Thermodynamic Study of Improving Efficiency of a Gas Turbine Locomotive

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Abstract: Although railroad electrification has multiple benefits and is one of the global initiatives to promote transportation sustainability, 50% of the railroads are still off the electrical grid. Use of the gas turbine as a source of mobile electricity is one of the promising technologies, crucial for the transition to electrical traction. This paper is a part of the project of PSC KUZNETSOV on developing the gas turbine locomotive. Current issues include low performance and resulting high exhaust temperature. These issues are because of high hydraulic losses due to the limited roof area used for the air intake.

Aim of this work is to find optimal thermodynamic operation point which provides efficiency boost, lower exhaust temperature and requires least alterations to the design. This data will be the basis for the next stages of development, including optimization of the turbomachines and structural design for strength improvement. This study used the numerical simulation of the thermodynamic behavior of the gas turbine power plant. Firstly, the virtual model of the engine was developed using the CAE-system ASTRA and the parameters of the engine provided by the PSC KUZNETSOV. Secondly, model adequacy was assured using the experimental data on climatic characteristics of the gas turbine power plant. The third step was to investigate how would removing the first one, two or three stages of the low-pressure compressor alter its characteristics, and the performance of the engine. Altered low-pressure compressor (LPC) required adjustments of the operating points of all turbines, so this issue was addressed at the next step. Finally, the thermodynamic characteristics of the power plant were calculated using the optimized compressor (three- and four-stage variants) and turbine. Optimization aimed at keeping target performance indicators while providing lower air flow rate and decreased exhaust temperature. It also included restrictions on the rotational speeds, geometry and other parameters to keep the stress-strain state of the engine elements close to the baseline.

The results of this research show two promising solutions for the 6MW and 8.3MW variants of the power plant having air flow rates 27 and 17 percent lower than the baseline, respectively.

The results of this study would be used to design the altered engine components: optimize blade geometry and strength of the critical elements of the engine.

1 INTRODUCTION

Transportation is one of the major sources of global warming emissions and air pollution that harms public health. Almost one third of the greenhouse emissions can be attributed to the transportation sector. Reducing transportation-related GHG emissions, and understanding the impacts of climate change on transportation systems are concerns of many decision makers. Electrifying the transportation sector is a proactive strategy to promote sustainability: it enables significant economic and environmental benefits and new opportunities for consumer engagement (Jones 2018, Smith 2012, Taptich 2016).

Railroad electrification increases reliability and traffic capacity of railroad, reduces operating costs and ecological impact, makes railway transport more comfortable. This is why a lot of effort is made towards the electrification (Bartosh, 1972; Lee, 1975; Duffy, 1998; Goldshtein, 2019; Rowe, 2015; Marin, 2010; Desjouis, 2015).

The percentage of electrified railways in Switzerland is almost 100%, in Sweden this number is above 60% (which is more than 7500 km), in Italy – 50% (8000 km). Despite multiple benefits of railroad electrification and numerous initiatives worldwide to promote transportation sustainability

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(Walmsley, 2015; Goldshtein, 2019; D'Ovidio, 2017; Hao, 2017; Lu, 2016; Puschmann, 2016), more than half of the railroads are still out of the electrical grid (Ryzhkova, 2013). Electrification of the rail systems faces various challenges (Stamatopoulos, 2016; Azadeh, 2018; Allen, 2018; Krastev, 2016; Mousavi, 2015) and use of the gas turbine as a source of mobile electricity is one of the promising technologies, crucial for the transition to electrical traction.

Soviet Union started to develop gas turbine locomotives in 1954. Several models were developed and the prototypes were designed, manufactured and tested. These projects were closed in 1970-s, as they were unable to compete with diesel and electrical locomotives.

This research is a part of the joint project of Samara National Research University and JSC Kuznetsov on development of the gas turbine locomotive within the framework of Russian Federation Government decree №218 of 09.04.2010 “On the measures of governmental support of the cooperation between russian institutions of higher education, state scientific institutions and organizations executing complex projects of development of high technology manufacturing” and the Subprogramme “Institutional development of research and development sector” of the State Programme “Development of science and technologies” for 2013-2020.

Initial version of the gas turbine locomotive faced several issues including low efficiency and resulting high exhaust temperature. These issues are because of high hydraulic losses due to the limited roof area used for the air intake. Multi-discipline team of researchers and engineers is currently working to address these drawbacks, and this paper describes the first stade of the development - thermodynamic optimization of the power plant.

This study included the following stages: adjustment and verification of the mathematical models of gas turbine power plant using the experimental data (Kuz'michev, 2014); investigation of the performance of the gas turbine power plant with decreased number of stages of low pressure compressor; development of thermodynamic measures for improving the efficiency and operability of a gas turbine locomotive. This work aims at finding the optimal thermodynamic operation point which provides efficiency boost, lower exhaust temperature and requires least alterations to the design. This data will be the basis for the next stages of development, including optimization of the turbomachines and structural design for strength improvement.

2 MATERIALS AND METHODS

2.1 Validation of the Gas Turbine Power Plant Simulator

First of all, the verification of the mathematical models used to develop the in-house software code ASTRA is required to confirm that the numerical simulation results agree with the experimental data (Baturin, 2017; Rybakov, 2016). This was done by calculating the climatic characteristics of the initial gas turbine power plant and comparing the results with the experimental data provided by the JSC Kuznetsov. Figure 1 shows the results of this comparison at the sea level at 6 MW.

It is evident that the results of simulation are identical to the experimental data and thus the mathematical models used to develop the software code show adequate accuracy and may be used for further investigations.

2.2 Influence of Number of LPC Stages on the Throttle Performance

As the roof area of locomotive is limited, the efficient air flow rate is restricted too. High hydraulic losses at the inlet air filter occur because of high airflow velocity. Unfortunately, this air flow rate is less than the required air flow rate of the gas turbine engine for the operational conditions. To address this issue we investigated the behavior and parameters of engine with 1-2 low pressure compressor (LPC) stages removed.

First, operation of the gas turbine power plant with removed stage(s) of the LPC was investigated. According to the equations of joint operation of engine components, the operating points on the performance map of low pressure compressor will hold the same position (with minor assumptions). At the same time, the performance map itself will alter.

The experimental parameters of each stage provided by the JSC Kuznetsov were used to obtain the performance maps of the 3- and 4-stage LPC. The non-dimensional performance map of the 4-stage LPC (one stage removed) will remain unaltered. To dimensionalize this performance map, we consider that the efficiency ($\eta^*_{\mathrm{st\ i}}$) and pressure ($\pi^*_{\mathrm{st\ i}}$) ratios of each remaining stage remain unchanged. The overall pressure ratio (π^*_{LPC}) and efficiency (η^*_{LPC}) of the remaining stages of low pressure compressor may be calculated using the parameters of each stage.

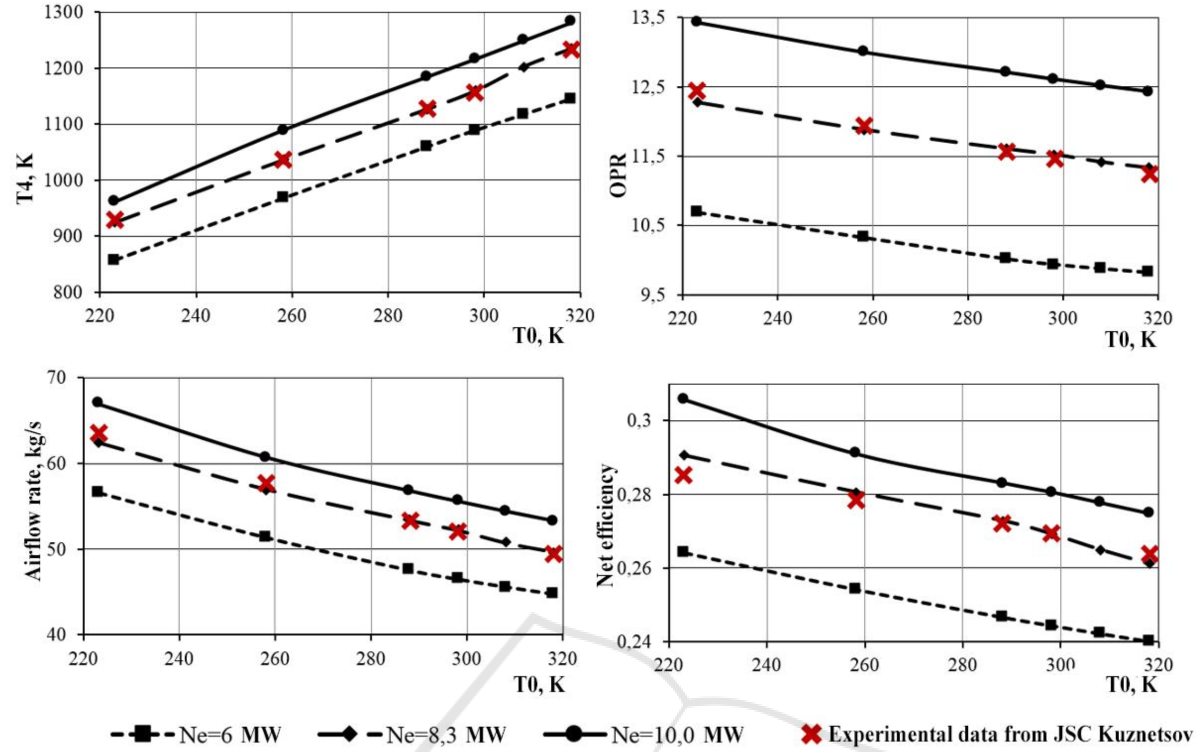

Figure 1: Comparison of the numerical simulation of the climatic characteristics and experimental data.

The temperature at the second stage inlet decreases with the first stage removed, thus the altered value of reduced rotational speed of the compressor ($n_{\text{LPC.red.alt}}$) in the design point may be calculated as the rotational speed reduced by the parameters at the inlet of the second stage. This value is used to dimensionalize the altered performance map of the low pressure compressor and perform the design-point calculations of the power plant.

The performance map of 3-stage low pressure compressor (two stages removed) is calculated in the same manner.

Figure 2 shows the performance maps of the 5-, 4- and 3-stage low pressure compressors with operational points plotted.

Throttle characteristics of the gas turbine power plant at the sea level and standard atmospheric conditions were calculated for each variant of low pressure compressor. The results show that removing the low pressure compressor stages without readjustment of the joint operation of the engine components (without changing the flow capacities of turbines) does not provide required improvements.

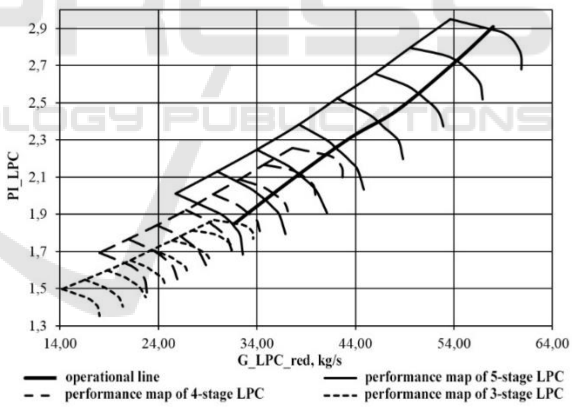

Figure 2: Relative position of the operational line at the performance maps of 5-, 4- and 3-stage low pressure compressors.

2.3 Adjusting Operation Points of the Low-pressure and Free Turbines

The parameters of gas turbine power plant at the sea level, standard atmospheric conditions, three levels of net power output (10 MW, 8.3 MW and 6 MW), and 3-, 4- and 5-stage variants of LPC were calculated. For these calculations the flow capacity of low pressure turbine varied in the range of 0…-15% and the flow capacity free turbine varied in the range of

0..-30%.The results for the 5-stage low pressure compressor are shown in Figure 3, for the 4-stage LPC – in Figure 4, and for the 3-stage LPC – in Figure 5. It must be noted that the power level of 10 MW was unattainable for the 3-stage LPC variant due to the turbine inlet temperature constraints.

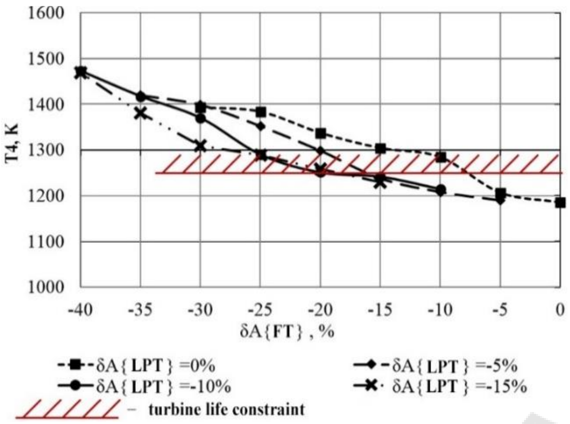

Figure 3: Impact of readjustment of the flow capacities of the low pressure turbine and free turbine for the 5-stage variant of low pressure compressor at 10 MW.

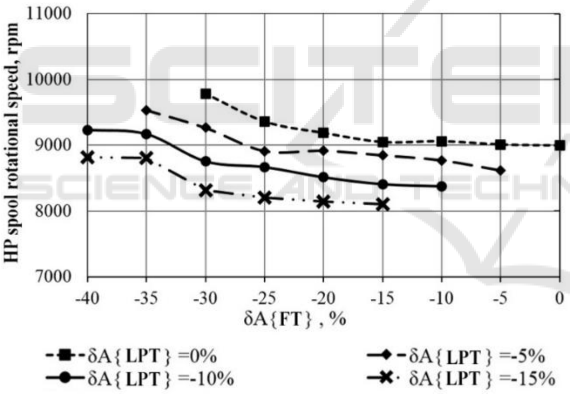

Figure 4: Impact of readjustment of the flow capacities of the low pressure turbine and free turbine for the 4-stage variant of low pressure compressor at 8.3 MW.

The results show that the most efficient variants of flow capacity readjustments are:

- 5-stage LPC power-plant: *δA(LPT)* = – 5% and *δA(FT)* = – 10%;
- 4-stage LPC power-plant: *δA(LPT)* = – 10% and *δA(FT)* = – 20%;
- 3-stage LPC power-plant: *δA(LPT)* = – 15% and *δA(FT)* = – 30%.

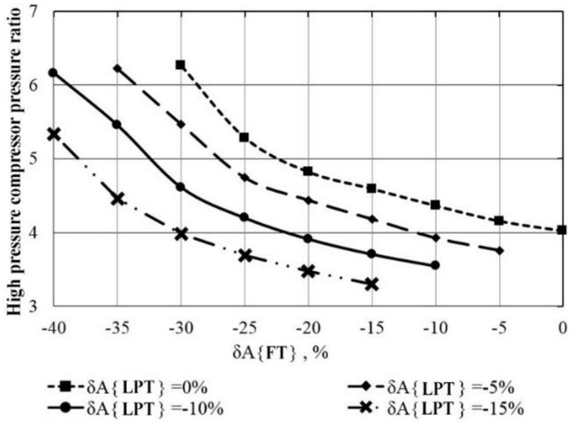

Figure 5: Impact of readjustment of the flow capacities of the low pressure turbine and free turbine for the 3-stage variant of low pressure compressor at 6 MW.

2.4 Influence of the Turbines' Operation Points Adjustment on the Throttle Characteristics

Throttle characteristics of the power-plant were calculated for the flow capacity readjustment variants described in the previous section. The results are compared to the initial throttle characteristics in Figure 6.

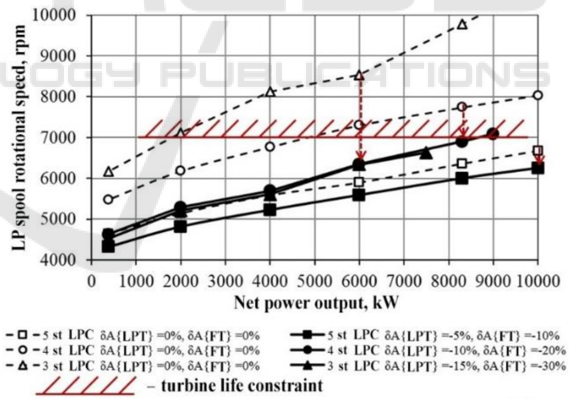

Figure 6: LP spool rotational speed variation along the throttling characteristic for the 3-, 4- and 5-stage LPC variants with initial and readjusted flow capacities at sea level.

3 CONCLUSIONS

This study has the following principal results.

- Experimental characteristics of the gas turbine power plant match the ones of the virtual prototype, showing adequacy of the simulation and mathematical models behind the CAE system ASTRA.

- Reducing the number of compressor stages proved to be an effective way of altering the operation point of the gas turbine in case a substantial change is necessary. Distortion of the performance map of the compressor changes the conditions of the joint operation of the corresponding turbine, so its operating point needs to be adjusted. Joint operation of the compressor and turbine is adjusted by changing the area of characteristic cross-sections.
- Parameters of the upgraded power plant were calculated for the 6 MW (3-stage low-pressure compressor) and 8.3 MW (4-stage LPC) variants, with the corresponding air flow rates 27 and 17 percent below the baseline engine, respectively.
- Restrictions on the rotational speeds and air-gas channel geometry were applied during the optimization to preserve the stress-strain state of the critical elements of the engine and keep most of its parts unaltered. Subsequent strength analyses will provide more specific data on this matter.
- Results of the thermodynamic optimization will be used as the initial input for the in-detail simulation (Filinov, 2018), optimization of turbomachines (Matveev, 2018; Marchukov, 2017; Popov, 2017,) and other engine's elements (Falaleev, 2017; Zubrilin, 2017), adjustments of the engine design and developing the manufacturing process of the engine parts (Kokareva, 2018).
- Results of the engine development project would be used to develop the method of combined use of the mathematical models suitable for the amount of available information at each design stage.

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