THE CHANGE IN EXERGY EFFICIENCIES AND LOSSES OF LOW-POWER STEAM TURBINE WITH STEAM EXTRACTIONS AT THREE LOADS

V. Mrzljak [1], J. Orović [2], I. Poljak [2] and I. Lorencin [1]

[1] Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia

[2] Department of maritime sciences, University of Zadar, Mihovila Pavlinovića 1, 23000 Zadar, Croatia

Email: vedran.mrzljak@riteh.hr, jorovic@unizd.hr, ipoljak1@unizd.hr, ilorencin@riteh.hr

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Abstract: An exergy analysis of low-power steam turbine with three steam extractions from cogeneration power plant is performed in this paper. The turbine is analyzed at three different loads. The most dominant exergy flow stream from the analyzed turbine is a steam stream at the turbine inlet, at all observed loads. Turbine developed power at low, middle and high load is equal to 25271.92 kW, 28474.22 kW and 28623.19 kW, respectively. An increase in turbine load resulted with a continuous increase in turbine exergy destruction (from 3378.67 kW at low turbine load to 4112.92 kW at high turbine load), while the same increase in turbine load resulted with a continuous decrease in turbine exergy efficiency (from 88.21 % at low turbine load to 87.44 % at high turbine load).

Introduction

The most of electricity today is produced by steam turbines, which are essential elements of steam power plants (conventional or nuclear), cogeneration power plants and combined power plants, regardless of produced power, [1] and [2]. Steam turbines are also used in marine steam power plants with [3] or without [4] steam re-heating. Each steam turbine, regardless of the number of its cylinders [5], get steam with a highest possible pressure and temperature directly from steam generator [6], what ensures turbine appropriate and adequate operation. After steam expansion in the turbine, steam is lead to the condenser which operation can significantly influence turbine expansion process and developed power [7]. For a low-power steam turbines, as the one investigated in this paper, can be performed numerical variation of developed power (based on the real, measured operating parameters), in order to achieve operation regimes where the turbine will have maximum efficiencies, [8] and [9]. In this paper is performed exergy analysis (analysis of exergy efficiencies and losses) of low-power steam turbine from cogeneration power plant [10]. Steam turbine is analyzed at three different loads, with an aim to investigate turbine characteristics in a wider operating range.

Analyzed low-power steam turbine description and operating characteristics

Analyzed low-power steam turbine operates in a cogeneration power plant, for which the additional operating data can be found in [10]. Basic scheme and operating points necessary for a turbine exergy analysis are presented in Fig. 1. Steam turbine has three extractions which lead steam to regenerative condensate/feed water heating system. Power consumer, which is driven by the analyzed low-power steam turbine, is electricity generator.

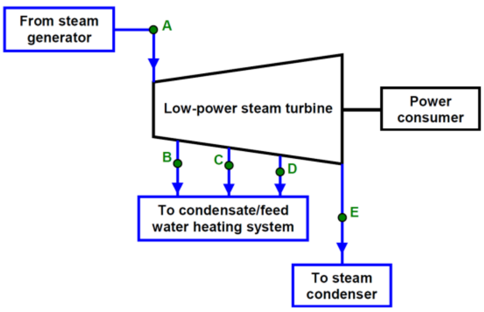

Fig. 1 Scheme and marked operating points of the analyzed low-power steam turbine

Exergy analysis equations

General equations for the exergy analysis of control volume

Exergy analysis of a control volume of any kind is developed from the second law of thermodynamics [11]. The overall exergy balance equation for a control volume in steady state is, according to [12], defined as:

$$\dot{X}_{\text{heat}} - P = \sum \dot{m}_{\text{OUT}} \cdot \varepsilon_{\text{OUT}} - \sum \dot{m}_{\text{IN}} \cdot \varepsilon_{\text{IN}} + \dot{E}_{\text{ex,D}} \,. \quad (1)$$

From the Eq. (1), calculation of several factors must be explained in detail:

- The heat exergy transfer ($\dot{X}_{\text{heat}}$) at temperature T, is defined according to [13] as:

$$\dot{X}_{\text{heat}} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} \,. \quad (2)$$

- According to [14], mass balance equation for any steady state control volume is:

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

- Specific exergy, according to [15], is defined by an equation:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) . \quad (4)$$

- The total exergy power of fluid flow [16] is defined by an equation:

$$\dot{E}_{ex} = \dot{m} \cdot \varepsilon = \dot{m} \cdot \left[(h - h_0) - T_0 \cdot (s - s_0) \right] . \quad (5)$$

Exergy efficiency can have different forms, what is dependable on the type and operation characteristics of a control volume. In general, exergy efficiency can be defined, according to [17], by an equation:

$$\eta_{ex} = \frac{\text{Exergy output}}{\text{Exergy input}} . \quad (6)$$

Equations for low-power steam turbine exergy analysis

Exergy analysis of the low-power steam turbine is performed according to turbine operating points from Fig. 1. The ambient conditions (dead state conditions) in this analysis are taken as proposed in [18]: pressure of 1 bar and temperature of 25 °C.

Equations for the exergy analysis of low-power steam turbine presented in Fig. 1 are:

- Turbine mass flows:

$$\dot{m}_A = \dot{m}_B + \dot{m}_C + \dot{m}_D + \dot{m}_E . \quad (7)$$

- Turbine developed power:

$$P = \dot{m}_A \cdot (h_A - h_B) + (\dot{m}_A - \dot{m}_B) \cdot (h_B - h_C) + (\dot{m}_A - \dot{m}_B - \dot{m}_C) \cdot (h_C - h_D) + (\dot{m}_A - \dot{m}_B - \dot{m}_C - \dot{m}_D) \cdot (h_D - h_E) . \quad (8)$$

- Turbine exergy power input:

$$\dot{E}_{ex,IN} = \dot{m}_A \cdot \varepsilon_A . \quad (9)$$

- Turbine exergy power output:

$$\dot{E}_{ex,OUT} = \dot{m}_B \cdot \varepsilon_B + \dot{m}_C \cdot \varepsilon_C + \dot{m}_D \cdot \varepsilon_D + \dot{m}_E \cdot \varepsilon_E + P . \quad (10)$$

- Turbine exergy destruction:

$$\dot{E}_{ex,D} = \dot{E}_{ex,IN} - \dot{E}_{ex,OUT} = \dot{m}_A \cdot \varepsilon_A - \dot{m}_B \cdot \varepsilon_B - \dot{m}_C \cdot \varepsilon_C - \dot{m}_D \cdot \varepsilon_D - \dot{m}_E \cdot \varepsilon_E - P . \quad (11)$$

- Turbine exergy efficiency:

$$\eta_{ex} = \frac{P}{\dot{E}_{ex,IN} - \dot{E}_{ex,OUT} + P} = \frac{P}{\dot{m}_A \cdot \varepsilon_A - \dot{m}_B \cdot \varepsilon_B - \dot{m}_C \cdot \varepsilon_C - \dot{m}_D \cdot \varepsilon_D - \dot{m}_E \cdot \varepsilon_E} . \quad (12)$$

Operating parameters of the analyzed low-power steam turbine at three loads

Essential data for the low-power steam turbine exergy analysis (steam temperatures, pressures and mass flows) can be found in [10]. It was investigated three different steam turbine loads. Required data for each operating point from Fig. 1, at each turbine load, are presented as follows - in Table 1 for low turbine load, in Table 2 for middle turbine load and finally in Table 3 for high turbine load.

Steam specific enthalpies and specific exergies in each turbine operating point (Fig. 1) and at each load were calculated by using NIST REFPROP 9.0 software [19].

Table 1. Operating parameters of the analyzed steam turbine - low turbine load

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
A	519.52	65.00	32.611	3464	1411.40
B	340.54	17.50	8.778	3122	1041.80
C	201.48	5.00	7.250	2859	756.33
D	116.91	1.80	1.833	2688	567.44
E	41.51	0.08	14.750	2348	115.82

Table 2. Operating parameters of the analyzed steam turbine - middle turbine load

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
A	512.50	67.00	31.250	3445	1403.60
B	366.08	23.30	2.750	3167	1103.30
C	247.58	8.60	2.889	2943	862.45
D	145.70	3.10	3.222	2751	656.52
E	49.42	0.12	22.389	2372	167.78

Table 3. Operating parameters of the analyzed steam turbine - high turbine load

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
A	488.77	66.00	32.611	3389	1367.20
B	340.73	22.20	2.944	3112	1068.10
C	223.45	7.90	3.111	2893	830.46
D	131.19	2.80	3.139	2713	632.57
E	51.03	0.13	23.417	2358	176.61

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

Exergy analysis results of low-power steam turbine with discussion

For the entire analyzed steam turbine, at any observed load, the most dominant exergy flow stream is a steam stream at the turbine inlet (in operating point A, Fig. 1), due to the high mass flow and temperature, as presented in Fig. 2. The exergy flow of each other steam stream from the analyzed low-power turbine is much smaller at any load when compared with a stream at the turbine inlet. Steam stream at the turbine outlet (operating point E, Fig. 1), regardless of significant mass flow, has a low specific exergy.

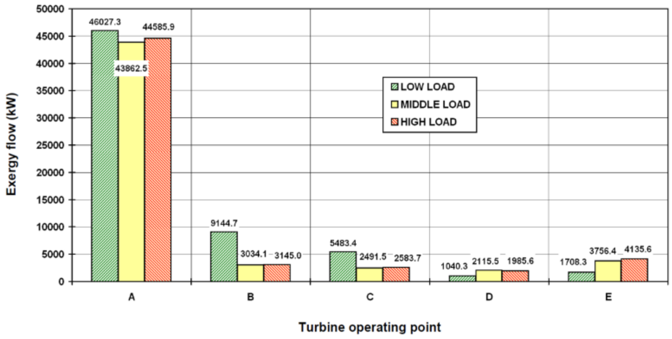

Fig. 2 Change in exergy flows at each analyzed steam turbine operating point for three different loads

Turbine power increases during the increase in turbine load. At low turbine load, turbine developed power is equal to 25271.92 kW, Fig. 3. Increase in turbine load (from low to middle turbine load) resulted firstly with a notable increase in turbine developed power – at middle turbine load developed power is 28474.22 kW. A further increase in turbine load (from middle to high turbine load) resulted with a slight increase in turbine developed power (from 28474.22 kW at middle to 28623.19 kW at high turbine load), Fig. 3.

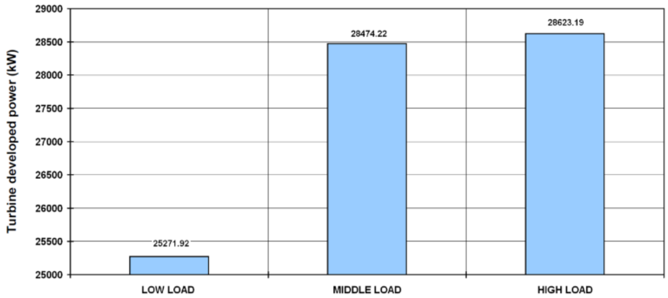

Fig. 3 Change in analyzed steam turbine developed power for three different turbine loads

Turbine exergy power input and output at each turbine load are presented in Fig. 4. From low to middle turbine load, both exergy power input and output decreases (from 46027.32 kW to 43862.50 kW for exergy power input and from 42648.65 kW to 39871.68 kW for exergy power output). A further increase in turbine load (from middle to high turbine load) resulted with an increase in both exergy power input and output – at high turbine load exergy power input amount 44585.91 kW and exergy power output amount 40472.99 kW, Fig. 4.

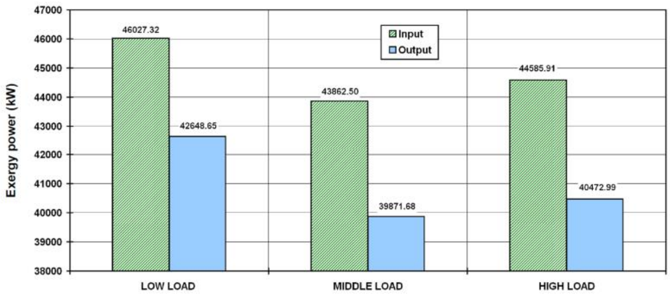

Fig. 4 Change in analyzed steam turbine exergy power input and output for three different turbine loads

An increase in turbine load resulted with a continuous increase in turbine exergy destruction (from 3378.67 kW at low turbine load to 4112.92 kW at high turbine load), while the same increase in turbine load resulted with a continuous decrease in turbine exergy efficiency (from 88.21 % at low turbine load to 87.44 % at high turbine load), Fig. 5. The change in turbine exergy efficiency is not significant during the change in turbine load, so it can be concluded that the analyzed turbine is designed to operate at approximately similar exergy efficiencies regardless of turbine load. From the calculated change of turbine exergy destruction and efficiency during the increase in turbine load can be concluded that exergy destruction and efficiency for the analyzed steam turbine are reverse proportional – increase in turbine exergy destruction resulted with a decrease in turbine exergy efficiency and vice versa.

Conclusions

The paper has presented an exergy analysis of low-power steam turbine from cogeneration power plant. Steam turbine is analyzed at three different loads. The most important conclusions from the obtained low-power steam turbine analysis are:

- According to presented operation data in each turbine operating point is obtained turbine developed power which amounts 25271.92 kW at low turbine load, 28474.22 kW at middle turbine load and 28623.19 kW at high turbine load.

- An increase in turbine load resulted with the same trend of change in turbine exergy power input and output. Both turbine exergy power input and output firstly decreases from low to middle turbine load, after which follows increase in exergy power input and output from middle to high turbine load.
- An increase in turbine load resulted with a continuous increase in turbine exergy destruction (from 3378.67 kW at low turbine load to 4112.92 kW at high turbine load), while the same increase in turbine load resulted with a continuous decrease in turbine exergy efficiency (from 88.21 % at low turbine load to 87.44 % at high turbine load).
- The change in turbine exergy efficiency is not significant during the change in turbine load - analyzed turbine is designed to operate at approximately similar exergy efficiencies regardless of turbine load.

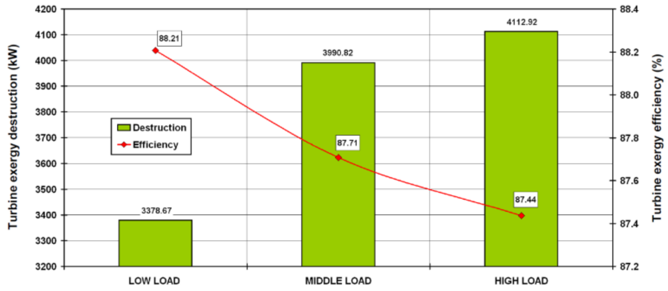

Fig. 5 Change in analyzed steam turbine exergy destruction and exergy efficiency for three different turbine loads

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Nomenclature

Latin symbols: $\dot{E}$ = the total flow exergy (kW), h = specific enthalpy (kJ/kg), $\dot{m}$ = mass flow (kg/s), p = pressure (bar), P = power (kW), $\dot{Q}$ = heat transfer (kW), s = specific entropy (kJ/kg·K), T = temperature (°C or K), $\dot{X}_{heat}$ = heat exergy transfer (kW). Greek symbols: ε = specific exergy (kJ/kg), η = efficiency (%). Subscripts: 0 = ambient state, D = destruction (exergy loss), ex = exergy, IN = inlet (input), OUT = outlet (output).

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