Exergy analysis of steam turbine from ultra-supercritical power plant

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Abstract: *In this paper is presented an exergy analysis of steam turbine (along with analysis of each cylinder and cylinder part) from ultra-supercritical power plant. Observation of all the cylinders shows that IPC (Intermediate Pressure Cylinder) is the dominant mechanical power producer (it produces mechanical power equal to 394.44 MW), it has the lowest exergy loss and simultaneously the highest exergy efficiency (equal to 95.84%). HPC (High Pressure Cylinder) has a very high exergy efficiency equal to 92.37% what confirms that ultra-supercritical steam process is very beneficial for the HPC (and whole steam turbine) operation. LPC (Low Pressure Cylinder) is a dissymmetrical dual flow cylinder, so both of its parts (left and right part) did not produce the same mechanical power, did not have the same exergy loss, but their exergy efficiency is very similar and in a range of entire LPC exergy efficiency (around 82.5%). Whole observed steam turbine produces mechanical power equal to 928.03 MW, has exergy loss equal to 93.45 MW and has exergy efficiency equal to 90.85%. The exergy efficiency of the whole analyzed steam turbine is much higher in comparison to other steam turbines from various conventional power plants.*
KEYWORDS*: EXERGY ANALYSIS, STEAM TURBINE, TURBINE CYLINDERS, ULTRA-SUPERCRITICAL PROCESS*

1. Introduction

Steam power plants are nowadays the dominant producers of the mechanical power which is directly converted to electrical energy by using electric generators [1, 2]. In such power plants the dominant mechanical power producers are complex steam turbines, which are usually composed of several cylinders connected to the same shaft [3, 4]. Low power steam turbines can be composed of one cylinder, but such turbines produce mechanical power sufficient for the auxiliary purposes only [5, 6].

Conventional and nuclear steam power plants improve its operation each day with an aim to increase efficiency and reduce losses [7, 8]. A new type of steam power plants are built more and more each day around the world – these are supercritical and ultra-supercritical steam power plants [9, 10]. This kind of steam power plants has maximum steam pressures notably higher than critical ones [11]. According to already published literature, supercritical and ultra-supercritical steam power plants have various benefits in comparison to conventional or nuclear steam power plants [12]. The most important benefit is fuel savings in steam generator due to the high pressure process, but the interesting question arises – are such high pressures beneficial to other components of these power plants?

In this paper is performed an exergy analysis of one randomly selected steam turbine from ultra-supercritical power plant. It is analyzed how high pressure steam influences whole turbine, turbine cylinders and parts of dissymmetrical cylinders. It is presented which cylinder of observed turbine show the best performance (the highest efficiency and the lowest losses). Finally, the overall performance of analyzed steam turbine is compared to steam turbines from conventional power plants.

2. Description and operation details of the analyzed steam turbine

General scheme of the analyzed steam turbine from ultra-supercritical power plant is presented in Fig. 1.

The observed steam turbine has three cylinders (HPC = High Pressure Cylinder, IPC = Intermediate Pressure Cylinder, LPC = Low Pressure Cylinder) connected to the same shaft which drives an electric generator. Steam produced in steam generator is firstly delivered to the HPC which has three steam extractions. After HPC, steam is delivered to reheater (mounted inside steam generator) which increases steam temperature before its expansion in IPC. IPC has two steam extractions and after IPC, steam is delivered to the LPC. Both HPC and IPC are single flow turbine cylinders. On the steam pipeline between IPC and the LPC is mounted one more steam extraction (operating point 8a, Fig. 1). LPC is a dissymmetrical dual flow turbine cylinder which means that through each LPC part (left and right) are extracted different steam mass flow rates. Dissymmetrical dual flow turbine cylinders should be carefully designed and maintained due to axial force imbalance [13]. Left LPC part has two, while right LPC part has only one steam extraction. Entire steam mass flow rate extracted through all presented steam extractions (from the turbine cylinders and from the steam pipeline) is delivered to condensation/feedwater heating system which increases condensate/water temperature before its return to the steam generator [14]. After expansion in all turbine cylinders, remaining steam mass flow rate at the LPC outlet (operating point 12, Fig. 1) is delivered to the main steam condenser for condensation [15].

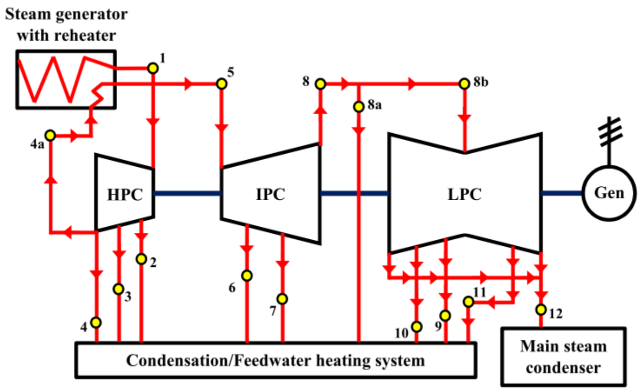

Fig. 1. *General scheme of the analyzed steam turbine from ultra-supercritical power plant along with operating points required for the exergy analysis*

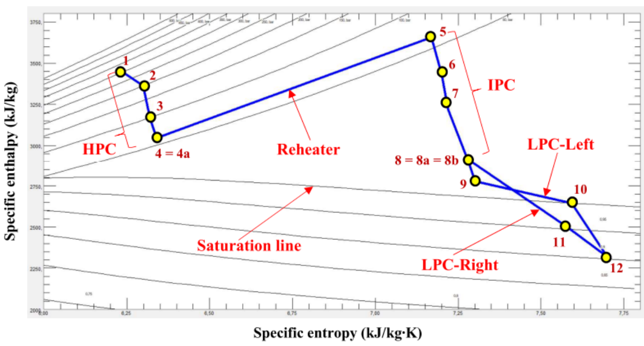

Fig. 2. *Steam expansion process in h-s diagram throughout all the cylinders of the analyzed turbine from ultra-supercritical power plant*

In Fig. 2 is presented steam expansion process in *h-s* diagram through all the cylinders of the observed steam turbine. The main characteristic of the steam turbine from ultra-supercritical power plant is that at the HPC entrance (operating point 1, Fig. 1 and Fig. 2) steam pressure is notably higher than the pressure at fluid critical point (for water, critical point pressure is equal to 220.64 bar). The steam reheating process is clearly visible in Fig. 2 between operating points 4 and 5 – increase in steam temperature results with simultaneous increase in steam specific enthalpy and specific entropy. Steam expansion process in Fig. 2 is presented separately for the left and right LPC part – a clear difference in the expansion process between left and right LPC part is another confirmation of the fact that the LPC is dissymmetrical dual flow turbine cylinder.

3. Equations for the steam turbine exergy analysis

3.1. Overall exergy equations and balances

Regardless of the analyzed component, component part or the entire system, in the exergy analysis exists several equations and balances which should always be satisfied [16]. These equations and balances will be presented in this paper part. The main exergy balance equation, according to [17] is:

$$\dot{X}_{\mathrm{in}} + P_{\mathrm{in}} + \sum \dot{E}x_{\mathrm{in}} - \dot{X}_{\mathrm{out}} - P_{\mathrm{out}} - \sum \dot{E}x_{\mathrm{out}} - \dot{E}x_{\mathrm{L}} = 0, \quad (1)$$

where P is mechanical power, index in is related to the inlet (input), index out is related to outlet (output) and index L is related to exergy loss. Exergy transfer by heat at the temperature T ($\dot{X}$) is defined according to [18] by the equation:

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

where $\dot{Q}$ is an energy transfer by heat and index 0 is related to the ambient state. The last undefined variable from the exergy balance equation is a total exergy flow of any fluid stream ($\dot{E}x$) which definition can be found in [19]:

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

where $\dot{m}$ is a fluid mass flow rate and ε is specific exergy of any fluid stream, which is defined by an equation [20]:

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

where h is fluid specific enthalpy and s is fluid specific entropy. If there is no fluid leakage, always valid mass flow rate balance is:

$$\sum \dot{m}_{\mathrm{in}} = \sum \dot{m}_{\mathrm{out}}. \quad (5)$$

Overall and general definition of the exergy efficiency is [19]:

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

3.2. Equations for the exergy analysis of observed turbine

Equations for the exergy analysis of the observed steam turbine, its cylinders and cylinder parts are composed according to recommendations from the literature [21] and by using operating points from Fig. 1. Equations for the produced mechanical power calculation of each cylinder, cylinder part and whole analyzed turbine are presented in Table 1.

Table 1. *Equations for the produced mechanical power calculation in each cylinder, cylinder part and whole observed turbine*

Component	Produced mechanical power	Eq.
HPC	$P_{\mathrm{HPC}} = \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3) \cdot (h_3 - h_4)$	(7)
IPC	$P_{\mathrm{IPC}} = \dot{m}_5 \cdot (h_5 - h_6) + (\dot{m}_5 - \dot{m}_6) \cdot (h_6 - h_7) + (\dot{m}_5 - \dot{m}_6 - \dot{m}_7) \cdot (h_7 - h_8)$	(8)
LPC-Left	$P_{\mathrm{LPC,Left}} = \frac{\dot{m}_{8b}}{2} \cdot (h_8 - h_9) + \left(\frac{\dot{m}_{8b}}{2} - \dot{m}_9\right) \cdot (h_9 - h_{10}) + \left(\frac{\dot{m}_{8b}}{2} - \dot{m}_9 - \dot{m}_{10}\right) \cdot (h_{10} - h_{12})$	(9)
LPC-Right	$P_{\mathrm{LPC,Right}} = \frac{\dot{m}_{8b}}{2} \cdot (h_8 - h_{11}) + \left(\frac{\dot{m}_{8b}}{2} - \dot{m}_{11}\right) \cdot (h_{11} - h_{12})$	(10)
LPC-Cumul.	$P_{\mathrm{LPC,Cumulative}} = P_{\mathrm{LPC,Left}} + P_{\mathrm{LPC,Right}}$	(11)
WT	$P_{\mathrm{WT}} = P_{\mathrm{HPC}} + P_{\mathrm{IPC}} + P_{\mathrm{LPC,Cumulative}}$	(12)

A total exergy flow of any fluid stream (in each operating point from Fig. 1) is calculated by using Eq. 3. Equations for the exergy loss calculation are presented in Table 2, while equations for the exergy efficiency calculation are presented in Table 3 (for each cylinder, cylinder part and whole analyzed turbine).

Table 2. *Equations for the exergy loss calculation in each cylinder, cylinder part and whole observed turbine*

Component	Exergy loss	Eq.
HPC	$\dot{E}x_{\mathrm{L,HPC}} = \dot{E}x_1 - \dot{E}x_2 - \dot{E}x_3 - \dot{E}x_4 - \dot{E}x_{4a} - P_{\mathrm{HPC}}$	(13)
IPC	$\dot{E}x_{\mathrm{L,IPC}} = \dot{E}x_5 - \dot{E}x_6 - \dot{E}x_7 - \dot{E}x_8 - P_{\mathrm{IPC}}$	(14)
LPC-Left	$\dot{E}x_{\mathrm{L,LPC,Left}} = \frac{\dot{E}x_{8b}}{2} - \dot{E}x_9 - \dot{E}x_{10} - \left(\frac{\dot{m}_{8b}}{2} - \dot{m}_9 - \dot{m}_{10}\right) \cdot \varepsilon_{12} - P_{\mathrm{LPC,Left}}$	(15)
LPC-Right	$\dot{E}x_{\mathrm{L,LPC,Right}} = \frac{\dot{E}x_{8b}}{2} - \dot{E}x_{11} - \left(\frac{\dot{m}_{8b}}{2} - \dot{m}_{11}\right) \cdot \varepsilon_{12} - P_{\mathrm{LPC,Right}}$	(16)
LPC-Cumul.	$\dot{E}x_{\mathrm{L,LPC,Cumulative}} = \dot{E}x_{\mathrm{L,LPC,Left}} + \dot{E}x_{\mathrm{L,LPC,Right}}$	(17)
WT	$\dot{E}x_{\mathrm{L,WT}} = \dot{E}x_{\mathrm{L,HPC}} + \dot{E}x_{\mathrm{L,IPC}} + \dot{E}x_{\mathrm{L,LPC,Cumulative}}$	(18)

Table 3. *Equations for the exergy efficiency calculation in each cylinder, cylinder part and whole observed turbine*

Component	Exergy efficiency	Eq.
HPC	$\eta_{\mathrm{ex,HPC}} = \frac{P_{\mathrm{HPC}}}{\dot{E}x_{\mathrm{L,HPC}} + P_{\mathrm{HPC}}}$	(19)
IPC	$\eta_{\mathrm{ex,IPC}} = \frac{P_{\mathrm{IPC}}}{\dot{E}x_{\mathrm{L,IPC}} + P_{\mathrm{IPC}}}$	(20)
LPC-Left	$\eta_{\mathrm{ex,LPC,Left}} = \frac{P_{\mathrm{LPC,Left}}}{\dot{E}x_{\mathrm{L,LPC,Left}} + P_{\mathrm{LPC,Left}}}$	(21)
LPC-Right	$\eta_{\mathrm{ex,LPC,Right}} = \frac{P_{\mathrm{LPC,Right}}}{\dot{E}x_{\mathrm{L,LPC,Right}} + P_{\mathrm{LPC,Right}}}$	(22)
LPC-Cumul.	$\eta_{\mathrm{ex,LPC,Cumulative}} = \frac{P_{\mathrm{LPC,Cumul.}}}{\dot{E}x_{\mathrm{L,LPC,Cumul.}} + P_{\mathrm{LPC,Cumul.}}}$	(23)
WT	$\eta_{\mathrm{ex,WT}} = \frac{P_{\mathrm{WT}}}{\dot{E}x_{\mathrm{L,WT}} + P_{\mathrm{WT}}}$	(24)

4. Steam operating parameters required for the observed turbine exergy analysis

Steam operating parameters in each operating point from Fig. 1 are found in [22] and presented in Table 4. It should be highlighted that in [22] are not found all steam operating parameters, missing ones which are required for the exergy analysis of observed turbine and its cylinders are additionally calculated by using NIST-Refprop 9.0 software [23].

Steam specific exergies (according to Eq. 4) are dependable on the state of the ambient in which analyzed turbine and its cylinders operate. Therefore, in each exergy analysis should be defined base ambient state. According to the recommendations from the literature [24], in this analysis the base ambient state is defined with ambient pressure of 1 bar and ambient temperature of 25 °C.

Table 4. *Steam parameters in each operating point of the analyzed turbine*

O. P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Specific exergy (kJ/kg)**
1	600.00	300.00	822.36	3446.7	6.2373	1591.60
2	539.00	200.00	122.00	3363.4	6.2988	1489.90
3	424.00	100.00	78.26	3169.1	6.3188	1289.80
4	351.00	60.00	43.18	3046.7	6.3402	1161.00
4a	351.00	60.00	578.92	3046.7	6.3402	1161.00
5	600.00	60.00	578.92	3658.7	7.1693	1525.80
6	488.00	30.00	35.88	3430.3	7.2007	1287.90
7	384.00	15.00	60.57	3221.8	7.2189	1074.10
8	225.00	4.00	482.47	2913.0	7.2795	747.14
8a	225.00	4.00	17.78	2913.0	7.2795	747.14
8b	225.00	4.00	464.69	2913.0	7.2795	747.14
9	154.00	2.00	34.18	2777.3	7.3004	605.29
10	81.35	0.50	11.65	2645.3	7.5932	385.93
11	60.06	0.20	18.18	2499.9	7.5800	244.49
12	28.96	0.04	400.68	2320.0	7.7000	28.84

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

** Specific exergies in each operating point are calculated for the base ambient state

5. Results of the analysis and discussion

Produced mechanical power in each cylinder, each LPC part and in the whole analyzed turbine is presented in Fig. 3.

The dominant mechanical power producer in the analyzed steam turbine is IPC, which produces 394.44 MW of mechanical power. HPC produces 280.73 MW of mechanical power, while the whole LPC produces the lowest mechanical power of all cylinders equal to 252.87 MW. LPC is dissymmetrical dual flow turbine cylinder which means that both turbine parts (due to different extracted steam mass flow rates in each part) will not produce the same mechanical power. Due to more extracted steam through two steam extractions in the left part of the LPC, it produces lower mechanical power in comparison to right LPC part (118.36 MW in comparison to 134.51 MW). In dissymmetrical dual flow turbine cylinders a special attention should be placed on the axial force balancing [13].

According to steam operating parameters presented in Table 4, whole analyzed steam turbine produces mechanical power equal to 928.03 MW, which is completely used for the electric generator drive (if all auxiliary mechanical power consumers are neglected because they use relatively small amounts of cumulatively produced mechanical power).

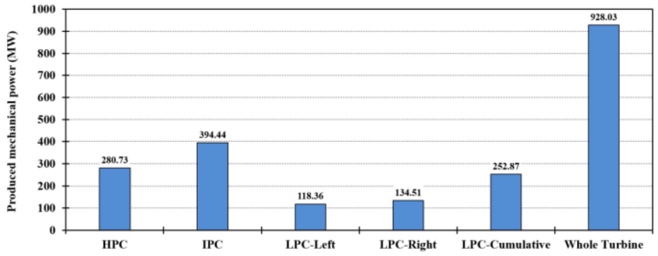

Fig. 3. *Produced mechanical power in all cylinders, cylinder parts and whole analyzed turbine from ultra-supercritical power plant*

The total exergy flow of each fluid stream (in each operating point from Fig. 1) is presented in Fig. 4.

From Fig. 4 is obvious that the highest total exergy flows occur at each turbine cylinder inlet and outlet. The only exception from this conclusion can be seen at the LPC outlet where the steam temperature is very close to the temperature of the ambient, what results with the small total exergy flow (operating point 12). Between operating points 4a and 5 total exergy flow increases due to steam reheating process. As expected and considering all operating points, the highest total exergy flow occurs at the HPC inlet (equal to 1308.87 MW).

If considering all steam extractions from all turbine cylinders, it can be seen that the highest total exergy flows are in the HPC, following by IPC, while the lowest total exergy flows are observed in LPC. Total exergy flows in steam extractions define arrangement of the condensation/feedwater heating system – heaters which operate with the highest temperatures must get steam from HPC and heaters which operate with the lowest temperatures must get steam from LPC.

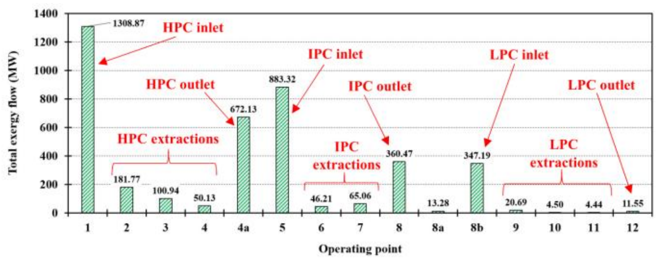

Fig. 4. *Total exergy flows in each operating point related to the observed steam turbine from ultra-supercritical power plant*

Observation of turbine cylinders shows that IPC is not only the dominant mechanical power producer in this turbine, Fig. 3, it also has the lowest exergy loss (equal to 17.14 MW), much lower in comparison to other turbine cylinders, Fig. 5.

As expected, the highest exergy loss can be found in LPC (approximately three times higher than the exergy loss of IPC and more than two times higher than the exergy loss of the HPC). Also, each LPC part (left and right) has higher exergy loss than IPC or HPC by itself, while LPC right part has a higher exergy loss in comparison to left LPC part (28.46 MW in comparison to 24.67 MW). Such high exergy loss in LPC (and each LPC part) can be expected because LPC operates with steam of much lower pressure and temperature in comparison to steam which expands in other turbine cylinders.

Whole observed steam turbine from ultra-supercritical power plant has cumulative exergy loss equal to 93.45 MW, Fig. 5.

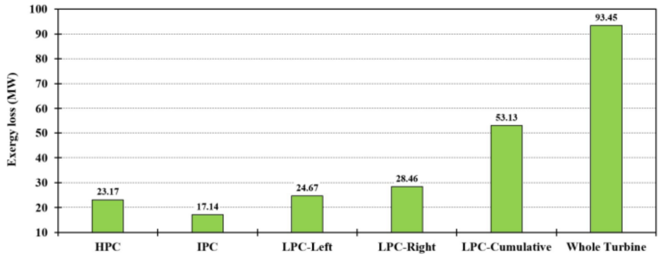

Fig. 5. *Exergy loss in all cylinders, cylinder parts and whole analyzed turbine from ultra-supercritical power plant*

The exergy efficiency of each cylinder, each LPC part and whole observed turbine is presented in Fig. 6.

IPC of the observed steam turbine is not only the dominant mechanical power producer, it also has the lowest exergy loss and the highest exergy efficiency (equal to 95.84%) in comparison to all other cylinders, Fig. 5 and Fig. 6. HPC has a very high exergy efficiency equal to 92.37%, regardless of the highest steam pressures and temperatures which occur in that cylinder. Very high exergy efficiency of HPC is one more confirmation that ultra-supercritical steam process is very beneficial for the HPC (and whole steam turbine) operation. The lowest exergy efficiency is observed in LPC and is equal to 82.64%. The exergy efficiency of each LPC part (both left and right) is very close to exergy efficiency of the whole LPC, so it can be concluded that exergy efficiency of the LPC parts did not deviate much between each other.

Whole observed steam turbine has exergy efficiency equal to 90.85%, what is much higher in comparison to other steam turbines from various conventional power plants. Ultra-supercritical steam process is obviously not beneficial only in reducing the amount of heat which should be delivered by fuel in steam generator, it is also beneficial for the steam turbine process.

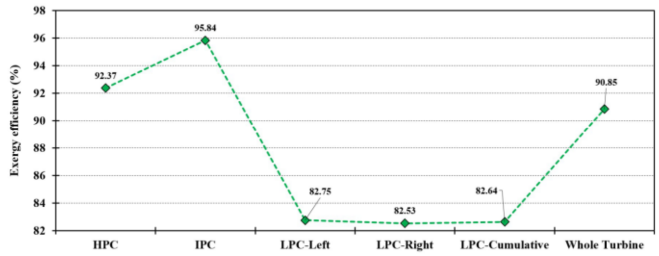

Fig. 6. *Exergy efficiency in all cylinders, cylinder parts and whole analyzed turbine from ultra-supercritical power plant*

Further research related to the observed steam turbine and its cylinders will be based on various Artificial Intelligence (AI) methods and processes [25-27] with an aim of more detail analysis and possible optimization.

6. Conclusions

This paper presents an exergy analysis of steam turbine (as well as all turbine cylinders and its parts) from ultra-supercritical power plant. Performed analysis allows detection of the cylinder with the lowest exergy efficiency (and the highest exergy loss) and can be used as a baseline in further research of ultra-supercritical steam processes and their turbines. The most important conclusions obtained in this analysis are:

- By observing all the cylinders of the analyzed turbine, it can be stated that IPC is the dominant mechanical power producer (it produces mechanical power equal to 394.44 MW), it has the lowest exergy loss and simultaneously the highest exergy efficiency (equal to 95.84%). The best IPC performance of all cylinders can be explained by the fact that it operates in optimal regime (it did not operate with the highest steam pressure and temperature – which are the reason of increased losses in HPC and it did not operate with wet steam – which is the reason of increased losses in LPC).
- HPC has a very high exergy efficiency equal to 92.37%, regardless of the highest steam pressures and temperatures which occur in that cylinder. Very high exergy efficiency of HPC is confirmation that ultra-supercritical steam process is very beneficial for the HPC (and whole steam turbine) operation.
- LPC is a dissymmetrical dual flow cylinder, so both of its parts (left and right part) did not produce the same mechanical power, did not have the same exergy loss, but their exergy efficiency is very similar and in a range of entire LPC exergy efficiency (around 82.5%).
- The highest total exergy flows occur at each turbine cylinder inlet and outlet. The only exception from this conclusion is LPC outlet where the steam temperature is very close to the temperature of the ambient, what results with the small total exergy flow. Considering all operating points, the highest total exergy flow occurs at the HPC inlet (equal to 1308.87 MW).
- Whole observed steam turbine produces mechanical power equal to 928.03 MW, has exergy loss equal to 93.45 MW and has exergy efficiency equal to 90.85%. The exergy efficiency of the whole analyzed steam turbine is much higher in comparison to other steam turbines from various conventional power plants.

7. Acknowledgment

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