Energy analysis of a steam turbine with two cylinders and steam re-heating

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Abstract: *This paper presents an energy analysis of middle-power steam turbine with two cylinders (High Pressure Cylinder - HPC and Low Pressure Cylinder - LPC) and steam re-heater after the HPC (and before the LPC). Based on a steam operating parameters from the literature, performed energy analysis show that LPC develops higher power and has higher energy efficiency (81.45%) in comparison to HPC (which energy efficiency equals 80.12%). Re-heater is a heat exchanger (flue gases are used for steam heating) which has low energy loss (824.19 kW) and high energy efficiency (97.76%), what is expected energy performance of such heat exchanger. The entire analyzed turbine develops a power of 127480.60 kW and has energy loss equal to 29848.21 kW with energy efficiency of 81.03%.*
KEYWORDS*: STEAM TURBINE, TURBINE CYLINDERS, STEAM RE-HEATING, ENERGY ANALYSIS*

1. Introduction

Nowadays, steam turbines are mostly used for the electricity production in steam power plants [1]. Such high-power steam turbines usually consist of at least three turbine cylinders (high, middle and low pressure cylinders) connected to the same shaft which drives an electricity generator [2].

As opposite to high-power steam plants, it is also possible to find a lot of steam power plants with low or medium developed power. Steam turbines in such plants usually consist of only one [3, 4] or two [5] turbine cylinders. In such situations, if the steam turbine is composed of two cylinders, between them is usually mounted steam re-heater, which increases steam temperature before expansion in the second cylinder [6].

In this paper is presented an energy analysis of middle-power steam turbine, which consists of two cylinders (High Pressure Cylinder - HPC and Low Pressure Cylinder - LPC) with steam re-heater after HPC. Energy power of each fluid flow stream was investigated. It is presented change in ideal and real developed power of each cylinder and the entire turbine. For the steam re-heater is calculated energy inputs and outputs. For each component of investigated turbine are calculated energy loss and energy efficiency.

2. Description and characteristics of analyzed steam turbine with two cylinders and steam re-heating

Analyzed steam turbine with all of its components is presented in Fig. 1. Steam turbine has two cylinders, High Pressure Cylinder - HPC and Low Pressure Cylinder - LPC. Between turbine cylinders is mounted steam re-heater - heat exchanger which uses flue gases to increase the steam temperature before it enters into LPC.

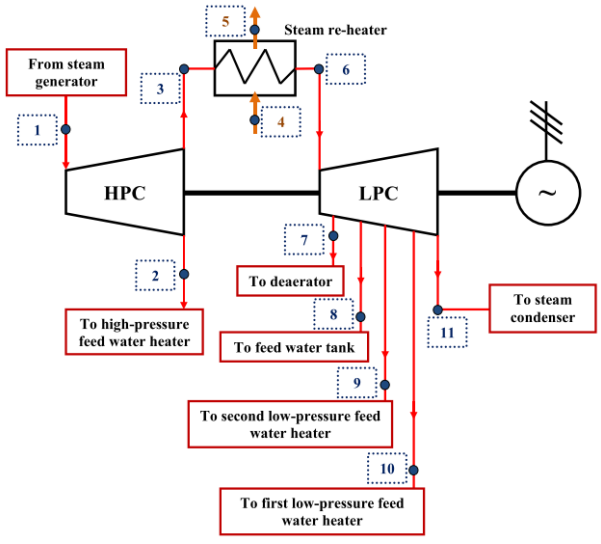

Fig. 1. *Scheme and operating points of the analyzed steam turbine with steam re-heating*

HPC gets steam directly from steam generator and has one steam extraction, near the cylinder end - those extraction lead steam to high-pressure feed water heater. Remaining steam at the HPC outlet after the expansion was led to steam re-heater. LPC gets steam after re-heater, which increases its temperature. LPC has four steam extractions which led steam to deaerator, feed water tank and to two low-pressure feed water heaters. After expansion, steam was led from the LPC directly to steam condenser. Both steam turbine cylinders are connected with one shaft and the produced power is delivered by the same shaft to an electricity generator.

Based on steam operating parameters at each observed point from Fig. 1 (which are presented in Table 1), it is drawn observed steam expansion process in h-s diagram by using NIST-REFPROP 9.0 software [7] and presented in Fig. 2. The operating points of the real steam expansion process in Fig. 2 are drawn by using the same marking as in Fig. 1, while the operating points of ideal (isentropic) steam expansion process in Fig. 2 are marked with extension - is. Ideal (isentropic) steam expansion assumes always the same steam specific entropy. The same markings are used in equations for the turbine energy analysis. From Fig. 2 can be seen that all observed turbine process is in the field of superheated steam except at the end of expansion in LPC (operating points from 10 to 11) when the process falls in the steam saturated area. Steam re-heat process is characterized by an increase in superheated steam temperature and with a pressure drop during heat exchange.

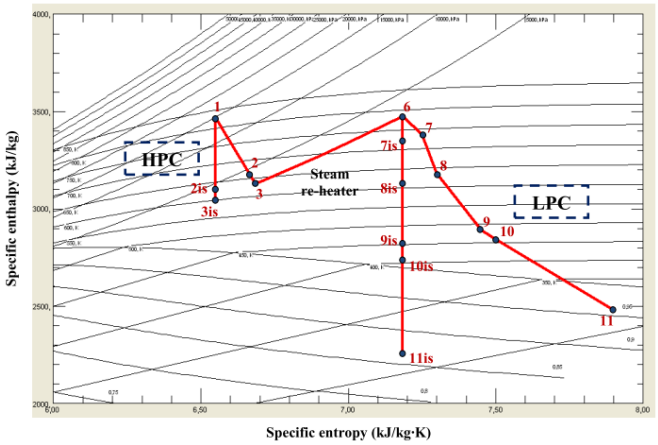

Fig. 2. *Operating process of the analyzed steam turbine in h-s diagram (for each turbine cylinder are presented ideal (isentropic – index is) and real (polytropic) steam expansions)*

3. Energy analysis

Energy analysis of any control volume or a system is defined by the first law of thermodynamics [8] which is based on the energy conservation [9]. Energy analysis does not take into account the parameters of the ambient (temperature and pressure) in which control volume or a system operates [10].

3.1. Overall equations for the energy analysis

For the analyzed control volume (steam turbine with all of its components) or a system are valid the same overall energy analysis equations. Mass and energy balance equations for a control volume or a system in steady state can be found in [11, 12]:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \tag{1}$$

$$\dot{Q}_{\text{in}} + P_{\text{in}} + \sum \dot{m}_{\text{in}} \cdot \left(h + \frac{c^2}{2} + g \cdot z \right)_{\text{in}} = \dot{Q}_{\text{out}} + P_{\text{out}} + \sum \dot{m}_{\text{out}} \cdot \left(h + \frac{c^2}{2} + g \cdot z \right)_{\text{out}} \tag{2}$$

Energy power of a flow for any fluid stream is [13]:

$$\dot{E}_{\text{en}} = \dot{m} \cdot h \tag{3}$$

A general energy efficiency equation of any system or control volume can be defined according to [14, 15] as:

$$\eta_{\text{en}} = \frac{\text{Energy output}}{\text{Energy input}} \tag{4}$$

3.2. Equations for the energy analysis of investigated turbine

Energy analysis of the investigated steam turbine and all of its components is based on turbine operating points presented in Fig. 1 and Fig. 2. For the High Pressure Cylinder (HPC) energy analysis equations are (according to [16]):

HPC real (polytropic) developed power:

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

HPC ideal (isentropic) power:

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

HPC energy loss:

$$\dot{E}_{\text{en,HPC,loss}} = P_{\text{HPC,IS}} - P_{\text{HPC,RE}} \tag{7}$$

HPC energy efficiency:

$$\eta_{\text{en,HPC}} = \frac{P_{\text{HPC,RE}}}{P_{\text{HPC,IS}}} \tag{8}$$

Energy analysis equations for the Low Pressure Cylinder (LPC) are (according to [17]):

LPC real (polytropic) developed power:

$$P_{\text{LPC,RE}} = \dot{m}_6 \cdot (h_6 - h_7) + (\dot{m}_6 - \dot{m}_7) \cdot (h_7 - h_8) + (\dot{m}_6 - \dot{m}_7 - \dot{m}_8) \cdot (h_8 - h_9) + \\ + (\dot{m}_6 - \dot{m}_7 - \dot{m}_8 - \dot{m}_9) \cdot (h_9 - h_{10}) + (\dot{m}_6 - \dot{m}_7 - \dot{m}_8 - \dot{m}_9 - \dot{m}_{10}) \cdot (h_{10} - h_{11}) \tag{9}$$

LPC ideal (isentropic) power:

$$P_{\text{LPC,IS}} = \dot{m}_6 \cdot (h_6 - h_{7\text{is}}) + (\dot{m}_6 - \dot{m}_7) \cdot (h_{7\text{is}} - h_{8\text{is}}) + (\dot{m}_6 - \dot{m}_7 - \dot{m}_8) \cdot (h_{8\text{is}} - h_{9\text{is}}) + \\ + (\dot{m}_6 - \dot{m}_7 - \dot{m}_8 - \dot{m}_9) \cdot (h_{9\text{is}} - h_{10\text{is}}) + (\dot{m}_6 - \dot{m}_7 - \dot{m}_8 - \dot{m}_9 - \dot{m}_{10}) \cdot (h_{10\text{is}} - h_{11\text{is}}) \tag{10}$$

LPC energy loss:

$$\dot{E}_{\text{en,LPC,loss}} = P_{\text{LPC,IS}} - P_{\text{LPC,RE}} \tag{11}$$

LPC energy efficiency:

$$\eta_{\text{en,LPC}} = \frac{P_{\text{LPC,RE}}}{P_{\text{LPC,IS}}} \tag{12}$$

Energy analysis equations for the entire steam turbine:

Turbine real (polytropic) developed power:

$$P_{\text{turbine,RE}} = P_{\text{HPC,RE}} + P_{\text{LPC,RE}} \tag{13}$$

Turbine ideal (isentropic) power:

$$P_{\text{turbine,IS}} = P_{\text{HPC,IS}} + P_{\text{LPC,IS}} \tag{14}$$

Turbine energy loss:

$$\dot{E}_{\text{en,turbine,loss}} = P_{\text{turbine,IS}} - P_{\text{turbine,RE}} \tag{15}$$

Turbine energy efficiency:

$$\eta_{\text{en,turbine}} = \frac{P_{\text{turbine,RE}}}{P_{\text{turbine,IS}}} \tag{16}$$

Equations for the energy analysis of steam re-heater [18]:

Steam re-heater energy input:

$$\dot{E}_{\text{en,re-heater,in}} = \dot{m}_4 \cdot h_4 - \dot{m}_5 \cdot h_5 = \dot{m}_4 \cdot (h_4 - h_5) \tag{17}$$

Steam re-heater energy output:

$$\dot{E}_{\text{en,re-heater,out}} = \dot{m}_6 \cdot h_6 - \dot{m}_3 \cdot h_3 = \dot{m}_6 \cdot (h_6 - h_3) \tag{18}$$

Steam re-heater energy loss:

$$\dot{E}_{\text{en,re-heater,loss}} = \dot{E}_{\text{en,re-heater,in}} - \dot{E}_{\text{en,re-heater,out}} \tag{19}$$

Steam re-heater energy efficiency:

$$\eta_{\text{en,re-heater}} = \frac{\dot{E}_{\text{en,re-heater,out}}}{\dot{E}_{\text{en,re-heater,in}}} \tag{20}$$

4. Operating parameters of the analyzed steam turbine

Operating parameters of the investigated steam turbine (Fig. 1) were found in [19] and modified in order to perform complete energy analysis. Modified steam and flue gases operating parameters (temperatures, pressures and mass flow rates from each operating point - Fig. 1) are presented in Table 1. From known pressures and temperatures are calculated additional operating parameters of steam in each operating point required for the energy analysis – specific enthalpies, specific entropies and specific volumes by using NIST-REFPROP 9.0 software [7].

Specific enthalpies of flue gases in each operating point are calculated by using the following equation:

$$h_{\text{FG}} = c_{\text{p,FG}} \cdot T_{\text{FG}} \tag{21}$$

where the specific heat capacity at constant pressure of flue gasses is a function of current flue gas temperature and is calculated as [19]:

$$c_{\text{p,FG}} = 0.9375 + \frac{0.03074}{10^2} \cdot T_{\text{FG}} + \frac{0.003116}{10^5} \cdot T_{\text{FG}}^2 - \frac{0.03902}{10^9} \cdot T_{\text{FG}}^3 \tag{22}$$

In the equation (22) flue gases temperature should be placed in (K) to obtain specific heat capacity at constant pressure c_{p} in (kJ/kg·K).

Table 1. *Steam and flue gases operating parameters of the analyzed turbine (modified from [19])*

O. P.*	Fluid	Temperature (K)	Pressure (kPa)	Mass flow rate (kg/s)
1	Steam	829.60	14896.00	119.25
2	Steam	643.15	3890.00	15.51
3	Steam	635.93	3667.00	103.74
4	Flue gases	1139.23	112.84	177.88
5	Flue gases	1002.48	110.74	177.88
6	Steam	785.32	3580.00	103.74
7	Steam	737.41	2353.00	6.97
8	Steam	635.99	1100.00	6.86
9	Steam	484.66	250.00	7.12
10	Steam	459.62	180.00	4.87
11	Steam	316.09	8.625	77.92

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

5. The results and discussion

Energy power of each fluid flow stream from the analyzed steam turbine is calculated by using equation (3) and presented in Fig. 3 for each observed turbine operating point. The highest energy power has steam at the HPC inlet (operating point 1) which is equal

to 413666.33 kW. The flue gases are the heating medium for steam which exits from the HPC - therefore, energy power of flue gases decreases from operating point 4 to operating point 5, while steam energy power increases from the HPC outlet to the LPC inlet (from operating point 3 to operating point 6, according to Fig. 1). From Fig. 3 should also be noted that energy power of steam flows extracted from both turbine cylinders (operating points 2, 7, 8, 9 and 10) is much lower when compared to energy power of steam flows at each cylinder inlet and outlet (operating points 1, 3, 6 and 11). Energy power of steam flows extracted from both turbine cylinders decreases developed power of each cylinder and the entire turbine what can be considered as turbine (or cylinder) lost power [20].

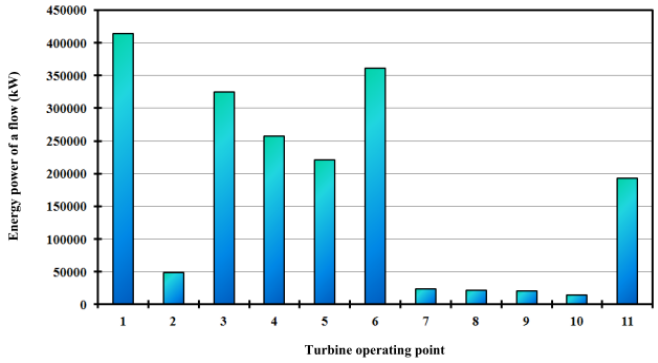

Fig. 3. *Energy power of each fluid flow stream from the analyzed steam turbine and its steam re-heater*

Real (polytropic) developed power of the entire analyzed steam turbine equals to 127480.60 kW (39966.42 kW for the HPC and 87514.18 kW for the LPC), Fig. 4. Ideal (isentropic) power of the entire steam turbine, as well as of each turbine cylinder, is always higher than the real (polytropic) one, because the ideal expansion process assumes always the same steam specific entropy, Fig. 2. Therefore, the ideal (isentropic) power of the entire steam turbine equals to 157328.81 kW (49885.02 kW for the HPC and 107443.79 kW for the LPC). Energy loss of the entire turbine and each turbine cylinder is the difference between the ideal (isentropic) and real (polytropic) turbine or cylinder power. For the entire turbine energy loss equals to 29848.21 kW (9918.60 kW for the HPC and 19929.61 kW for the LPC), Fig. 4.

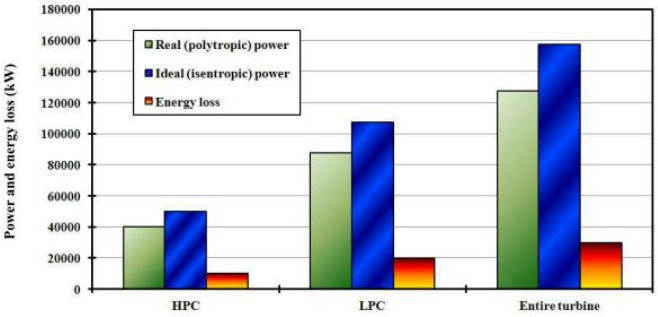

Fig. 4. *Energy loss and developed power (real and ideal) for each turbine cylinder and the entire steam turbine*

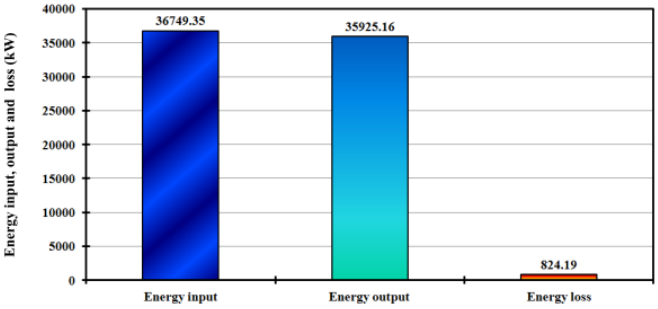

Fig. 5. *Energy input, output and loss of steam re-heater from the analyzed steam turbine system*

From the energy point of view, heat exchangers are usually well balanced devices with low energy losses and high energy efficiencies [21-23], what is also valid for steam re-heater which is a constituent part of the observed system. Steam re-heater from the analyzed turbine system has an energy loss equal to 824.19 kW, Fig. 5.

Energy input in steam re-heater represents heat amount transferred from the flue gases to steam and equals 36749.35 kW, while the steam re-heater energy output is heat amount actually transferred from flue gases to steam which is lower in comparison to energy input for losses during heat transfer.

Energy efficiencies of the analyzed steam turbine and all of its components are presented in Fig. 6. Regardless of worse operating conditions and entrance into the saturated area in the last few stages [24], LPC has higher energy efficiency in comparison to HPC (81.45% for LPC and 80.12% for HPC). The energy efficiency of the entire steam turbine (81.03%) is between energy efficiencies of HPC and LPC. As mentioned before, a heat exchanger (steam re-heater) has low energy loss and simultaneously high energy efficiency which is equal to 97.76%, Fig. 6.

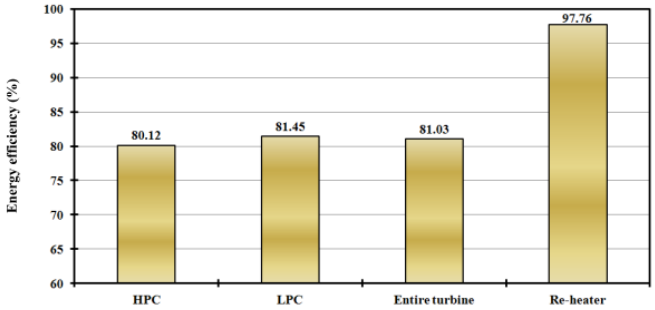

Fig. 6. *Energy efficiencies for all observed components of the analyzed steam turbine system*

6. Conclusions

In this paper is presented an energy analysis of steam turbine with two cylinders and steam re-heater between cylinders. For all of the observed steam turbine components are calculated required operating parameters, energy losses and energy efficiencies. The most important conclusions of the presented analysis are:

- Energy power of fluid flows throughout turbine is much higher at turbine cylinders inlet and outlet in comparison to steam extractions.
- LPC of the analyzed turbine develops higher power and has a higher energy loss in comparison to HPC. This fact leads to higher energy efficiency of LPC (81.45%) in comparison to HPC (80.12%).
- Steam re-heater, as many other heat exchangers, has low energy loss (824.19 kW) and proportionally high energy efficiency (97.76%).
- According to presented operating parameters, the entire analyzed turbine produced real power equal to 127480.60 kW, has energy loss equal to 29848.21 kW and its energy efficiency is 81.03%.

7. Nomenclature

Abbreviations:

HPC	High Pressure Cylinder
LPC	Low Pressure Cylinder

Latin symbols:

c	velocity, m/s
c_p	specific heat capacity at constant pressure, kJ/kg·K
$\dot{E}$	energy power of a flow, kW
g	acceleration of gravity, m/s^2
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
T	temperature, K
v	specific volume (m^3/kg)
z	elevation, m

Greek symbols:

η	efficiency, %

Subscripts:

en	energy
FG	flue gases
in	input (inlet)

p	pressure, kPa	IS	isentropic (ideal) steam expansion
P	power, kW	out	output (outlet)
$\dot{Q}$	heat amount, kW	RE	real (polytropic) steam expansion
s	specific entropy, kJ/kg·K		

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