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Analysis and Comparison of Main Steam Turbines from Four Different Thermal Power Plants

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ABSTRACT

This paper presents an analysis and comparison of four steam turbines and their cylinders from four different power plants (marine, conventional, ultra-supercritical and nuclear power plants). The main goal was to find which steam turbine and their cylinders show the best performances, the highest efficiencies, the lowest specific steam consumption and which turbine is the lowest influenced by the ambient temperature change. The highest efficiencies, both isentropic and exergy, are observed in the steam turbine and their cylinders from the ultra-supercritical power plant (whole turbine from ultra-supercritical power plant has an isentropic efficiency equal to 88.36% and exergy efficiency equal to 91.05%). Also, this turbine has the lowest specific steam consumption (7.32 kg/kWh) and exergy parameters of this turbine are the lowest influenced by the ambient temperature change. The worst performance (the lowest efficiencies, high specific steam consumption and the highest sensitivity to the ambient temperature change) show the cylinders and whole turbine from marine propulsion power plant. The same analysis and comparison are also performed for several other steam turbines from four mentioned power plants, so the presented relations and dominant conclusions have general validity. It can be concluded that steam turbines in ultra-supercritical power plants show the best performances in comparison to steam turbines from any other power plant.

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1 Introduction

Today in an energy sector, steam turbines have been dominantly used as mechanical power producers. Steam turbines did not have any competition in other mechanical power producers (such as internal combustion engines, gas turbines and others) in the field of high amount produced mechanical power [1, 2]. For a lower amount of mechanical power production, along with steam turbines can be used many other mechanical power producers [3-5].

Mechanical power produced by main steam turbines is dominantly used in many power plants for the electrical generator drive and for electricity production [6, 7]. Auxiliary steam turbines are usually low-power steam turbines, which can be used for any mechanical power consumer drive [8, 9]. Main steam turbines are dominantly composed of several cylinders connected to the same shaft, while auxiliary low-power steam turbines are usually composed of only one cylinder [10, 11]. Along with an electricity production, in the marine sector steam turbines can be often found in marine steam propulsion power plants where main steam turbines are used for the ship propulsion [12], while auxiliary steam turbines are used for electricity production as well as for other purposes [13].

Steam turbines can be found nowadays in many types of various power plants. They are essential components of any conventional, supercritical or ultra-supercritical steam power plants [14-16]. Also, steam turbines are essential components of any nuclear steam power plant, regardless of its origin (stationary or marine type) [17, 18]. In many complex power plants, such as cogeneration or combined power plants, steam turbines are also inevitable elements [19, 20].

In the analysis and operation observation of any steam power plant can be used various methods and techniques [21-23]. Literature review shows that, due its simplicity, various researchers use isentropic and exergy analyses for that purpose [24, 25], regardless of the fact that both of them require measured operating parameters from the observed power plant during its real exploitation [26, 27]. Mentioned analyses allow detection of the problematic components inside power plant or detection of components which did not show expected performance [28].

In the scientific and professional literature, steam turbines are rarely analyzed individually, dominantly they are analyzed along with other components of any observed power plant [29, 30]. Literature offers many interesting relations related to the various steam power plants, for example, it is well known that marine and nuclear steam power plants have the lowest overall efficiencies, while supercritical and ultra-supercritical steam power plants have the highest overall efficiencies [31, 32]. Combined power plants have higher overall efficiencies in comparison to any steam power plant [33], while the highest overall efficiencies (up to 85%) can be found in the cogeneration power plants (with high amount of steam delivered for a heating purposes) [34].

At the moment, the authors of this paper did not find in the literature any exact comparison of various main steam turbines from different steam power plants. It is currently unknown or hard to find which operating parameters are preferable for any main steam turbine operation, which main turbines produce the highest losses, destructions and have the highest efficiencies. For complex main steam turbines composed of several cylinders it is unknown which cylinder operate in the best or optimal regimes.

To resolve a literature gap, in this paper are analyzed and compared four steam turbines from four different steam power plants (marine, conventional, ultra-supercritical and nuclear power plants). According to steam operating parameters for each turbine during its exploitation, it is performed a calculation of both isentropic and exergy efficiencies, losses and destructions. Also, there are calculated specific steam consumption and specific heat consumption as additional operating parameters. All of the mentioned is calculated for the whole turbines as well as for each cylinder of each observed turbine. Direct comparison, based on the results of the performed analysis, shows that the best performance is obtained for main steam turbine from ultra-supercritical steam power plant, while intermediate pressure cylinder of any steam turbine operates in an optimal condition. The presented relations and dominant conclusions have general validity because the same analysis and comparison is performed not only for the steam turbines presented in this paper, but also for at least one more steam turbine from each observed steam power plant.

2 Description and operation characteristics of the analyzed steam turbines

In the performed analysis are observed and compared four steam turbines from four different steam power plants. General schemes of all observed steam turbines, along with operating points in which steam operating parameters are required for the analysis are presented in Fig. 1.

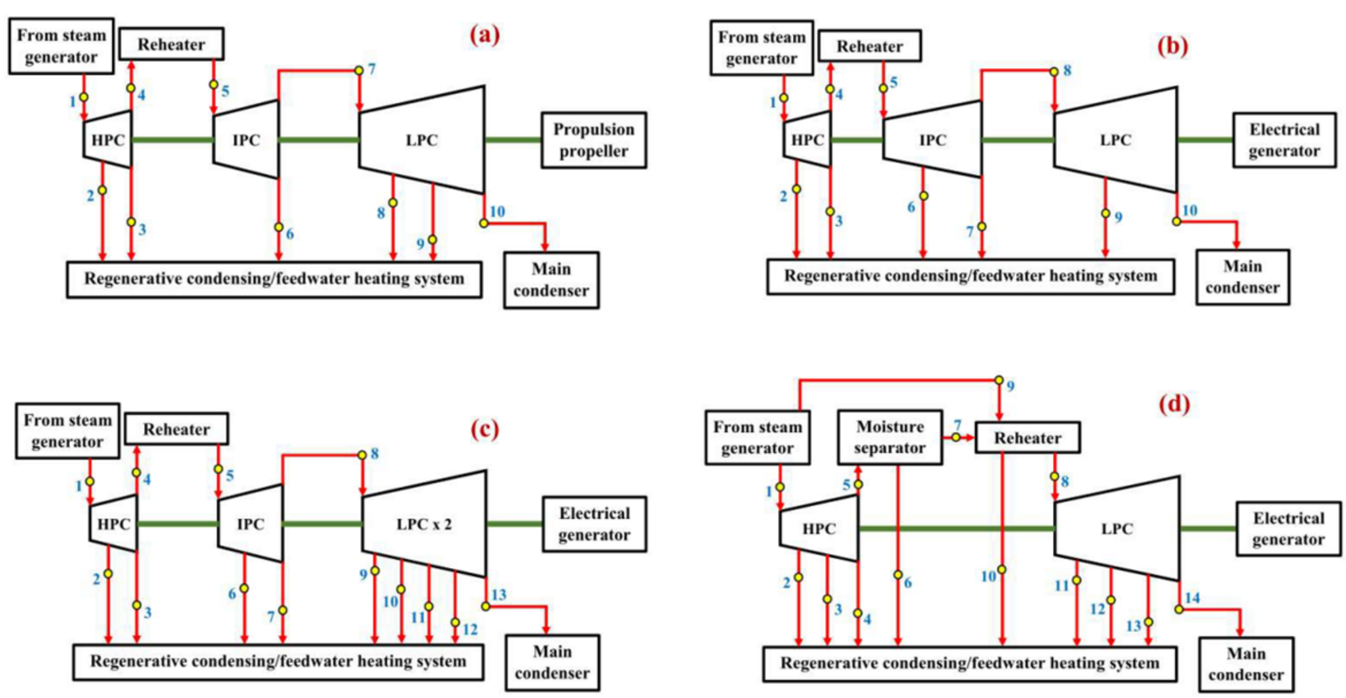

Fig. 1 General schemes of the observed steam turbines along with operating points required for the analysis: (a) Marine propulsion steam turbine; (b) Steam turbine from the conventional power plant; (c) Steam turbine from ultra-supercritical power plant; (d) Steam turbine from nuclear power plant

Source: Authors

The first observed steam turbine, Fig. 1 (a) is a main steam turbine from marine steam power plant [35]. This turbine is composed of three cylinders (HPC, IPC and LPC) connected to the same shaft, steam is reheated between HPC and IPC, and the turbine is used for ship propulsion (propulsion propeller drive). Observed main marine turbine operates in a novel marine steam propulsion system (older marine steam propulsion systems have main steam turbines composed of only two cylinders, without steam reheating [36]). HPC of this turbine has two steam extractions, IPC has only one steam extraction, while LPC has two steam extractions, as presented in Fig. 1 (a). All steam extractions lead certain amount of steam to the components of regenerative condensing/feedwater heating system [37, 38]. After expansion in the last cylinder (LPC), remaining steam is delivered to the seawater-cooled main condenser for condensation.

Second and third observed steam turbines are turbines from conventional, Fig. 1 (b), and from ultra-supercritical power plants, Fig. 1 (c). Both mentioned turbines have three cylinders connected to the same shaft which drives an electrical generator (turbine from ultra-supercritical power plant has two identical low pressure cylinders, which are presented in Fig. 1 (c) as one) [39, 40]. Also, both turbines have steam reheating between HPC and IPC. HPC and IPC of both turbines have two extractions each, while the only difference in extractions can be seen in LPC – LPC of the turbine from a conventional power plant has only one, while each LPC of the turbine from ultra-supercritical power plant have four steam extractions. Along with the difference in operating parameters in each operating point, the main difference between turbines from conventional and ultra-supercritical power plant is in steam pressure at the HPC entrance – in conventional power plant steam at the entrance of the HPC has a pressure lower than critical (220.64 bar), while in ultra-supercritical power plant steam pressure at the HPC entrance is around 250 bar or higher.

In comparison to other observed steam turbines, which has three cylinders and steam reheating between HPC and IPC, due to much lower steam pressure at the HPC entrance, steam turbine from nuclear power plant has only two cylinders – HPC and LPC, what is the common steam turbine arrangement in nuclear power plant [41]. Both cylinders are connected to the same shaft which drives an electrical generator [42], Fig. 1 (d). In a nuclear power plant steam reheating process is placed between the HPC and the LPC and the steam reheating process is completely different in comparison to all other power plants. In a nuclear power plant steam reheating process is composed of a moisture separator first (due to the wet steam, which is dominantly used in the nuclear power plant process) after which follows steam reheating in steam/steam heat exchanger (steam of the higher temperature transfers heat to a steam of lower temperature which passes between HPC and LPC). In this way, after reheating process, steam before LPC in nuclear power plant can be slightly superheated. In all other power plants, steam reheating process is performed by using combustion gasses obtained from fossil fuel, so the steam reheaters are usually placed in the steam generators [43, 44]. Each cylinder of the turbine from nuclear power plant (HPC and LPC) has three steam extractions which lead certain amount of steam to the components of regenerative condensing/feedwater heating system. In comparison to other steam turbines, steam turbines from nuclear power plants operate with much higher steam mass flow rates [45], what is also the case for the turbine observed in this analysis.

Real (polytropic) steam expansion processes of each cylinder for all observed steam turbines are presented in Fig. 2. Fig. 2 is obtained by using steam operating parameters in each operating point of each turbine according to

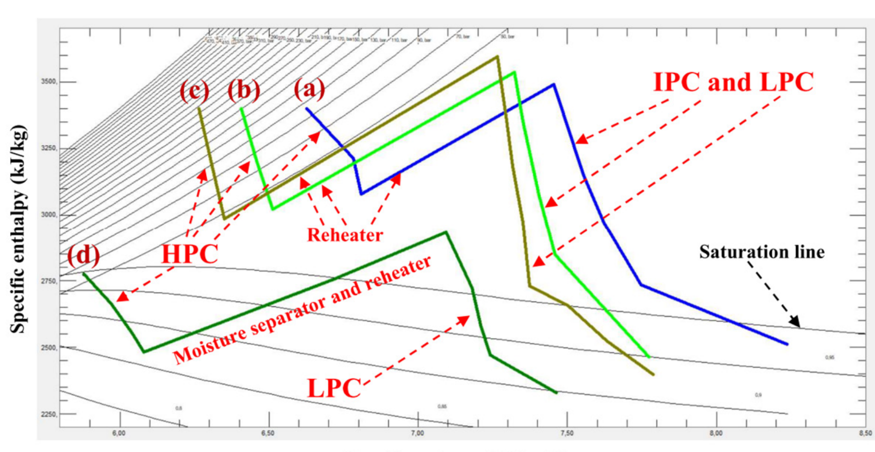

Fig. 2 Steam expansion and reheating process in *h-s* diagram through all cylinders of all analyzed steam turbines: (a) Marine propulsion steam turbine; (b) Steam turbine from the conventional power plant; (c) Steam turbine from ultra-supercritical power plant; (d) Steam turbine from nuclear power plant

Source: Authors

Fig. 1 (data are presented in Tables from 4 to 7) and by using NIST-REFPROP 9.0 software [46].

From Fig. 2 can be clearly seen that turbines from the marine, conventional and ultra-supercritical power plants dominantly operate by using superheated steam (only the last few stages of LPC operate with a wet steam). In a nuclear power plant almost entire expansion process in both cylinders is in the area of wet steam (the only stages which operate with superheated steam are first few stages of LPC, after steam reheating). Operation with wet steam notably increases losses and destructions in both cylinders of the turbine from nuclear power plant due to water droplets collision with turbine blades [47]. The steam reheating process did not increase the steam temperature (and consequentially developed mechanical power) of each observed turbine only, the steam reheating process ensures that the last stages of LPC operate with wet steam of the highest possible quality. In such way, steam turbine stages will be protected as much as possible and turbine blades replacement interval will be prolonged [47, 48].

3 Equations used in the analysis of all steam turbines and their cylinders

3.1 General isentropic and exergy equations and balances

For the purpose of this analysis and comparison the isentropic analysis and exergy analysis methods were selected. The reason why both of these analyses were selected is that each of them consider different kind of losses in the observed turbines and their cylinders.

Isentropic analysis did not consider any parameter of the ambient inside which steam turbine or its cylinder operates [49]. The only possibility how the isentropic analysis of any turbine or its cylinder can be performed is a comparison of real (polytropic) and ideal (isentropic) steam expansion processes through the turbine or cylinder [50]. In comparison to real (polytropic) expansion process, ideal (isentropic) expansion process is the process between the same pressures, with the same mass flow rates, but it assumes always the same steam specific entropy. The ideal (isentropic) steam expansion process neglects any losses during expansion, so it will result with the highest possible mechanical power which can be developed inside the turbine (or turbine cylinder). Real (polytropic) steam expansion process of any cylinder or whole turbine considers various losses which occur during expansion, so in the real expansion process will be developed lower mechanical power [51].

Real (polytropic) mechanical power developed in each turbine cylinder is:

$$P_{\mathrm{cylinder,j,PT}} = \sum_{i=1}^{n} \dot{m}_i \cdot \Delta h_i, \tag{1}$$

where n is the number of cylinder segments. The first segment of each turbine cylinder is placed between cylinder inlet and first steam extraction, inner segments are between steam extractions, while the last turbine segment is placed between last steam extraction and cylinder outlet. If cylinder did not have steam extractions, then it has only one segment – between inlet and outlet. Real (polytropic) mechanical power of the whole turbine is:

$$P_{\mathrm{WT,PT}} = \sum_{j=1}^{k} P_{\mathrm{cylinder,j,PT}}, \tag{2}$$

where k is the number of turbine cylinders. Ideal (isentropic) mechanical power of each cylinder and whole turbine is calculated by using the same above equations (Eq. 1 and Eq. 2), but the ideal specific enthalpy drop of each cylinder segment (Δh_i) is placed on the main cylinder isentrope. The isentropic loss of each cylinder and whole turbine is the difference between ideal and real mechanical power, while isentropic efficiency (of each cylinder and whole turbine) is the ratio of real and ideal mechanical power.

Exergy analysis considers the parameters of the ambient (ambient pressure and temperature) in which turbine or their cylinders operate because exergy analysis is based on the second law of thermodynamics [52]. Therefore, in the exergy analysis of any turbine or cylinder it is essential to define the ambient temperature and pressure (base ambient state) [53]. In addition, exergy analysis also enables the change in the ambient parameters (especially change in the ambient temperature, which has a much higher influence on the component efficiencies and destructions in comparison to the ambient pressure change).

The general exergy balance equation for any control volume at steady state with negligible potential and kinetic energy changes is [54]:

$$\dot{X} - P = \sum \dot{E}x_{\mathrm{out}} - \sum \dot{E}x_{\mathrm{in}} + \dot{E}x_{\mathrm{D}}. \tag{3}$$

Fluid total exergy flow ($\dot{E}x$) is [55]:

$$\dot{E}x = \dot{m} \cdot \varepsilon. \tag{4}$$

In Eq. 4, operating fluid specific exergy (ε) can be defined as [56]:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0). \tag{5}$$

Definition of exergy transfer by heat at the temperature T ($\dot{X}$) can be found in [57] and presented with a following equation:

$$\dot{X} = \sum \left(1 - \frac{T_0}{T}\right) \cdot \dot{Q}. \tag{6}$$

Always valid mass flow rate balance for any component is:

$$\sum \dot{m}_{\mathrm{in}} = \sum \dot{m}_{\mathrm{out}}. \tag{7}$$

3.2 Analysis equations – example of steam turbine from conventional power plant

The equations used in the isentropic and exergy analyses (as well as in the calculation of other operation parameters) for the observed steam turbines and their cylinders are composed according to the recommendations and processes from the literature [11, 12, 55, 58].

In this paper will be presented complete equations used in the analysis of steam turbine (as well as turbine cylinders) from the conventional power plant. For all the other observed steam turbines equations are composed in a same manner, according to their operating parameters presented in Tables from 4 to 7 and in relation to operating points for each turbine from Fig. 1.

Ideal and real steam expansion processes for each cylinder and a whole turbine from the conventional power plant are presented in Fig. 3. According to operating points from Fig. 1 and Fig. 3 will be defined all equations used in the analysis of the turbine from the conventional plant.

Equations for ideal (isentropic) and real (polytropic) mechanical power calculation of each cylinder and whole turbine from the conventional power plant are presented in Table 1.

The isentropic loss of each cylinder and whole turbine from the conventional power plant is the difference between ideal and real mechanical power, while isentropic efficiency (of each cylinder and whole turbine) is the ratio of real and ideal mechanical power.

Exergy destruction and exergy efficiency of each cylinder and the whole turbine from the conventional power plant are calculated by using equations presented in Table 2. It should be noted that the variation in the ambient temperature, performed at the end of this analysis, is done by using the same equations from Table 2.

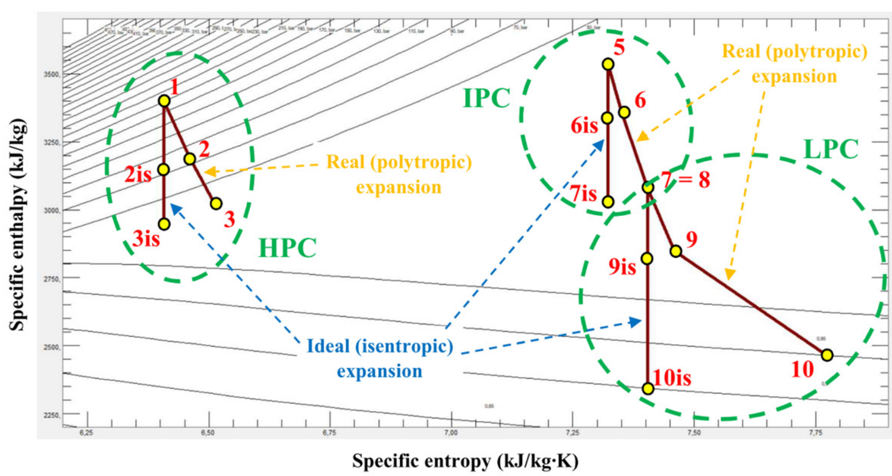

Fig. 3 Comparison of ideal (isentropic) and real (polytropic) steam expansion processes through all cylinders of steam turbine from the conventional power plant

Source: Authors

Table 1 Equations for ideal (isentropic) and real (polytropic) mechanical power calculation

Component	Ideal (isentropic) mechanical power	Eq.	Real (polytropic) mechanical power	Eq.
HPC	$P_{\mathrm{HPC,IS}} = \dot{m}_1 \cdot (h_1 - h_{2\mathrm{is}}) + (\dot{m}_1 - \dot{m}_2) \cdot (h_{2\mathrm{is}} - h_{3\mathrm{is}})$	(8)	$P_{\mathrm{HPC,PT}} = \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3)$	(12)
IPC	$P_{\mathrm{IPC,IS}} = \dot{m}_5 \cdot (h_5 - h_{6\mathrm{is}}) + (\dot{m}_5 - \dot{m}_6) \cdot (h_{6\mathrm{is}} - h_{7\mathrm{is}})$	(9)	$P_{\mathrm{IPC,PT}} = \dot{m}_5 \cdot (h_5 - h_6) + (\dot{m}_5 - \dot{m}_6) \cdot (h_6 - h_7)$	(13)
LPC	$P_{\mathrm{LPC,IS}} = \dot{m}_8 \cdot (h_8 - h_{9\mathrm{is}}) + (\dot{m}_8 - \dot{m}_9) \cdot (h_{9\mathrm{is}} - h_{10\mathrm{is}})$	(10)	$P_{\mathrm{LPC,PT}} = \dot{m}_8 \cdot (h_8 - h_9) + (\dot{m}_8 - \dot{m}_9) \cdot (h_9 - h_{10})$	(14)
WT	$P_{\mathrm{WT,IS}} = P_{\mathrm{HPC,IS}} + P_{\mathrm{IPC,IS}} + P_{\mathrm{LPC,IS}}$	(11)	$P_{\mathrm{WT,PT}} = P_{\mathrm{HPC,PT}} + P_{\mathrm{IPC,PT}} + P_{\mathrm{LPC,PT}}$	(15)

Source: Authors

Table 2 Equations for the exergy destruction and exergy efficiency calculation

Component	Exergy destruction	Eq.	Exergy efficiency	Eq.
HPC	$\dot{E}x_{\mathrm{D,HPC}} = \dot{E}x_1 - \dot{E}x_2 - \dot{E}x_3 - \dot{E}x_4 - P_{\mathrm{HPC,PT}}$	(16)	$\eta_{\mathrm{ex,HPC}} = \frac{P_{\mathrm{HPC,PT}}}{\dot{E}x_{\mathrm{D,HPC}} + P_{\mathrm{HPC,PT}}}$	(20)
IPC	$\dot{E}x_{\mathrm{D,IPC}} = \dot{E}x_5 - \dot{E}x_6 - \dot{E}x_7 - \dot{E}x_8 - P_{\mathrm{IPC,PT}}$	(17)	$\eta_{\mathrm{ex,IPC}} = \frac{P_{\mathrm{IPC,PT}}}{\dot{E}x_{\mathrm{D,IPC}} + P_{\mathrm{IPC,PT}}}$	(21)
LPC	$\dot{E}x_{\mathrm{D,LPC}} = \dot{E}x_8 - \dot{E}x_9 - \dot{E}x_{10} - P_{\mathrm{LPC,PT}}$	(18)	$\eta_{\mathrm{ex,LPC}} = \frac{P_{\mathrm{LPC,PT}}}{\dot{E}x_{\mathrm{D,LPC}} + P_{\mathrm{LPC,PT}}}$	(22)
WT	$\dot{E}x_{\mathrm{D,WT}} = \dot{E}x_{\mathrm{D,HPC}} + \dot{E}x_{\mathrm{D,IPC}} + \dot{E}x_{\mathrm{D,LPC}}$	(19)	$\eta_{\mathrm{ex,WT}} = \frac{P_{\mathrm{WT,PT}}}{\dot{E}x_{\mathrm{D,WT}} + P_{\mathrm{WT,PT}}}$	(23)

Source: Authors

Table 3 Equations for the specific steam consumption and specific heat consumption calculation

Component	Specific steam consumption	Eq.	Specific heat consumption	Eq.
HPC	$SSC_{\mathrm{HPC}} = \frac{\dot{m}_1}{P_{\mathrm{HPC,PT}}}$	(24)	$SHC_{\mathrm{HPC}} = \frac{\dot{m}_2 \cdot h_2 + \dot{m}_3 \cdot h_3}{P_{\mathrm{HPC,PT}}}$	(28)
IPC	$SSC_{\mathrm{IPC}} = \frac{\dot{m}_5}{P_{\mathrm{IPC,PT}}}$	(25)	$SHC_{\mathrm{IPC}} = \frac{\dot{m}_6 \cdot h_6 + \dot{m}_7 \cdot h_7}{P_{\mathrm{IPC,PT}}}$	(29)
LPC	$SSC_{\mathrm{LPC}} = \frac{\dot{m}_8}{P_{\mathrm{LPC,PT}}}$	(26)	$SHC_{\mathrm{LPC}} = \frac{\dot{m}_9 \cdot h_9}{P_{\mathrm{LPC,PT}}}$	(30)
WT	$SSC_{\mathrm{WT}} = \frac{\dot{m}_1 + \dot{m}_5 + \dot{m}_8}{P_{\mathrm{WT,PT}}}$	(27)	$SHC_{\mathrm{WT}} = \frac{\dot{m}_2 \cdot h_2 + \dot{m}_3 \cdot h_3 + \dot{m}_6 \cdot h_6 + \dot{m}_7 \cdot h_7 + \dot{m}_9 \cdot h_9}{P_{\mathrm{WT,PT}}}$	(31)

Source: Authors

With an aim of deeper comparison, in this research are also used two additional operating parameters of each cylinder and whole turbine. These parameters are specific steam consumption (in kg/kWh) and specific heat consumption (in kJ/kWh). Specific steam consumption shows how much steam mass flow rate (in kg) is used at the entrance of each turbine cylinder for the production of one kWh of useful mechanical power. Specific heat consumption shows how much heat (in kJ) is extracted from each turbine cylinder and delivered to regenerative condensing/feedwater heating system per one kWh of useful produced mechanical power. For turbine and each turbine cylinder from the conventional power plant, specific steam consumption and specific heat consumption are calculated by using equations presented in Table 3.

4 Steam operating parameters of all observed turbines and their cylinders

Steam operating parameters for each turbine in each operating point presented in Fig. 1 are presented in Table 4 for marine propulsion turbine, in Table 5 for turbine from conventional power plant, in Table 6 for turbine from ultra-supercritical power plant and in Table 7 for steam turbine from nuclear power plant. It should be highlighted that turbine from ultra-supercritical power plant has two low pressure cylinders – in Table 6 are presented cumulative steam mass flow rates for both of them (in accordance to Fig. 1 (c)).

In the literature are found just some steam parameters in each operating point of each turbine, all the others are calculated by using NIST-REFPROP 9.0 software [46]. Isentropic specific enthalpies for all cylinders of all observed turbines are calculated assuming always the same steam specific entropy during the expansion process.

In all tables (from Table 4 up to Table 7) steam specific exergies in each operating point are calculated at the base ambient state. The base ambient state can be defined arbitrarily [49] and in this analysis the base ambient state is defined by the ambient pressure of 1 bar and the ambient temperature of 25 °C.

Table 4 Steam properties in each operating point of marine propulsion turbine

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality	Isentropic specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)**
1	510.00	101.000	15.593	3399.7	6.6268	Superheated	3399.7	1428.50
2	398.00	38.700	1.055	3212.0	6.7821	Superheated	3111.1	1194.50
3	327.00	22.600	1.679	3079.7	6.8094	Superheated	2974.2	1054.00
4	327.00	22.600	12.859	3079.7	6.8094	Superheated	-	1054.00
5	510.00	20.300	12.859	3490.0	7.4549	Superheated	3490.0	1271.90
6	341.95	5.600	0.421	3150.2	7.5538	Superheated	3090.7	902.54
7	341.95	5.600	12.438	3150.2	7.5538	Superheated	3150.2	902.54
8	249.92	2.400	0.808	2969.7	7.6236	Superheated	2933.8	701.31
9	126.97	0.600	0.683	2734.4	7.7462	Superheated	2661.0	429.42
10	32.87	0.050	10.947	2512.3	8.2354	0.980	2303.7	61.43

* O. P. = Operating Point (in accordance with Fig. 1); ** Specific exergy at the base ambient state.

Source: [35] and calculation of the authors

Table 5 Steam properties in each operating point of turbine from conventional power plant

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality	Isentropic specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)**
1	540.00	171.0	272.22	3399.7	6.4068	Superheated	3399.7	1494.10
2	415.73	76.0	14.56	3190.0	6.4613	Superheated	3152.8	1268.10
3	317.86	36.0	22.76	3022.2	6.5118	Superheated	2961.3	1085.20
4	317.86	36.0	234.90	3022.2	6.5118	Superheated	-	1085.20
5	536.00	31.0	234.90	3537.2	7.3222	Superheated	3537.2	1358.60
6	445.17	17.0	10.35	3351.6	7.3511	Superheated	3331	1164.50
7	308.20	6.0	21.15	3079.1	7.4035	Superheated	3032.7	876.28
8	308.20	6.0	203.40	3079.1	7.4035	Superheated	3079.1	876.28
9	188.59	2.0	15.16	2847.7	7.4589	Superheated	2822.5	628.43
10	46.63	0.1	188.24	2464.3	7.7738	0.95	2346.1	151.05

* O. P. = Operating Point (in accordance with Fig. 1); ** Specific exergy at the base ambient state.

Source: [39] and calculation of the authors

Table 6 Steam properties in each operating point of turbine from ultra-supercritical power plant

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality	Isentropic specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)**
1	566.00	242.000	532.000	3398.7	6.2659	Superheated	3398.7	1535.00
2	367.20	67.970	35.500	3073.0	6.3311	Superheated	3031.7	1190.00
3	315.10	45.670	48.100	2985.8	6.3510	Superheated	2936.4	1096.80
4	315.10	45.670	448.400	2985.8	6.3510	Superheated	-	1096.80
5	566.00	41.100	448.400	3596.0	7.2661	Superheated	3596.0	1434.10
6	457.00	20.580	20.100	3372.8	7.2938	Superheated	3352.7	1202.80
7	362.90	10.650	53.400	3184.4	7.3159	Superheated	3153.1	1007.70
8	362.90	10.650	374.900	3184.4	7.3159	Superheated	3184.4	1007.70
9	253.60	4.374	26.300	2970.6	7.3514	Superheated	2952.1	783.36
10	128.80	1.333	13.100	2731.2	7.3735	Superheated	2708.4	537.37
11	88.20	0.655	17.400	2656.6	7.5015	Superheated	2589.5	424.58
12	60.91	0.208	13.200	2522.3	7.6300	0.963	2417.4	252.02
13	35.85	0.059	304.900	2397.7	7.7900	0.930	2251.2	79.65

* O. P. = Operating Point (in accordance with Fig. 1); ** Specific exergy at the base ambient state.

Source: [40] and calculation of the authors

Table 7 Steam properties in each operating point of turbine from nuclear power plant

O.P.*	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Quality	Isentropic specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)**
1	274.63	59.130	1543.58	2776.2	5.88	0.994	2776.2	1027.60
2	225.11	25.550	129.94	2663.9	5.97	0.925	2619.1	888.51
3	185.28	11.306	64.63	2551.3	6.04	0.885	2477.9	755.04
4	163.33	6.724	127.42	2481.4	6.08	0.865	2394.1	673.21
5	163.33	6.724	1221.59	2481.4	6.08	0.865	-	673.21
6	163.13	6.690	164.30	707.2	2.02	0.009	-	110.91
7	162.89	6.650	1057.29	2757.1	6.72	0.998	-	759.14
8	239.67	6.600	1057.29	2933.5	7.09	Superheated	2933.5	823.03
9	274.63	59.130	117.53	2776.2	5.88	0.994	-	1027.60
10	268.99	58.500	117.53	1180	2.97	Subcooled	-	300.26
11	128.19	1.961	46.72	2723.8	7.18	Superheated	2689.7	587.64
12	93.72	0.807	43.55	2584.5	7.21	0.964	2541.8	439.40
13	73.32	0.360	45.72	2470.5	7.24	0.931	2420.0	316.46
14	40.63	0.076	921.30	2328.7	7.46	0.898	2213.2	109.06

* O. P. = Operating Point (in accordance with Fig. 1); ** Specific exergy at the base ambient state.

Source: [42] and calculation of the authors

5 Results and Discussion

Real developed mechanical power of each cylinder and whole turbine for all observed steam turbines is presented in Fig. 4.

HPC of marine and ultra-supercritical steam turbine develops higher mechanical power in comparison to IPC, while IPC of the steam turbine from conventional power plant develops higher mechanical power in comparison to HPC. In all observed steam turbines, the dominant mechanical power producer is LPC, regardless of the fact that the LPC operates with low pressures and by using wet steam (at least at the last few turbine stages before main condenser). Also for the steam turbine from nuclear power plant which did not possess IPC (due to low steam pressures and temperatures), LPC produces notably higher mechanical power in comparison to HPC.

Comparison of whole observed steam turbines shows that steam turbine from nuclear power plant produces notably higher mechanical power in comparison to all other observed steam turbines, regardless of the lowest heat drop in each cylinder, Fig. 2. Steam turbines in nuclear power plants have much higher steam mass flow rate in comparison to all other steam power plants. In the analyzed case, steam turbine from nuclear power plant produces 1030.18 MW of mechanical power, followed by 666.69 MW produced in ultra-supercritical power plant and by 324.35 MW produced in the conventional steam power plant. Marine steam turbine, which is used for the ship propulsion propeller drive, produces notably lower mechanical power (equal to 16.63 MW) in comparison to all other observed steam turbines.

When observing isentropic loss of each cylinder and whole turbine, Fig. 5, it is evident that (for the most of the turbines) the highest mechanical power producers are simultaneously the highest isentropic loss generators.

Considering all cylinders, for all observed turbines is valid that LPC is the highest isentropic loss generator. The only turbine which deviates from this conclusion is the turbine from nuclear power plant, which HPC has a higher isentropic loss in comparison to LPC (128.33 MW in comparison to 112.17 MW), regardless of the fact that in nu-

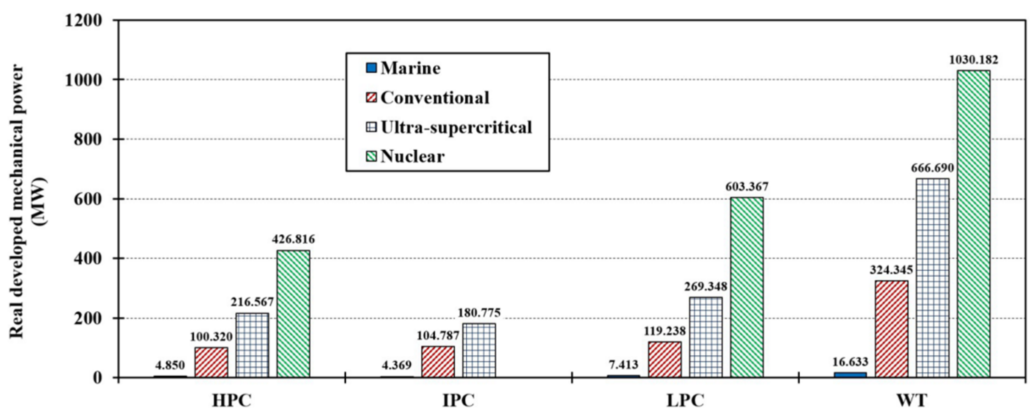

Fig. 4 Real developed mechanical power of each cylinder and whole turbine

Source: Authors

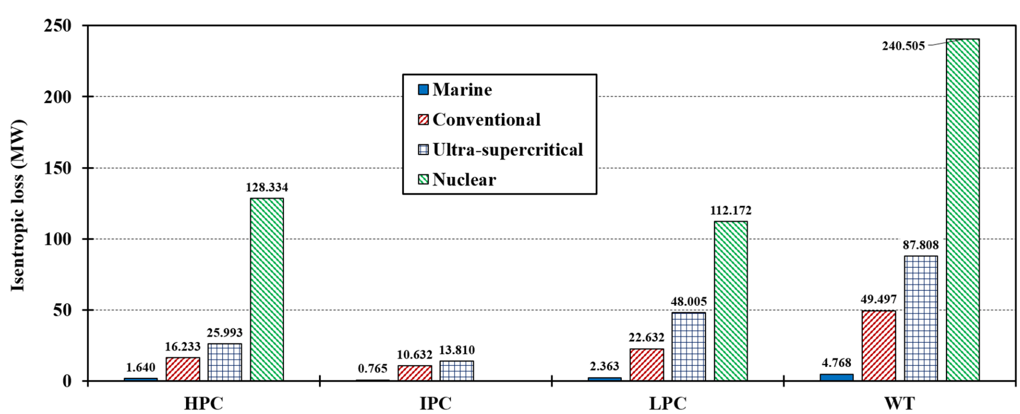

Fig. 5 Isentropic loss of each cylinder and whole turbine

Source: Authors

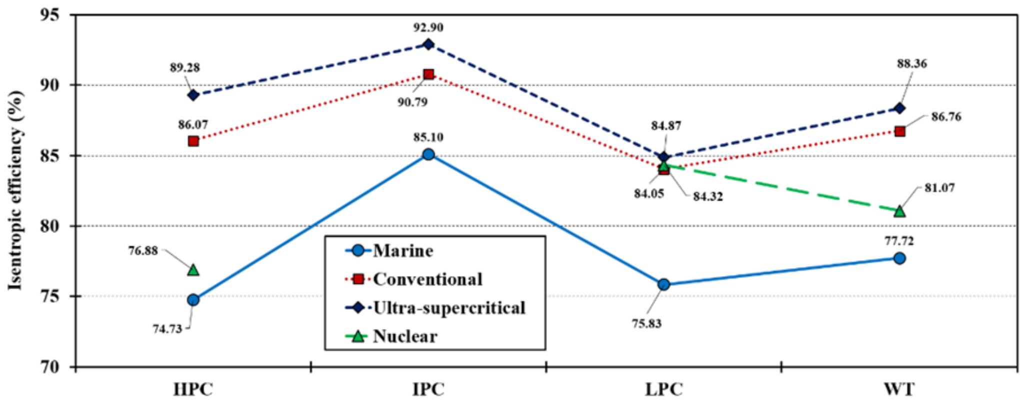

Fig. 6 Isentropic efficiency of each cylinder and whole turbine

Source: Authors

clear power plant LPC produces notably higher mechanical power, Fig. 4 and Fig. 5. For the turbines from marine, conventional and ultra-supercritical power plants can be concluded that from the isentropic aspect, IPC is the best balanced cylinder which has the lowest isentropic loss in comparison to the other cylinders.

Isentropic loss of the whole turbine is directly proportional to the turbine produced mechanical power – higher produced mechanical power results in the higher isentropic loss and vice versa. Therefore, whole turbine from nuclear power plant has notably higher isentropic loss (equal to 240.51 MW) in comparison to all other turbines considered in this analysis, while whole marine steam turbine has the lowest isentropic loss (equal to 4.77 MW), Fig. 5.

The isentropic efficiency of each cylinder and whole turbine for all observed steam turbines is presented in Fig. 6.

Fig. 6 shows that isentropic efficiency of whole steam turbine (as well as of each cylinder) from ultra-supercritical power plant is higher in comparison to all other observed turbines. It can be concluded that steam pressure higher than the critical (water critical pressure is equal to 220.64 bar) is very beneficial to the isentropic efficiency of steam turbine and turbine cylinders. That is one of the reasons (along with fuel savings due to avoiding steam evaporation process) why supercritical and ultra-supercritical steam power plants have higher overall efficiencies in comparison to conventional power plants [59, 60].

Marine steam turbine and all its cylinders have the lowest isentropic efficiency, much lower than all other observed steam turbines. Regardless of the fact that steam turbine from nuclear power plant dominantly operates by using wet steam, the isentropic efficiency of that steam turbine is still higher in comparison to marine steam turbine (what is also valid for all cylinders).

For all observed steam turbines can be seen that IPC has an isentropic efficiency notably higher in comparison to other cylinders (that conclusion is not related only to steam turbine from nuclear power plant which did not possess the IPC), Fig. 6. As the IPC of any steam turbine did not operate with the highest steam pressures and temperatures (which causes higher losses in HPC) and did not operate by using wet steam (which increases losses in at least last stages of LPC), it is clear that IPC of any steam turbine operates in the best possible conditions.

Exergy destruction in the cylinders of marine, conventional and ultra-supercritical steam turbine show the same trend as isentropic loss (the highest destruction occur in LPC, followed by HPC while the lowest exergy destruction occurs in IPC), Fig. 7.

In the cylinders of steam turbine from nuclear power plant occur reverse proportional trend of exergy destruction in comparison to isentropic loss – exergy destruction is notably higher in LPC than in HPC. For a steam turbine from nuclear power plant is obvious that exergy destruction related to wet steam (which occur in LPC) is notably higher in comparison to exergy destruction related to the steam of the highest pressure and temperature (which occur in HPC).

Considering whole analyzed turbines it can be concluded that both isentropic losses and exergy destructions are directly proportional to produced mechanical power – higher produced mechanical power results with higher isentropic losses and exergy destructions (and vice versa).

Trends in exergy efficiency for the cylinders of steam turbines from marine, conventional and ultra-supercritical power plants are identical as trends in isentropic efficiency – the highest exergy efficiency is achieved in IPC, followed by HPC, while the LPC has the lowest exergy efficiency, Fig. 8. As concluded for the exergy destruction, Fig. 7, exergy analysis is notable sensitive to the turbine cylinders which operates by using wet steam at low steam pressures and temperatures – their exergy efficiency notably decreases in comparison to the other cylinders. Exergy analysis also shows that exergy efficiency of HPC is lower for steam turbine from nuclear power plant in comparison to HPC from marine power plant (due to wet steam opera-

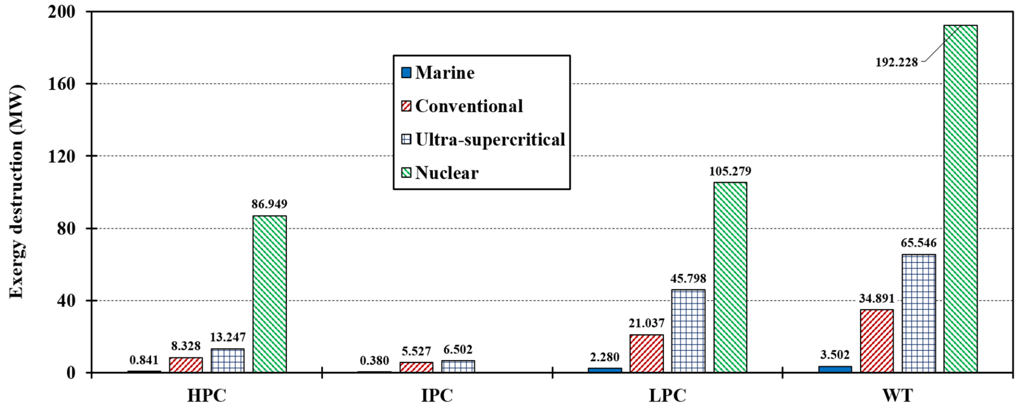

Fig. 7 Exergy destruction of each cylinder and whole turbine

Source: Authors

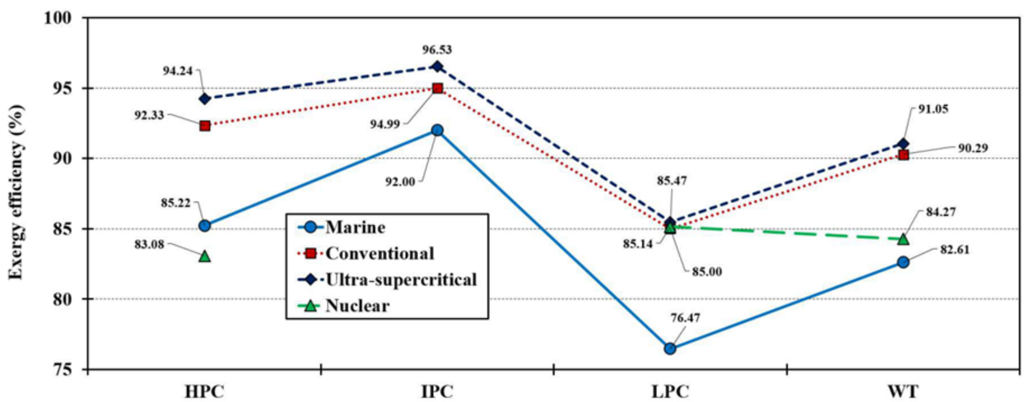

Fig. 8 Exergy efficiency of each cylinder and whole turbine

Source: Authors

tion in nuclear power plant), while isentropic analysis shows reverse proportional ratio.

Considering each analyzed steam turbine as a whole, it can be seen that the same trends obtained for isentropic efficiency are also obtained for exergy efficiency – the highest exergy efficiency of 91.05% can be observed for a steam turbine from ultra-supercritical power plant, followed by steam turbines from the conventional and nuclear power plants, while the lowest exergy efficiency (equal to 82.61%) is obtained for the marine steam turbine.

Specific steam consumption, for any cylinder and the whole turbine, is a parameter which shows how much steam (in kg) is used for production of one kWh of mechanical power. Each cylinder and the whole turbine should have the value of specific steam consumption as low as possible.

Specific steam consumption results of each cylinder and whole turbine for all observed steam turbines analyzed in this paper are presented in Fig. 9. If observing turbine cylinders, it can be concluded that the highest specific steam consumption has turbine cylinders from nuclear power plant. Slightly lower specific steam consumption (in comparison to turbine cylinders from nuclear power plant) has cylinders of marine steam turbine. The lowest specific steam consumption of all observed steam turbines has cylinders of the turbine from ultra-supercritical power plant (the only deviation from this conclusion can be seen in IPC where the turbine cylinder from a conventional power plant has lower specific steam consumption in comparison to the same cylinder from ultra-supercritical power plant).

For the cylinders of all observed steam turbines in this paper can also be concluded that HPC has the highest specific steam consumption, while in the IPC specific steam consumption notably decreases in comparison to HPC. The only turbine which deviates from this trend is turbine from ultra-supercritical power plant where IPC has slightly higher specific steam consumption (8.93 kg/kWh) in comparison to HPC (8.84 kg/kWh). In all observed steam turbines LPC is the cylinder with the lowest specific steam consumption (in comparison to other cylinders).

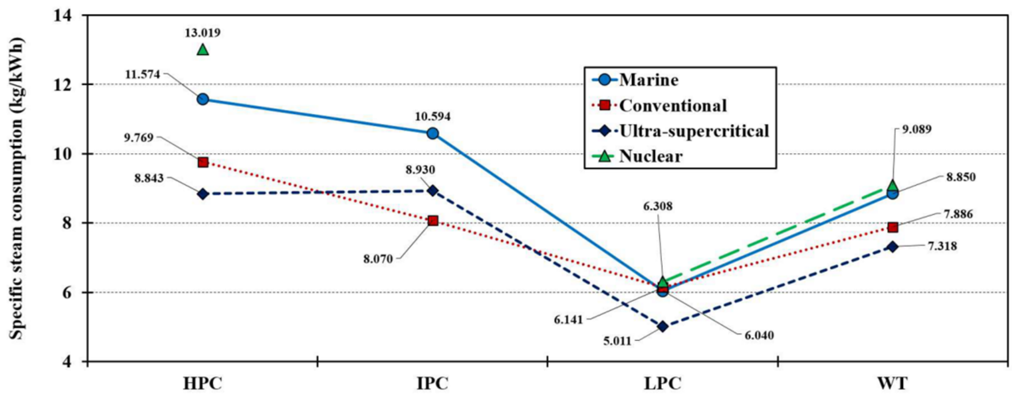

Fig. 9 Specific steam consumption of each cylinder and whole turbine

Source: Authors

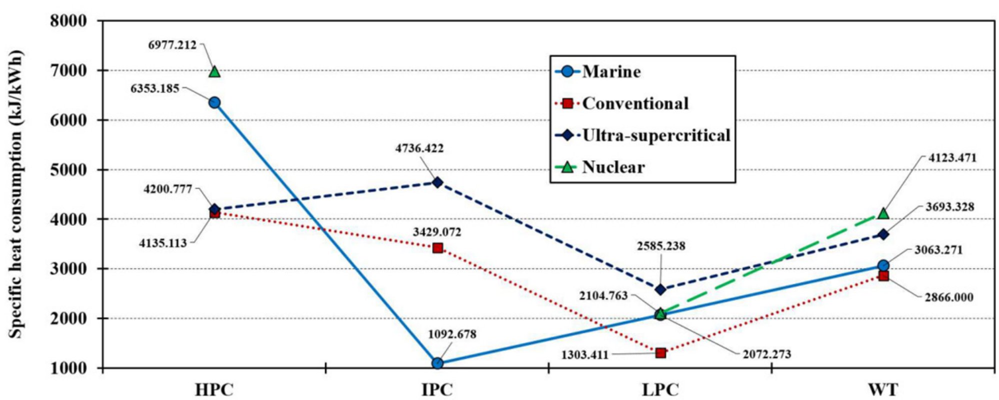

Fig. 10 Specific heat consumption of each cylinder and whole turbine

Source: Authors

Comparison of the whole turbines shows that steam turbine from ultra-supercritical power plant has notably lower specific steam consumption (7.32 kg/kWh) in comparison to all other observed turbines. Therefore, steam turbine from ultra-supercritical power plant shows its dominancy over other analyzed turbines not only in efficiencies (both isentropic and exergy) but also in the specific steam consumption. The highest specific steam consumption is observed in a whole steam turbine from nuclear power plant (9.09 kg/kWh). Whole marine steam turbine, along with the lowest isentropic and exergy efficiencies in comparison to other analyzed turbines, also show very high specific steam consumption, only slightly lower than the turbine from nuclear power plant (8.85 kg/kWh). Whole steam turbine from a conventional power plant has isentropic and exergy efficiency slightly lower in comparison to the turbine from ultra-supercritical power plant, along with a slightly higher specific steam consumption, equal to 7.89 kg/kWh.

In this analysis, specific heat consumption is a parameter which shows how much heat (in kJ) from each cylinder and whole turbine per one kWh of produced mechanical power is delivered to regenerative condensing/feedwater heating system. Specific heat consumption of each cylinder and whole turbine for all observed steam turbines is presented in Fig. 10.

Comparison of the cylinders of all analyzed turbines shows that in the most of the cases HPC is the cylinder with the highest specific heat consumption, mostly because of the highest steam pressures and temperatures (in comparison to other cylinders). Only for the turbine from ultra-supercritical power plant IPC has higher specific steam consumption than HPC. Dominantly, the LPC has the lowest specific steam consumption due to the lowest steam operating parameters (pressure and temperature). The turbine from marine power plant deviates from this conclusion – for this turbine LPC has higher specific heat consumption than IPC.

Observation of the whole turbines shows that the highest specific heat consumption has a turbine from nuclear power plant (4123.47 kJ/kWh). Whole steam turbine from ultra-supercritical power plant has notably higher specific

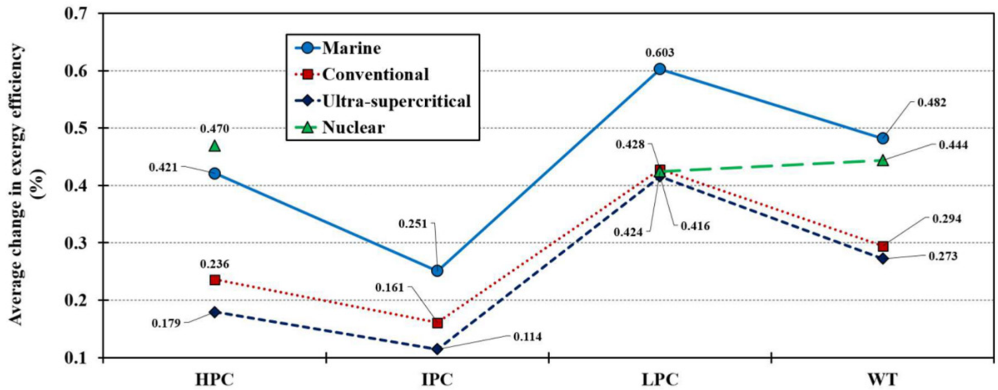

Fig. 11 Average change in exergy efficiency (between ambient temperatures 5 °C and 45 °C) of each cylinder and whole turbine

Source: Authors

heat consumption than turbines from marine and conventional power plants, but still lower in comparison to the turbine from nuclear power plant. The lowest specific heat consumption is obtained in the whole turbine from conventional power plant, equal to 2866 kJ/kWh.

For the turbine from ultra-supercritical power plant can be concluded that along with the highest efficiencies and the lowest specific steam consumption, this turbine delivers a high amount of heat per one kWh of produced mechanical power to regenerative condensing/feedwater heating system, comparable to steam turbines from nuclear power plant.

In the last part of this analysis is observed how the ambient temperature change influences exergy efficiencies of all observed turbines and their cylinders. During this variation the ambient pressure remains the same as at the base ambient state (equal to 1 bar), while the ambient temperature is varied from 5 °C up to 45 °C in steps of 10 °C. The main goal was to obtain which cylinder and the whole turbine are the most sensitive in relation to the ambient temperature change.

The average change in exergy efficiency of each cylinder and whole turbine for all observed steam turbines during the ambient temperature variation is presented in Fig. 11. For any cylinder or whole steam turbine is always valid following conclusion (it has a general validation for all steam turbines, not only for the analyzed ones): an increase in the ambient temperature decreases exergy efficiency and vice versa [44].

From Fig. 11 can be concluded that the exergy efficiency of cylinders from the marine steam turbine is the most influenced by the ambient temperature change, more than exergy efficiency of any other turbine cylinder (the only deviation from this conclusion can be seen in HPC – HPC exergy efficiency of turbine from nuclear power plant is more influenced by the ambient temperature change than exergy efficiency of HPC from marine turbine). Cylinders exergy efficiency of steam turbine from ultra-supercritical power plant is the lowest influenced by the ambient temperature change in comparison to all other analyzed cylinders.

It should also be highlighted that (in comparison to HPC and IPC), exergy efficiency of LPC is much more influenced by the ambient temperature change for all observed steam turbines. The only deviation from this conclusion can be found in steam turbine from nuclear power plant.

Finally, while observing whole analyzed turbines, it can be concluded that exergy efficiency of whole steam turbine from marine power plant is the most influenced by the ambient temperature change, while simultaneously, exergy efficiency of whole steam turbine from ultra-supercritical power plant is the lowest influenced by the ambient temperature change. Steam turbine (and its cylinders) from ultra-supercritical power plant show that their exergy efficiency will not change significantly during the ambient temperature variation, what is another benefit of this turbine in comparison to all other observed ones.

At the end of this analysis, it can be stated that ultra-supercritical steam processes are beneficial from many aspects, while steam turbines in such processes operate with the highest efficiencies, lowest specific steam consumption and such turbines are low influenced by the ambient temperature change. Therefore, steam turbines from ultra-supercritical steam power plants show better performance in comparison to steam turbines from other comparable power plants. Along with a fact that ultra-supercritical steam processes have much higher overall efficiencies in comparison to the conventional steam processes [61], almost optimal turbine operation in that power plants is one more reason why they have more and more involvement in practical applications [62, 63].

6 Conclusions

In this paper is performed an analysis and comparison of four steam turbines (and their cylinders) from four different power plants. Comparison of the isentropic losses, exergy destructions, isentropic and exergy efficiencies, specific steam and specific heat consumption as well as analysis related to the ambient temperature change sensitivity results with the finding of optimal steam turbine process. The most important conclusions are:

- In all observed steam turbines, the dominant mechanical power producer is LPC, regardless of the fact that the LPC operates with low pressures and by using wet steam (at least at the last few turbine stages before main condenser).
- Steam turbine from nuclear power plant produces notably higher mechanical power in comparison to all other observed steam turbines, due to much higher steam mass flow rate.
- For all observed turbines is valid that LPC is the highest isentropic loss generator.
- Isentropic efficiency of whole steam turbine (as well as of each cylinder) from ultra-supercritical power plant is higher in comparison to all other observed turbines, while marine steam turbine and all its cylinders have the lowest isentropic efficiency. IPC has an isentropic efficiency notably higher in comparison to other cylinders because IPC of any steam turbine did not operate with the highest steam pressures and temperatures (which causes higher losses in HPC) and did not operate by using wet steam (which increases losses in at least last stages of LPC).
- Considering whole analyzed turbines it can be concluded that both isentropic losses and exergy destructions are directly proportional to produced mechanical power – higher produced mechanical power results with higher isentropic losses and exergy destructions.
- The highest exergy efficiency of 91.05% is obtained for a whole steam turbine from ultra-supercritical power plant, followed by whole steam turbines from the conventional and nuclear power plants, while the lowest exergy efficiency (equal to 82.61%) is obtained for the whole marine steam turbine.
- In all observed steam turbines LPC is the cylinder with the lowest specific steam consumption. The lowest specific steam consumption of all observed steam turbines has cylinders of the turbine from ultra-supercritical power plant.
- Comparison of the whole turbines shows that steam turbine from ultra-supercritical power plant has notably lower specific steam consumption (7.32 kg/kWh) in comparison to all other observed turbines. The highest specific steam consumption is observed in a whole steam turbine from nuclear power plant (9.09 kg/kWh).
- In the most of the cases HPC is the cylinder with the highest specific heat consumption, mostly because of the highest steam pressures and temperatures. The highest specific heat consumption has a whole turbine from nuclear power plant (4123.47 kJ/kWh).
- The exergy efficiency of cylinders from the marine steam turbine is the most influenced by the ambient temperature change, while simultaneously exergy efficiency of cylinders from ultra-supercritical power plant steam turbine is the lowest influenced by the ambient temperature change.

As a final result of this analysis and comparison, it can be concluded that steam turbines in ultra-supercritical processes operate with the highest efficiencies, lowest specific steam consumption, sufficiently high specific heat consumption and such turbines are low influenced by the ambient temperature change. Therefore, steam turbines in ultra-supercritical processes show the best performances in comparison to steam turbines from any other power plants.

NOMENCLATURE

Abbreviations

HPC	High Pressure Cylinder
IPC	Intermediate Pressure Cylinder
LPC	Low Pressure Cylinder
WT	Whole Turbine

Latin symbols

$\dot{E}x$	total exergy fluid flow, kW
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
P	mechanical power, kW
$\dot{Q}$	energy transfer by heat, kW
s	specific entropy, kJ/kg·K
SHC	specific heat consumption, kJ/kWh
SSC	specific steam consumption, kg/kWh
T	temperature, K or °C
$\dot{X}$	exergy transfer by heat, kW

Greek symbols

ε	specific exergy, kJ/kg
η	efficiency, %

Subscripts

0	base ambient state
ex	exergy
in	inlet (input)
IS	isentropic (ideal) steam expansion
k	the number of turbine cylinders
D	destruction
n	the number of cylinder segments
out	outlet (output)
PT	polytropic (real) steam expansion

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