot (h_5 - h_{6is}) + (\dot{m}_5 - \dot{m}_6) \cdot (h_{6is} - h_{7is})$	(11)
Energy loss (kW)	$\dot{E}_{loss,HPC} = P_{HPC,is} - P_{HPC,re}$	(7)	$\dot{E}_{loss,IPC} = P_{IPC,is} - P_{IPC,re}$	(12)
Specific energy loss (%)	$\dot{E}_{sp,loss,HPC} = \frac{\dot{E}_{loss,HPC}}{P_{HPC,re}}$	(8)	$\dot{E}_{sp,loss,IPC} = \frac{\dot{E}_{loss,IPC}}{P_{IPC,re}}$	(13)
Energy efficiency (%)	$\eta_{HPC} = \frac{P_{HPC,re}}{P_{HPC,is}}$	(9)	$\eta_{IPC} = \frac{P_{IPC,re}}{P_{IPC,is}}$	(14)

Table 2. *Equations for the energy (isentropic) analysis of LPC and whole steam turbine*

	LPC	Eq.	WHOLE TURBINE	Eq.
Real (polytropic) power (kW)	$P_{LPC,re} = \dot{m}_8 \cdot (h_8 - h_9) + (\dot{m}_8 - \dot{m}_9) \cdot (h_9 - h_{10}) + (\dot{m}_8 - \dot{m}_9 - \dot{m}_{10}) \cdot (h_{10} - h_{11}) + \dot{m}_{12} \cdot (h_{11} - h_{12})$	(15)	$P_{WT,re} = \sum P_{re,cylinders}$	(20)
Ideal (isentropic) power (kW)	$P_{LPC,is} = \dot{m}_8 \cdot (h_8 - h_{9is}) + (\dot{m}_8 - \dot{m}_9) \cdot (h_{9is} - h_{10is}) + (\dot{m}_8 - \dot{m}_9 - \dot{m}_{10}) \cdot (h_{10is} - h_{11is}) + \dot{m}_{12} \cdot (h_{11is} - h_{12is})$	(16)	$P_{WT,is} = \sum P_{is,cylinders}$	(21)
Energy loss (kW)	$\dot{E}_{loss,LPC} = P_{LPC,is} - P_{LPC,re}$	(17)	$\dot{E}_{loss,WT} = P_{WT,is} - P_{WT,re}$	(22)
Specific energy loss (%)	$\dot{E}_{sp,loss,LPC} = \frac{\dot{E}_{loss,LPC}}{P_{LPC,re}}$	(18)	$\dot{E}_{sp,loss,WT} = \frac{\dot{E}_{loss,WT}}{P_{WT,re}}$	(23)
Energy efficiency (%)	$\eta_{LPC} = \frac{P_{LPC,re}}{P_{LPC,is}}$	(19)	$\eta_{WT} = \frac{P_{WT,re}}{P_{WT,is}}$	(24)

4. Turbine steam operating parameters required for the energy (isentropic) analysis

Energy (isentropic) analysis of any steam turbine or any of its cylinders requires knowledge of steam specific enthalpies and mass flow rates in each operating point for the real (polytropic) and ideal (isentropic) steam expansion processes.

For the observed turbine, steam mass flow rates, pressures and temperatures in each operating point of the real (polytropic) expansion process, Fig. 1, are found in [17] and presented in Table 3. Steam specific enthalpies and specific entropies are calculated in each operating point from known steam temperature and pressure by using Nist-REFPROP 9.0 software [18]. Steam specific entropies are necessary for two reasons - for proper defining isentropic (ideal) steam expansion process through each turbine cylinder and for data validation (in real steam expansion process steam specific entropy should increase from the inlet into the first turbine cylinder until the outlet of the last turbine cylinder).

Table 3. *Steam parameters in each operating point for real (polytropic) expansion (nominal turbine load)*

O.P.*	Pressure (MPa)	Temperature (°C)	Mass flow rate (kg/s)	Steam specific enthalpy (kJ/kg)	Steam specific entropy (kJ/kg·K)
1	23.72	564.3	536.88	3398.6	6.2737
2	7.28	381.8	38.14	3103.4	6.3500
3	4.77	321.9	43.97	2998.7	6.3551
4	4.77	321.9	454.77	2998.7	6.3551
5	4.2	565.7	454.77	3594.5	7.2545
6	2.36	473.6	26.39	3405.7	7.2764
7	1.22	376.8	30.91	3211.2	7.2961
8	1.22	376.8	397.48	3211.2	7.2961
9	0.44	255.4	14.19	2974.2	7.3556
10	0.24	191.3	14.48	2851.1	7.3831
11	0.12	123.5	29.05	2721.7	7.3975
12	0.02	60.1	339.75	2467.5	7.4827

* Operating points (O.P.) are defined according to Fig. 1 and Fig. 2.

Ideal (isentropic) steam expansion process is a process between the same pressures and with identical mass flow rates as in the real (polytropic) one, but while retaining the same steam specific entropy [19]. As presented in Fig. 2, ideal (isentropic) steam expansion process for each turbine cylinder is defined from the cylinder inlet until the outlet, without any change in steam specific entropy during the expansion.

According to such ideal expansion process, each turbine cylinder will develop higher power (in comparison to real process), because this process did not take into account losses during steam expansion. Steam parameters in each operating point of each observed turbine cylinder, Fig. 2, during ideal (isentropic) steam expansion process are summarized and presented in Table 4.

Table 4. *Steam parameters in each operating point for ideal (isentropic) expansion (nominal turbine load)*

O.P.*	Pressure (MPa)	Temperature (°C)	Steam specific entropy (kJ/kg·K)	Steam specific enthalpy (kJ/kg)
1	23.72	564.3	6.2737	3398.6
2is	7.28	364.8	6.2737	3054.0
3is	4.77	305.5	6.2737	2951.0
5	4.20	565.7	7.2545	3594.5
6is	2.36	466.3	7.2545	3389.4
7is	1.22	364.3	7.2545	3184.5
8	1.22	376.8	7.2961	3211.2
9is	0.44	240.4	7.2961	2943.2
10is	0.24	172.0	7.2961	2811.6
11is	0.12	104.8	7.2961	2682.5
12is	0.02	60.1	7.2961	2405.3

* Operating points (O.P.) are defined according to Fig. 2.

5. Results and discussion

A comparison of real and ideal developed power for the whole observed steam turbine and each of its cylinders is presented in Fig. 3. The whole turbine develops real power equal to 655.35 MW; while in the ideal conditions, it could develop 716.18 MW (if in all turbine cylinders isentropic steam expansion occurs).

While observing turbine cylinders, the highest power (both real and ideal) develops LPC, while the lowest power (again, both real and ideal) will be developed in IPC. For the LPC, which is a dominant power producer, should be noted that its operating conditions are worst in comparison to other cylinders (high steam volume flow rate, occurrence of water droplets in steam for the last few stages - under the saturation line, long curved turbine blades - high centrifugal forces, etc.), therefore this cylinder should be carefully designed and maintained.

Steam re-heat process applied for the observed turbine, Fig. 1 and Fig. 2, ensures operation of the majority of LPC turbine stages in the superheated area (an area in which water droplets did not occur), therefore it surely improves turbine operation and have a positive influence on the entire power plant efficiency.

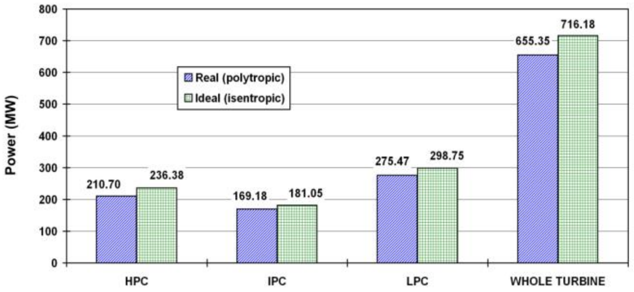

Fig. 3. Real and ideal power of each turbine cylinder and the whole turbine

Energy loss of the entire analyzed steam turbine and all of its cylinders are calculated as a difference between real (polytropic) and ideal (isentropic) power. The whole turbine energy loss equals to 60.82 MW, while when observing turbine cylinders the highest energy loss occurs in HPC (25.67 MW) and the lowest energy loss can be seen in IPC (11.87 MW), Fig. 4.

Specific energy loss of the whole turbine and all of its cylinders is obtained by dividing the energy loss with real (polytropic) developed power. This variable is similar to specific fuel consumption, which is a commonly used for defining operating conditions of internal combustion engines [20, 21]. In the case of the analyzed steam turbine and all of its cylinders, it can be concluded that the dominant value of specific energy loss occurs in HPC (12.18%), which means that HPC has the highest energy loss in regards to real developed power (significantly higher when compared to other cylinders and to the whole turbine). The lowest specific energy loss is observed for IPC (7.01%), while the whole observed steam turbine has specific energy loss equal to 9.28%.

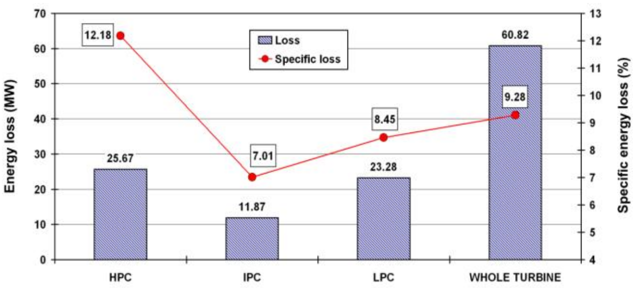

Fig. 4. Energy loss and specific energy loss of each cylinder and the whole turbine

Comparison of Fig. 4 and Fig. 5 leads to the important conclusion that for the whole observed turbine and each of its cylinders specific energy loss and energy efficiency are reverse proportional.

HPC which has the highest specific energy loss, Fig. 4, simultaneously has the lowest energy efficiency equal to 89.14%, Fig. 5, while the highest energy efficiency (93.44%) can be observed in the IPC, which has the lowest specific energy loss.

Whole analyzed steam turbine has energy efficiency equal to 91.51%. In comparison to low power steam turbines [22], turbine analyzed in this paper has a much higher energy efficiency what is expected for such high power steam turbine.

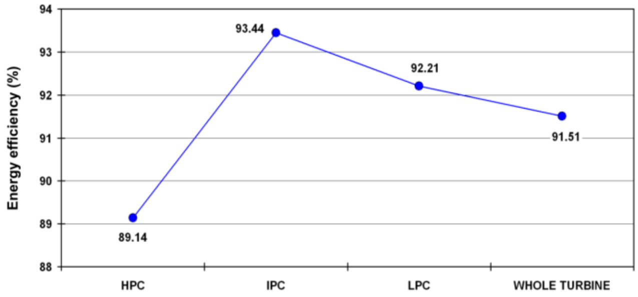

Fig. 5. The energy efficiency of each turbine cylinder and the whole turbine

6. Conclusions

The paper present energy (isentropic) analysis of three-cylinder high power steam turbine in which operation process is included steam re-heater. Comparison of steam expansion processes (ideal and real) through each turbine cylinder at nominal load leads to several notable conclusions:

- While observing turbine cylinders, the highest power (both real and ideal) develops low pressure cylinder, while the lowest power is developed in the intermediate pressure cylinder. A whole turbine at nominal load develop real power equal to 655.35 MW, while ideal (isentropic) power which can be obtained in ideal situation is 716.18 MW.
- Due to the highest steam pressures and temperatures, high pressure turbine cylinder has the highest energy loss, while the lowest energy loss occurs in the intermediate pressure cylinder. The same conclusion is valid if observing specific energy loss. The energy loss in the whole observed turbine is 60.82 MW and specific energy loss for the whole turbine is 9.28%.
- Specific energy loss of any turbine cylinder and of the whole turbine is reverse proportional to energy efficiency.
- High pressure cylinder has the lowest, while intermediate pressure cylinder has the highest energy efficiency (89.14% in comparison to 93.44%). The energy efficiency of the whole observed turbine is 91.51%, what is in the expected range for such high power steam turbines at nominal load.
- Further research and possible improvements will be firstly based on high pressure turbine cylinder and the aim will be to decrease its losses and increase its efficiency.

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