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Vedran Mrzljak
E-mail: vedran.mrzljak@riteh.hr
Nikola Anđelić
E-mail: nandelic@riteh.hr
Ivan Lorencin
E-mail: ilorencin@riteh.hr
Zlatan Car
E-mail: zlatan.car@riteh.hr
Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia

Analysis of Gas Turbine Operation before and after Major Maintenance

Abstract

This paper presents an analysis of the gas turbine real process (with all losses included) before and after a major maintenance. The analysis of both gas turbine operating regimes is based on data measured during its exploitation. Contrary to authors' expectations, the major maintenance process did not result either in any decrease in losses or increase in efficiencies for the majority of the gas turbine components. However, the major maintenance influenced positively the gas turbine combustion chambers (reduction in losses and increase in the combustion chambers efficiency). After the major maintenance, the overall process efficiency decreased from 43.796% to 41.319% due to a significant decrease in the air mass flow rate and to an increase in the fuel mass flow rate in combustion chambers. A decrease in the gas turbine produced cumulative and useful power after a major maintenance also increased the specific fuel consumption.

Keywords: gas turbine, turbine major maintenance, efficiency, losses, specific fuel consumption

1. Introduction

Gas turbines nowadays have application in many power systems. They are essential components of combined power plants [1, 2] where used as a primary element for the power and heat production [3]. Operation of the steam part of the combined power plant along with all of its components [4] is highly dependable on gas turbine process and exhaust gas parameters [5]. The wide usage of gas turbines today also includes various cogeneration plants [6].

In marine power systems diesel engines prevail in general [7, 8], while the usage of gas turbines in such systems is usually limited due to many important factors [9]. Gas turbines in marine power systems can be used as independent components [10] or in various combinations with internal combustion engines or steam turbines along with all necessary equipment required for such plant operation [11-14].

Several researchers have analyzed gas turbines as stand-alone devices either without any upgrades [15] or with several upgrades [16]. One specific upgrade of gas turbine cycles concerns the air bottoming cycle, presented in [17].

An interesting comparison of four different gas turbine cycles is presented in [18], in addition to the advanced exergy analysis presented in respect of the most effective gas turbine cycle. Exergy analysis is a commonly used technique for research and analysis of various steam and gas turbines [19-21] which shows that highest losses of the gas turbine cycle occur in combustion chambers [22, 23] regardless of gas turbine operation characteristics and power output.

Several methods have been developed for improving the efficiency of power plants having a gas turbine as an essential component. One of such efficiency improvement methods is based on the specific entropy generation [24].

This paper presents an analysis of a gas turbine without any upgrades included, taking into account all the losses occurring during the gas turbine operation. Based on measured operating parameters, the gas turbine performance was investigated before and after a major maintenance. Usually, it would be expected that the major maintenance process reduces losses and increases efficiencies of gas turbine components. It will be interesting to investigate whether such expectations are also valid for the observed gas turbine.

2. Description of the gas turbine operating process

The main scheme of the gas turbine operating process along with four characteristic operating points is presented in Figure 1. The turbo-compressor compresses the air from the atmosphere and brings it with increased pressure to combustion chambers, where fuel combustion takes place. Fuels in the gas turbine process must be of high-quality and therefore very expensive, so the majority of gas turbine operational costs are dependable on current fuel prices (also valid for other power producers where fuels of lower quality can also be used [25-27]). The maximum process temperature (maximum combustion gas temperature) occurs at the combustion chamber outlet (gas turbine inlet) - point 3, Figure 1. After the combustion gas expansion through a turbine, gases are released from the gas turbine process into the atmosphere. One part of the produced turbine cumulative power (usually about 50%) is used for the turbo-compressor drive, while the other part of the produced cumulative power (useful power) drives any power consumer. The beginning of the gas turbine operation from its dead-state is ensured with a starting electro-motor. The temperature-specific entropy diagram of the real gas turbine process that includes losses on each gas turbine component is shown in Figure 2.

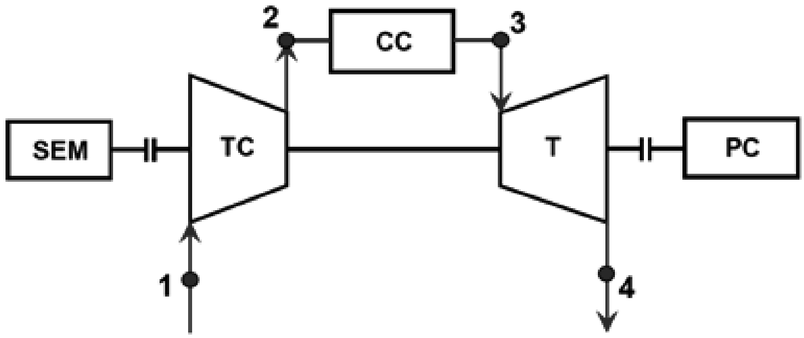

Figure 1 - Gas turbine main scheme (SEM = Starting Electro-Motor; TC = Turbo-Compressor; CC = Combustion Chambers; T = Turbine; PC = Power Consumer)

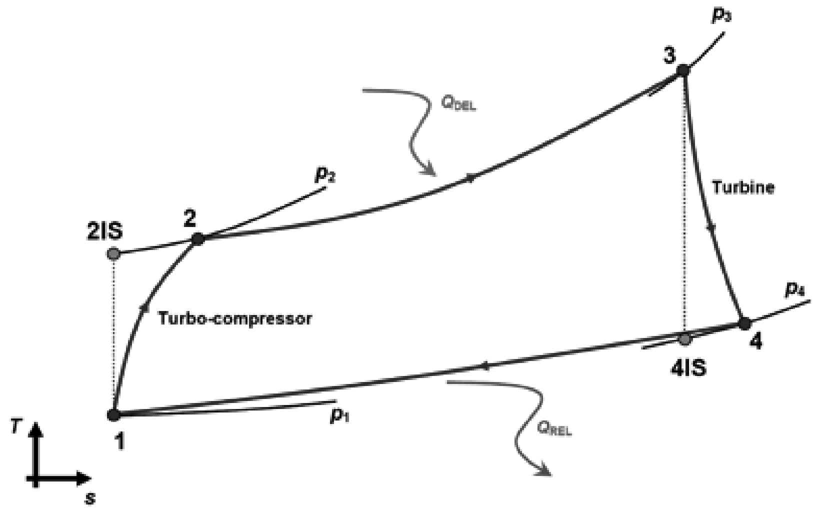

Figure 2 - Temperature-specific entropy (T-s) diagram of the gas turbine real process with included losses

3. Gas turbine analysis – main equations

The majority of equations for the gas turbine process analysis can be found in [28] and [29]. Each operating point of the gas turbine process, Figure 1, can be calculated the specific enthalpy of the operating medium (air or combustion gases) as:

$$h = c_p \cdot T \tag{1}$$

where c_p is the specific heat capacity of the operating medium at constant pressure and T is the current operating medium temperature. Specific heat capacity at constant pressure (c_p) is a function of the current operating medium temperature.

Regarding the air, the specific heat capacity at constant pressure is calculated according to [30] by using Eq. 2:

$$c_{p,air}(T) = 1.0484 - 0.0003837 \cdot T + \frac{9.45378}{10^7} \cdot T^2 - \frac{5.49031}{10^{10}} \cdot T^3 + \frac{7.92981}{10^{14}} \cdot T^4 \tag{2}$$

while for combustion gases (cg), the specific heat capacity at constant pressure is also calculated according to [30] by using Eq. 3:

$$c_{p,cg}(T) = 0.936087 + \frac{0.010749}{10^2} \cdot T + \frac{0.0172103}{10^5} \cdot T^2 - \frac{0.07247}{10^9} \cdot T^3 \tag{3}$$

In Eq. 2 and Eq. 3 temperature T must be inserted in (K) to obtain c_p in (kJ/kg·K).

By using Figure 1 and Figure 2, the gas turbine process operating parameters are as follows:

- Turbo-compressor real power:

$$P_{TC} = \dot{m}_{air} \cdot (h_2 - h_1) = \dot{m}_{air} \cdot (T_2 \cdot c_{p,2} - T_1 \cdot c_{p,1}) \tag{4}$$

Air temperature after the ideal (isentropic) compression is calculated using equation Eq. 5:

$$T_{2IS} = T_1 \cdot \left(\frac{p_2}{p_1} \right)^{\frac{\kappa_{air} - 1}{\kappa_{air}}} \tag{5}$$

where κ_{air} is according to [31] is equal to 1.4.

- Turbo-compressor isentropic power:

$$P_{TC,IS} = \dot{m}_{air} \cdot (h_{2IS} - h_1) = \dot{m}_{air} \cdot (T_{2IS} \cdot c_{p,2IS} - T_1 \cdot c_{p,1}) \tag{6}$$

- Turbo-compressor power losses:

$$P_{TC,PL} = P_{TC} - P_{TC,IS} = \dot{m}_{air} \cdot (h_2 - h_{2IS}) = \dot{m}_{air} \cdot (T_2 \cdot c_{p,2} - T_{2IS} \cdot c_{p,2IS}) \tag{7}$$

- Turbo-compressor efficiency:

$$\eta_{TC} = \frac{P_{TC,IS}}{P_{TC}} = \frac{h_{2IS} - h_1}{h_2 - h_1} = \frac{T_{2IS} \cdot c_{p,2IS} - T_1 \cdot c_{p,1}}{T_2 \cdot c_{p,2} - T_1 \cdot c_{p,1}} \tag{8}$$

- Turbine real cumulative power:

$$P_{\mathrm{T}} = \dot{m}_{\mathrm{cg}} \cdot (h_3 - h_4) = \dot{m}_{\mathrm{cg}} \cdot (T_3 \cdot c_{\mathrm{p,3}} - T_4 \cdot c_{\mathrm{p,4}}) \tag{9}$$

Temperature of combustion gases after the ideal (isentropic) expansion is calculated using equation Eq. 10:

$$T_{\mathrm{4IS}} = T_3 \cdot \left(\frac{p_4}{p_3}\right)^{\frac{\kappa_{\mathrm{cg}}-1}{\kappa_{\mathrm{cg}}}} \tag{10}$$

where κ_{cg} is equal to 1.3 according to [31] .

- Turbine isentropic cumulative power:

$$P_{\mathrm{T,IS}} = \dot{m}_{\mathrm{cg}} \cdot (h_3 - h_{\mathrm{4IS}}) = \dot{m}_{\mathrm{cg}} \cdot (T_3 \cdot c_{\mathrm{p,3}} - T_{\mathrm{4IS}} \cdot c_{\mathrm{p,4IS}}) \tag{11}$$

- Turbine power losses:

$$P_{\mathrm{T,PL}} = P_{\mathrm{T,IS}} - P_{\mathrm{T}} = \dot{m}_{\mathrm{cg}} \cdot (h_4 - h_{\mathrm{4IS}}) = \dot{m}_{\mathrm{cg}} \cdot (T_4 \cdot c_{\mathrm{p,4}} - T_{\mathrm{4IS}} \cdot c_{\mathrm{p,4IS}}) \tag{12}$$

- Turbine efficiency:

$$\eta_{\mathrm{T}} = \frac{P_{\mathrm{T}}}{P_{\mathrm{T,IS}}} = \frac{h_3 - h_4}{h_3 - h_{\mathrm{4,IS}}} = \frac{T_3 \cdot c_{\mathrm{p,3}} - T_4 \cdot c_{\mathrm{p,4}}}{T_3 \cdot c_{\mathrm{p,3}} - T_{\mathrm{4IS}} \cdot c_{\mathrm{p,4IS}}} \tag{13}$$

It should be noted that gas turbine power losses (Eq. 12) and efficiency (Eq. 13) are calculated identically as power losses and efficiency of a steam turbine [32, 33] or of each steam turbine cylinder (for multi-cylinder steam turbines) [34].

- Useful power (real):

$$P_{\mathrm{US}} = P_{\mathrm{T}} - P_{\mathrm{TC}} \tag{14}$$

- Useful power (isentropic):

$$P_{\mathrm{US,IS}} = P_{\mathrm{T,IS}} - P_{\mathrm{TC,IS}} \tag{15}$$

- Chemical energy delivered by fuel in the combustion chambers:

$$Q_{\mathrm{CHE}} = \dot{m}_{\mathrm{F}} \cdot LHV \tag{16}$$

where *LHV* is the lower heating value of the fuel used and $\dot{m}_{\mathrm{F}}$ is the combustion chambers fuel mass flow rate.

- The amount of heat transferred in combustion chambers:

$$Q_{\mathrm{DEL}} = \dot{m}_{\mathrm{cg}} \cdot (h_3 - h_2) = \dot{m}_{\mathrm{cg}} \cdot (T_3 \cdot c_{\mathrm{p},3} - T_2 \cdot c_{\mathrm{p},2}) \quad (17)$$

- The amount of the heat released from the process:

$$Q_{\mathrm{REL}} = \dot{m}_{\mathrm{cg}} \cdot (h_4 - h_1) = \dot{m}_{\mathrm{cg}} \cdot (T_4 \cdot c_{\mathrm{p},4} - T_1 \cdot c_{\mathrm{p},1}) \quad (18)$$

- Heat transfer losses in the combustion chambers:

$$Q_{\mathrm{HTL}} = Q_{\mathrm{CHE}} - Q_{\mathrm{DEL}} \quad (19)$$

- Combustion chambers efficiency:

$$\eta_{\mathrm{CC}} = \frac{Q_{\mathrm{DEL}}}{Q_{\mathrm{CHE}}} = \frac{\dot{m}_{\mathrm{cg}} \cdot (h_3 - h_2)}{\dot{m}_{\mathrm{F}} \cdot LHV} = \frac{\dot{m}_{\mathrm{cg}} \cdot (T_3 \cdot c_{\mathrm{p},3} - T_2 \cdot c_{\mathrm{p},2})}{\dot{m}_{\mathrm{F}} \cdot LHV} \quad (20)$$

- Gas turbine process overall efficiency:

$$\eta_{\mathrm{GT}} = \frac{P_{\mathrm{US}}}{Q_{\mathrm{DEL}}} = \frac{P_{\mathrm{T}} - P_{\mathrm{TC}}}{Q_{\mathrm{DEL}}} \quad (21)$$

- Specific fuel consumption (based on the useful power):

$$SFC = \frac{\dot{m}_{\mathrm{F}}}{P_{\mathrm{US}}} = \frac{\dot{m}_{\mathrm{F}}}{P_{\mathrm{T}} - P_{\mathrm{TC}}} \quad (22)$$

- Specific fuel consumption (based on the cumulative produced power):

$$SFC = \frac{\dot{m}_{\mathrm{F}}}{P_{\mathrm{T}}} \quad (23)$$

4. Operating parameters of the gas turbine process before and after a major maintenance

Operating parameters of the gas turbine process at each characteristic operating point, Figure 1 and Figure 2, before and after a major maintenance are found in [35]. Table 1 presents the gas turbine process operating parameters before a major maintenance and Table 2 presents the gas turbine process operating parameters after a major maintenance.

Table 1 - Operating parameters of the gas turbine before a major maintenance [35]

BEFORE MAJOR MAINTENANCE			
Operating point*	**Medium operating mass flow rate (kg/s)**	**Medium operating pressure (MPa)**	**Medium operating temperature (K)**
1	434.753	0.1033	288.15
2	434.753	1.6099	662.08
3	443.706	1.5536	1509.13
4	443.706	0.1071	819.99
Used fuel	Natural gas		
Fuel lower heating value (*LHV*)	50000 kJ/kg		
Fuel mass flow rate	8.953 kg/s		

* *According to Figure 1 and Figure 2*

Table 2 - Operating parameters of the gas turbine after a major maintenance [35]

AFTER MAJOR MAINTENANCE			
Operating point*	**Operating medium mass flow rate (kg/s)**	**Operating medium pressure (MPa)**	**Operating medium temperature (K)**
1	407.776	0.1026	295.70
2	407.776	1.5400	679.00
3	416.884	1.5400	1600.15
4	416.884	0.1070	898.18
Used fuel	Natural gas		
Fuel lower heating value (*LHV*)	50000 kJ/kg		
Fuel mass flow rate	9.108 kg/s		

* *According to Figure 1 and Figure 2*

5. Results of the gas turbine process analysis before and after a major maintenance

The developed or used power for each gas turbine component is shown in Figure 3. Turbo-compressor as a power consumer in the real process always uses more power for its operation compared to an ideal (isentropic) process. After a major maintenance, turbo-compressor used a lower power amount than before a major maintenance and this was mostly caused by a reduction in the air mass flow rate, Table 1 and Table 2.

Unlike a turbo-compressor, turbine is a power producer which in the real process always produced lower cumulative power compared to an ideal (isentropic) one. After a major maintenance, the real cumulative power produced by the turbine was lower than before a major maintenance, which was again mostly caused by a reduction in the combustion gas mass flow rate, Table 1 and Table 2.

Reduction in air and combustion gas mass flow rates after a major maintenance resulted in a decrease in real useful power produced by a gas turbine process (from 189.62 MW before a major maintenance to 184.02 MW after a major maintenance), Figure 3.

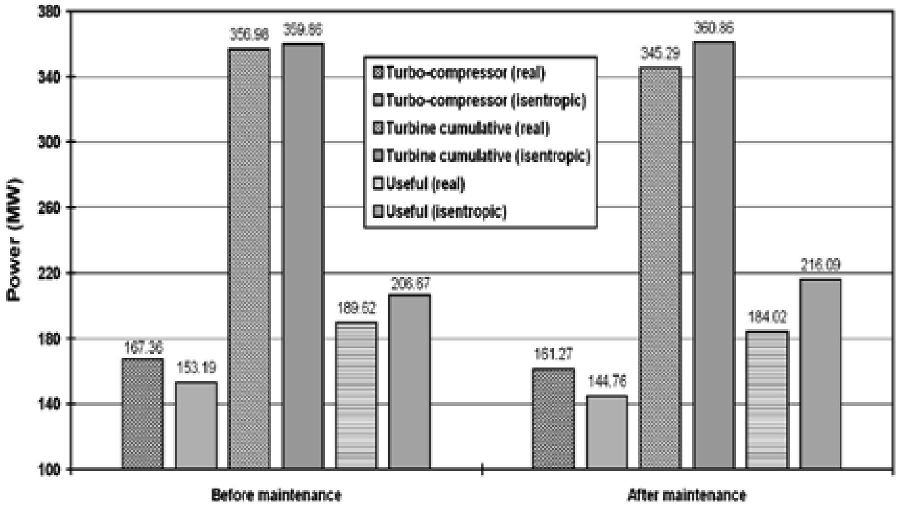

Figure 3 - Changes in the real and isentropic useful, turbo-compressor and turbine power before and after a gas turbine major maintenance

The increase in the fuel mass flow rate after a gas turbine major maintenance resulted in a higher chemical energy amount delivered by fuel in combustion chambers, Figure 4. After major gas turbine maintenance, a higher fuel mass flow rate also resulted in a higher heat amount transferred in combustion chambers, compared with the performance before a major maintenance. The turbine major maintenance also resulted in a higher heat amount released from the gas turbine process. The released heat amount can be used for additional heating purposes, therefore the gas turbine major maintenance offers a higher amount of heat that can be used in several heat consumers.

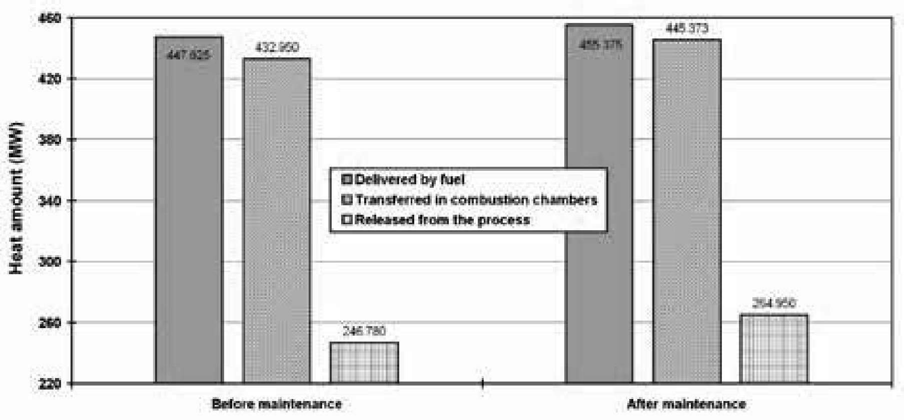

Figure 4 - Heat amounts (delivered by fuel, transferred in combustion chambers and released from the process) before and after a major maintenance

Compared with the gas turbine performance before major maintenance, the process of major maintenance resulted in a small increase in turbo-compressor power losses and in significant increase in turbine power losses, Figure 5. Increased power losses for turbo-compressor and turbine lead to the conclusion that the major maintenance process made the compression and expansion processes worse.

The major maintenance process had a positive influence on combustion chambers losses that decreased from 14.675 MW before a major maintenance to 10.002 MW after a major maintenance, Figure 5.

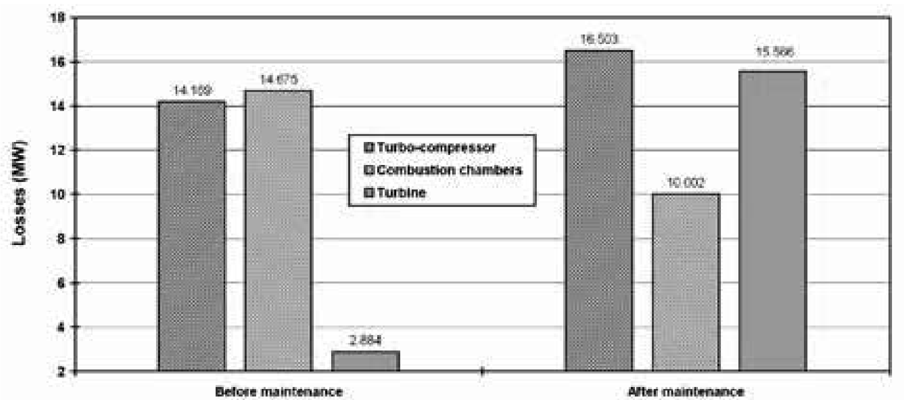

Figure 5 - Losses at gas turbine components before and after a major maintenance

Increase in power losses of turbo-compressor and turbine after a major maintenance compared with the process before a major maintenance leads to a decrease in the turbo-compressor and turbine efficiency (from 91.534% to 89.767% for turbo-compressor and from 99.199% to 95.686% for turbine), Figure 6. The major maintenance process increases combustion chambers efficiency from 96.722% before to 97.804% after a major maintenance.

The major maintenance process decreases the overall process efficiency from 43.796% to 41.319%. This fact is a result of the decrease in the useful gas turbine power produced along with a simultaneous increase in the heat amount transferred in combustion chambers.

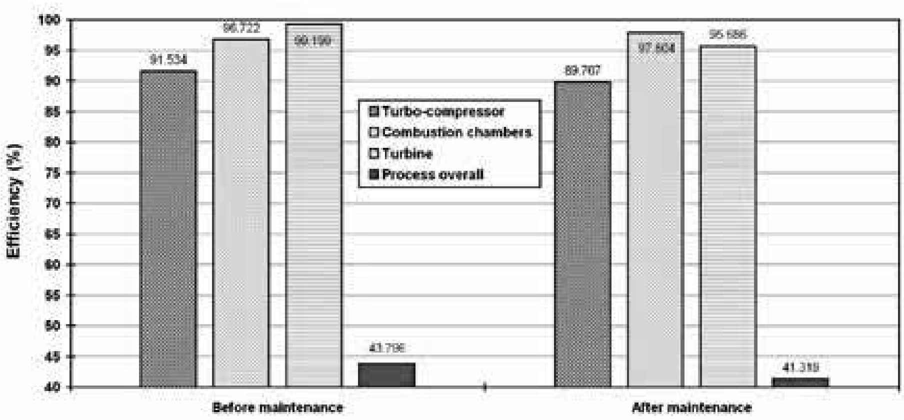

Figure 6 - Efficiencies of gas turbine parts and the overall process efficiency before and after a major maintenance

Specific fuel consumption for the gas turbine process can be defined using any of two different approaches – either in regards to the useful produced power or in regards to the cumulative developed power. The comparison of gas turbine processes before and after a major maintenance resulted in the conclusion that the increase in the fuel mass flow rate with a simultaneous decrease in the cumulative and useful produced power resulted in an increase in both specific fuel consumptions after a major maintenance, Figure 7. The specific fuel consumption in regards to the useful produced power is a much often used operating parameter for comparison with other gas turbine processes.

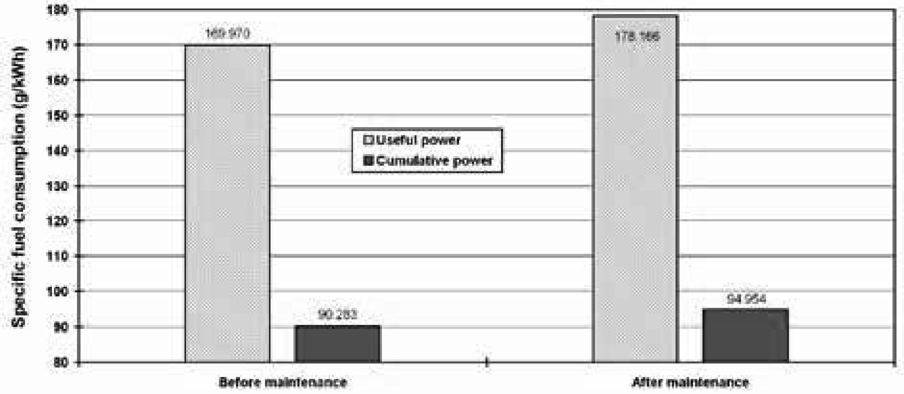

Figure 7 - Gas turbine specific fuel consumption based on the useful and cumulative developed power before and after a major maintenance

Further investigation of the gas turbine presented in this paper will be based on the research and possible optimization of its operating parameters and characteristics by using several machine learning methods such as convolutional and multi-layer perceptron (MLP) neural networks [36, 37], genetic algorithm (GA) [38, 39], particle swarm optimization (PSO) [40], and many others.

6. Conclusions

The paper presents an analysis of a gas turbine based on measured operating parameters before and after a major maintenance. The major maintenance process did not offer any expected results, because usually it would be expected that the major maintenance process reduces losses on each gas turbine component with a simultaneous increase in the efficiency.

The most important conclusions that can be derived from the presented analysis are:

After the turbine major maintenance, there occur lower air and combustion gas mass flow rates in the gas turbine process that cause a decrease in the turbo-compressor real used power and decrease in the real turbine cumulative developed power. A decrease in the turbine real cumulative developed power is higher than the decrease in the turbo-compressor real used power, so as a result, the turbine real useful produced power decreases after a major maintenance.

After the turbine major maintenance, the fuel mass flow rate delivered to combustion chambers increases compared with the process before a major maintenance, whereby the heat amount transferred in combustion chambers and the heat amount released from the process increase.

Turbo-compressor and turbine losses increase after a major maintenance, what means that the compression and expansion processes deviate from the ideal ones much more after than before a major maintenance. The result of that occurrence is also a decrease in the turbo-compressor and turbine efficiency after a major maintenance process.

The major maintenance process positively influences combustion chambers, because it causes a decrease in combustion chambers heat losses and increases their efficiency.

The overall gas turbine process efficiency decreases after a major maintenance due to the decrease in the turbine useful produced power and simultaneous increase in the heat amount transferred in combustion chambers.

The increase in the combustion chambers fuel mass flow rate and simultaneous decrease in the turbine cumulative or useful developed power after a major maintenance increases the gas turbine specific fuel consumption.

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