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Numerical and experimental investigation of the main parameters of a small gas turbine engine

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Abstract. A numerical and experimental study of the main parameters of a small gas turbine engine is conducted in this paper. An experimental bench was developed for determining both the integral parameters (thrust and fuel consumption) of the gas turbine engine and the local parameters (temperatures and pressures) of its gas-air path. Besides, full-scale gas-turbine engine tests Jetcat P200-RX were done with and without gas-air path equipment. The existing small gas turbine engine sample was digitized and the gas flow in its gas-air path was simulated using the CFD method in a three-dimensional setting in ANSYS CFX. A comparative analysis of the results of full-scale tests and CFD modeling was carried out.

1. Introduction

The interest in the development of unmanned aerial vehicles (UAV) has grown significantly over the past decade. This is caused by performing various military and civilian missions using UAV, for example, photo and video reconnaissance, reconnaissance of chemical and radiation conditions, as well as using false targets to complicate the air situation.

The key point in UAV development is small gas turbine engines (SGTE). SGTE currently has a wide scope. SGTE are used as auxiliary or power plants of light aircraft, cruise missiles, helicopters, as well as power plants of land and water vehicles. In addition, they are used as drives of electric generators, and as sources of compressed air. Nowadays, finite-element supercomputer modeling tools for the basic physical processes that occur in the SGTE (hydro and gas dynamics, heat transfer, combustion, etc.) are actively used. This can significantly accelerate and reduce the cost of the design process for new SGTEs. At the same time, there is still a problem of insufficient verification of design models at both the engine level and its components.

The analysis and selection of the object of study were conducted for SGTE research. The main engine selection parameters were:

– market availability of finished small gas turbine engines in Russia;

– relativity low cost;

– dimensions allowing easy transport and equipment;

– universal scope;

– availability of scientific and technical research materials, which develops a methodology for designing and calculating a small gas turbine engine.

Based on the above parameters, a small single-shaft Jetcat P200-RX turbojet engine was adopted as an analog by the Customer. The appearance of this engine is shown in Figure 1.

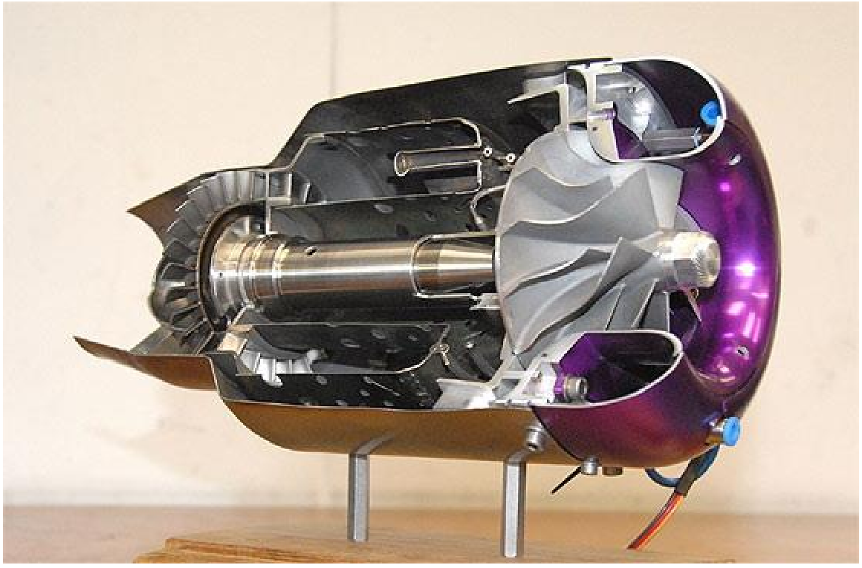

Figure 1. The appearance of the small single-shaft turbojet Jetcat P200-RX.

The goal of this work is to determine the main parameters of the Jetcat P200-RX SGTE and its components using experimental research, as well as mathematical modeling methods.

On the one hand, there is a sufficiently large data on this engine, but on the other hand, the incomplete set of experimental data.

A large number of direct measurements of the thermal state of the stator parts of this engine is considered in the dissertation [1]. However, the parameters of the gas-air path are not fully measured, and those that are measured are given in dimensionless relative values, which makes them inaccessible for analysis.

Reverse engineering of this engine was performed, and the aerodynamic characteristics of its centrifugal compressor were studied in detail in [2] and [3] works. At the same time, there are no experimental and numerical data on the hot part in the engine. Similar data on experimental studies of the compressor parameters of this engine are given in [4] and [5].

The literature analysis shows that the experimentally measured characteristics of the gas flow for the engine under consideration are still insufficient in an open press, as well as insufficient data on a comprehensive comparison of the measured and obtained by CFD modeling of the main and local parameters of the engine. This makes the work relevant.

The main specifications of the Jetcat P200-RX engine, as declared by the manufacturer [6], are shown in Table 1.

Table 1. Specifications of the Jetcat P200-RX engine.

Brand	JetCat
Model	P200-RX
Idle speed, rpm	33000
Maximum, rpm	112000
Thrust at idle, N	9
Thrust maxRpm, N	230
Exhaust gas temperature, ^{o}C	750
Pressure ratio	3.7
Mass flow, kg / s	0.45
Exhaust gas velocity (km/h)	1840
Power, kW	58.8
Consumption Full load (ml/min)	730
Consumption idle (ml/min)	129

Repair interval, h	25
Weight, g	2560
Dimensions of the diameter (mm)	132
Length (with starter), mm	355

2. Description of the experimental setup

x`On the basis of the "Turbine" department of St. Petersburg Polytechnic University, an experimental bench has been made for a full-scale engine test, which is shown in Figure 2.

The bench consists of the main blocks: the research object, the support frame, the flow measurement system, the fuel supply system, the JetCat P200-RX gas turbine engine, the fuel combustion products exhaust pipe, the plant control system and the experimental data collection.

The object of the study is installed in the block supports and is attached with clamps using M8 bolts. Asbestos tapes provide thermal insulation of the support system from the engine housing. Both supports are attached to the base with four M8 bolts.

The support block allows the engine to move along its axis on radial ball bearings along two guides, fastened with M8 bolts to the foundation plate. Bearing blocks are installed in pairs in two housings attached to the base with four M8 bolts.

The fuel system provides the engine with the necessary fuel consumption and measuring its consumption. Fuel is supplied by a gear pump TN under pressure through a filter. The system pressure is set and maintained automatically by a regulating solenoid valve installed on the bypass line of the fuel system.

The control system for the installation and the collection of experimental data consists of a remote control panel, a personal computer, a jet engine thrust measurement system (JTMS).

The JetCat P200-RX engine was equipped with appropriate thermal and pneumatic combs to measure temperatures and pressures that characterize the working process in the flow part (Figures 3-5).

1 – support frame; 2 – air supply pipe; 3 – fuel supply systems; 4 – protective casing; 5 – investigated object; 6 – exhaust pipe for fuel combustion products; 7 – pressure measuring unit; 8 – temperature measuring unit

Figure 2. The experimental bench.

IOP Conf. Series: Materials Science and Engineering **986** (2020) 012052 doi:10.1088/1757-899X/986/1/012052

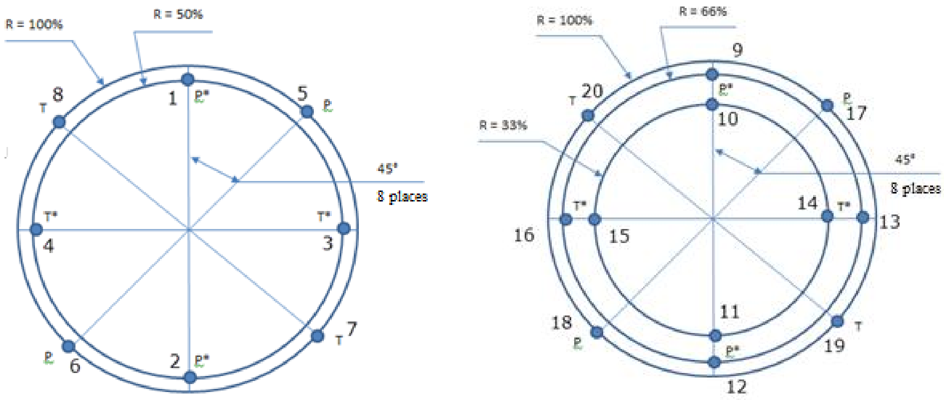

Figure 3. Section A (left, behind the compressor) and B (right, behind the compressor). View from the nozzle side.

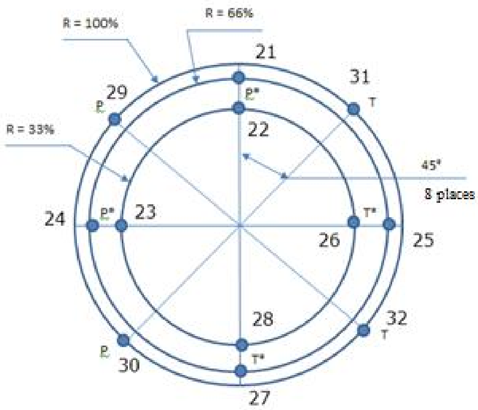

Figure 4. Section B (behind the turbine). View from the nozzle side.

Figure 5. The general view of the equipped SGTE.

IOP Conf. Series: Materials Science and Engineering **986** (2020) 012052 doi:10.1088/1757-899X/986/1/012052

The remote control panel (Figure 6) is intended for monitoring, registering, displaying parameters and automatically regulating the bench. Circuit breaker, fuses, terminal block for connecting temperature and pressure sensors and emergency sirens are installed in the panel.

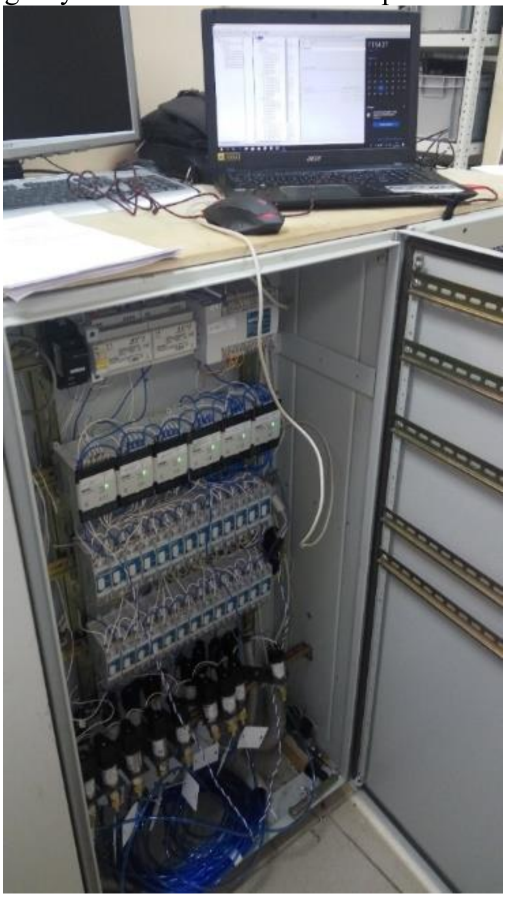

Figure 6. Remote control panel connected to a personal computer.

The design of the experimental setup allows the engine to move on the support frame along the axis of the engine (Figure 7).

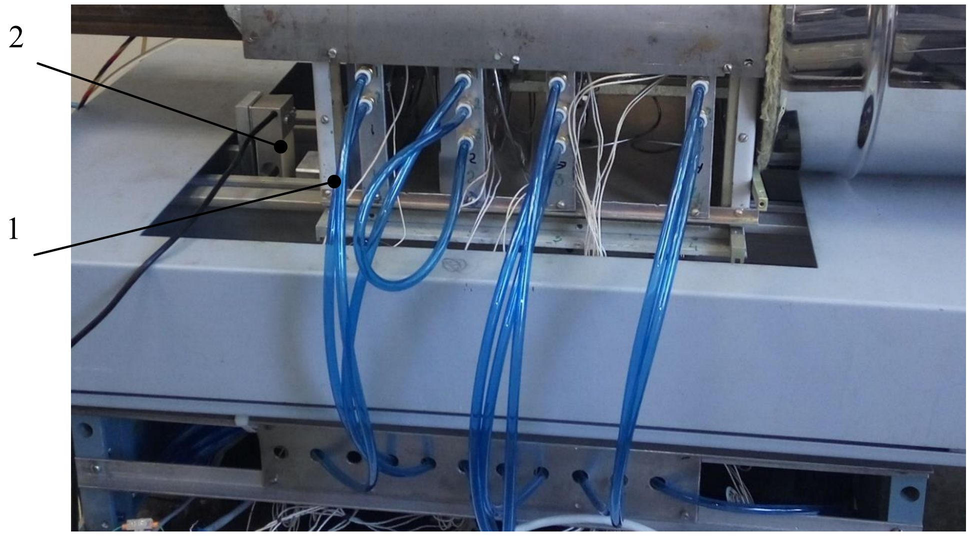

Figure 7. Jet engine thrust measurement system.
1 – support frame; 2 – force sensor frequency

A frequency force sensor is used to measure the amount of jet thrust. Calibration of JTMS was carried out using a traction calibration system by applying a known axial load and determining the frequency of oscillations of the force sensor. Five measurements were done with increasing load in the entire range of changes in traction force and five measurements with decreasing load. After the experiment, the calibration was repeated.

Characteristics of bench measuring devices are given in Table 2.

Table 2. Characteristics of measuring devices used at the experimental bench.

Equipment	Main characteristics
Thermometer (measuring the ambient temperature)	Measurement limit: +283…+323 K The limits of permissible error: 0.5 K
Barometer (environmental pressure measurement)	Measurement limit: 98655… 103990 Pa The limits of permissible error: no more than 100 Pa
Manometer (fuel pressure measurement)	Measurement limit: 1 … 10 atm The limits of permissible error: 3 %
Thermometer (fuel temperature measured at the outlet of the fuel system)	Measurement limit: +283…+373 K The limits of permissible error: 0.5
Load cell with MVA8 analog input module to load cell	Measurement limit: 0…30 kg The limits of permissible error ±1%
Temperature measuring unit (in sections) TRM38+ MVA8	limit of the basic reduced error (BRE) up to 0.5% temperature ranges +278…+1373 K nature of the medium being measured: air, fuel combustion products
Pressure measuring unit (in sections) AIR20	limit of the basic reduced error (BRE) up to 0,5 % static pressure limits: 10…400000 Pa temperature ranges +283…1373 K nature of the medium being measured: air, fuel combustion products

Engine tests were performed in 2 stages:

1. First, the engine was tested without equipment, its main parameters were measured;
2. Then the engine was equipped and the tests were repeated.

At the stage of preliminary preparation of the experiment, a fuel mixture in the ratio of 5% oil and 95% kerosene was prepared in the fuel tank. A visual inspection of the cleanliness of the fuel supply line was performed, as well as checking the charge level of the battery of the gas turbine engine control unit.

The main unit with the engine was placed in the protective box; visual observations were conducted through the armored glass of the protective box. To ensure safety, carbon dioxide fire extinguishers were located near the front door of the box and at the operator's position.

Then, the engine was started and waited for when the automatic start-up mode of the gas turbine engine is stabilized at low gas, and engine control would be transferred from the electronic unit to the engine control lever.

After starting and switching the gas turbine engine to idle gas mode (corresponding to an engine rotor speed of approximately 33,000 rpm), measurements were made in the following sequence:

- the frequency mode of rotor rotation using the engine control lever was not regulated and the engine was heated for at least 1 minute to stabilize the parameters in this mode;
- engine performance was measured for 30 seconds.

Measurements of modes in the range from 60,000 to 105,000 rpm were performed in a similar sequence.

3. The mathematical model of the engine

Numerical simulation of the aerodynamic parameters of the engine on the SGTE virtual test bench by the resources of the Polytechnic supercomputer center was performed using the CML-Bench digital platform and ANSYS CFX 2019R3 software.

The numerical model of the engine was based on geometric models obtained by detailed three-dimensional scanning of the real engine. The numerical models of the turbine flow section and the SGTE nozzle were scaled taking into consideration the engine heating process based on the assessment of its thermal state [1]. Figure 8 shows the constructed computational domain; the entire engine was simulated.

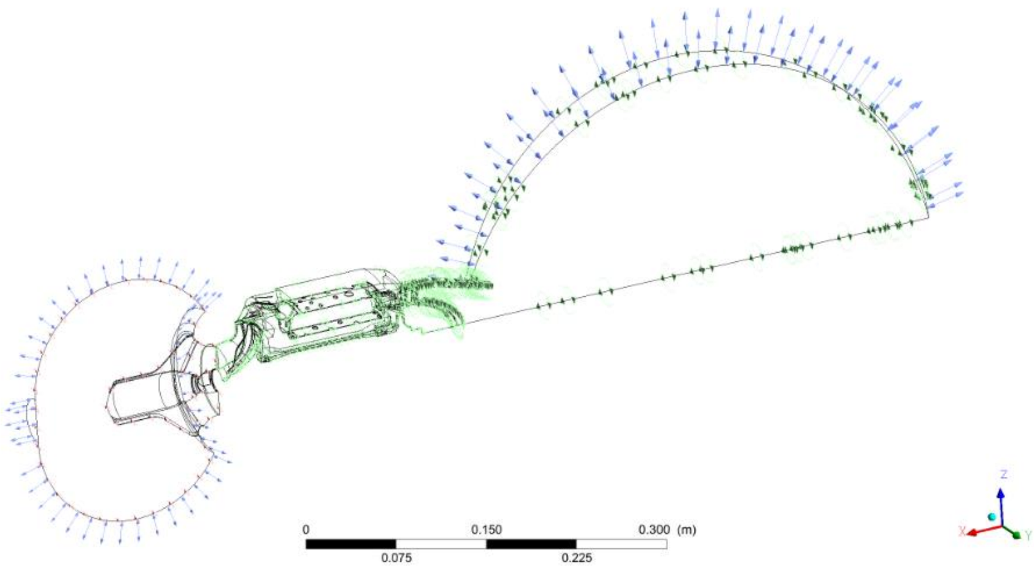

Figure 8. The estimated domain of SGTE.

The estimated SGTE domain modeled with the following features:

- the sector of the SGTE input device was modeled in 180 ° setting under the condition of symmetry;
- two compressor blades (blade and splitter), instead of 12 ones were modeled under a periodicity condition;
- one compressor diffuser blade, instead of 17 ones was modeled under a periodicity condition;
- two straightening compressor blades, instead of 34 ones were modeled under a periodicity condition;
- the combustor sector modeled directed 30 ° under a periodicity condition;
- one nozzle blade of the turbine, instead of 22 ones was simulated under a periodicity condition;
- one turbine blade, instead of 29 ones was simulated under a periodicity condition;
- the sector of the nozzle chamber was modeled at 12.414 ° under the condition of periodicity;
- the radial clearance on the compressor working blades was taken equal to 0.2 mm, turbines - 0.45 mm.

The SGTE grid model has a dimension of about 7.5 million nodes and 22.5 million elements. The type of grid model is mixed; the model consists of tetrahedral elements in the main volume and prismatic elements of the wall zone with a triangular base. The wall layer is divided into 10 layers. The minimum size of the final element is 0.1 mm; the maximum one is 1 mm.

According to [7], the BSL turbulence model with a turbulent Prandtl number equal to 0.2 was chosen as the turbulence model according to [8]. The equation for total energy includes accounting for the work of friction forces.

Kerosene was specified as a dispersed liquid phase to simulate combustion processes and a particle-droplet transfer model was used to describe the motion path, based on the equation of motion of Lagrange particles taking into account the influence of the carrier gas mixture flow (flow resistance force, pressure gradient force). The possibility of crushing droplets, as a result of which the droplets break up into smaller particles under certain conditions, was taken into account in the model.

The phase transition of particles from the liquid state to the gas state was determined using a liquid evaporation model, which uses different heat and mass transfer ratios depending on the boiling point. The boiling point was determined using the Antoine equation.

IOP Conf. Series: Materials Science and Engineering **986** (2020) 012052 doi:10.1088/1757-899X/986/1/012052

The theory of combustion of a pre-mixed mixture (diffusion combustion) was used to simulate a chemical reaction in which fuel and oxidizer enter the reaction zone separately, in contrast to pre-mixed systems in which the reactants are mixed at the molecular level before combustion. To describe diffusion combustion, such an approach was used in which the instantaneous thermochemical state of the liquid (concentration of the components of the substance, temperature, and density) is unambiguously associated with a passive scalar quantity - a mixing variable. This approach solves only one transport equation for the mixing variable regardless of the number of chemical components.

The interaction of the chemical kinetics of the diffusion flame with the turbulent flow field was described using the model of micro laminar flame. There, the turbulent flame is considered as a combination of thin, one-dimensional, laminar flame structures embedded in the field of the turbulent flow. The statistical method of the probability density function was used to couple the chemical kinetics of the laminar flame with the changing field of the turbulent flow.

A simplified spectral equation of radiation transfer for isotropic radiation intensity without scattering was used to simulate radiation.

To simulate the combustion process, a chemical kinetic combustion scheme was used for aviation kerosene (with a 100% content of n-C10H22) with the complete formation of nitrogen oxides. The following stoichiometric ratio was used: n-C10H22+14O2→(combustion product) for the mixing variable. This kinetic combustion scheme contains 1127 chemical reactions for 127 components. Kerosene properties were taken according to the reference data [9].

The real air model is used as the working medium in the compressor, i.e. the values of heat capacity, thermal conductivity and viscosity for calculations are selected for air [10,11].

The mixture of air and kerosene combustion products at the outlet of the combustion chamber was selected as the working medium.

Between the domains, the Stage (MixingPlane) interfaces were used while keeping the velocity vector.

Unbalances of the results of the equations being solved, as well as the values of the main parameters of the engine components, were monitored to assess the stability and convergence of the calculation. The convergence of the calculation was considered achieved when the parameters were established, and the fluctuations in the unbalance took on an unchanged character (with the amplitude of the oscillations reaching 0.1%).

The time step was taken equal to 10-4 s, the calculation scheme is High Resolution.

The boundary conditions were the atmospheric parameters (pressure and temperature) in the box, the rotor speed of the turbocompressor, and the fuel consumption measured during the SGTE test.

4. The results of comparing the simulation and experimental data

For getting a general idea of the mathematical model of the engine, Figure 9 shows the calculated field of the total gas temperature in the middle section of the engine at the maximum thrust mode.

IOP Conf. Series: Materials Science and Engineering **986** (2020) 012052 doi:10.1088/1757-899X/986/1/012052

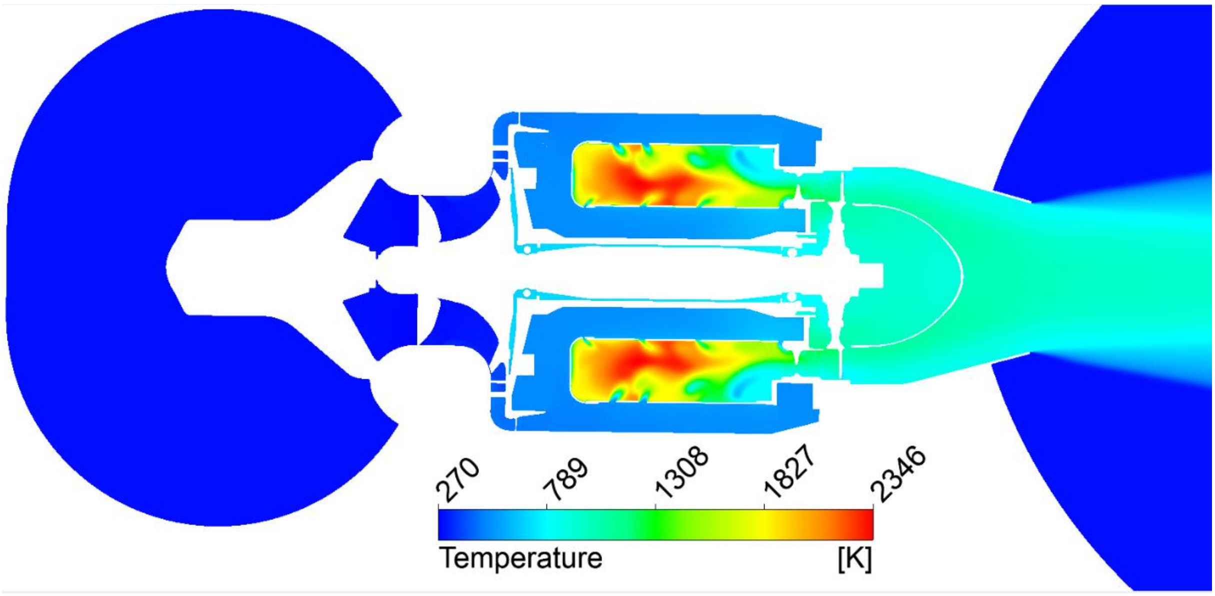

Figure 9. Field of full gas temperature in the middle section of the gas turbine engine at the maximum thrust mode.

Figures 10-16 show the main results of comparing mathematical modeling data with experimental data. The results of mathematical modeling are designated as VTB, i.e. virtual test bench.

All figures show the extrapolation of graphs up to 112,000 rpm (maximum). Extrapolation was performed by constructing a trend line (polynomial of the 3rd degree) and is shown on the graphs as dashed lines.

Figure 10 compares the measured and simulated jet thrust of the engine. The simulation results are in agreement with the test results of the unequipped SGTE in the range of rotor rotation frequencies from 60 to 105 thousand rpm. The equipped SGTE shows 10 ... 12% less thrust than the unequipped one, which indicates the negative impact of the preparation of the compressor and turbine on the integral parameters of the engine.

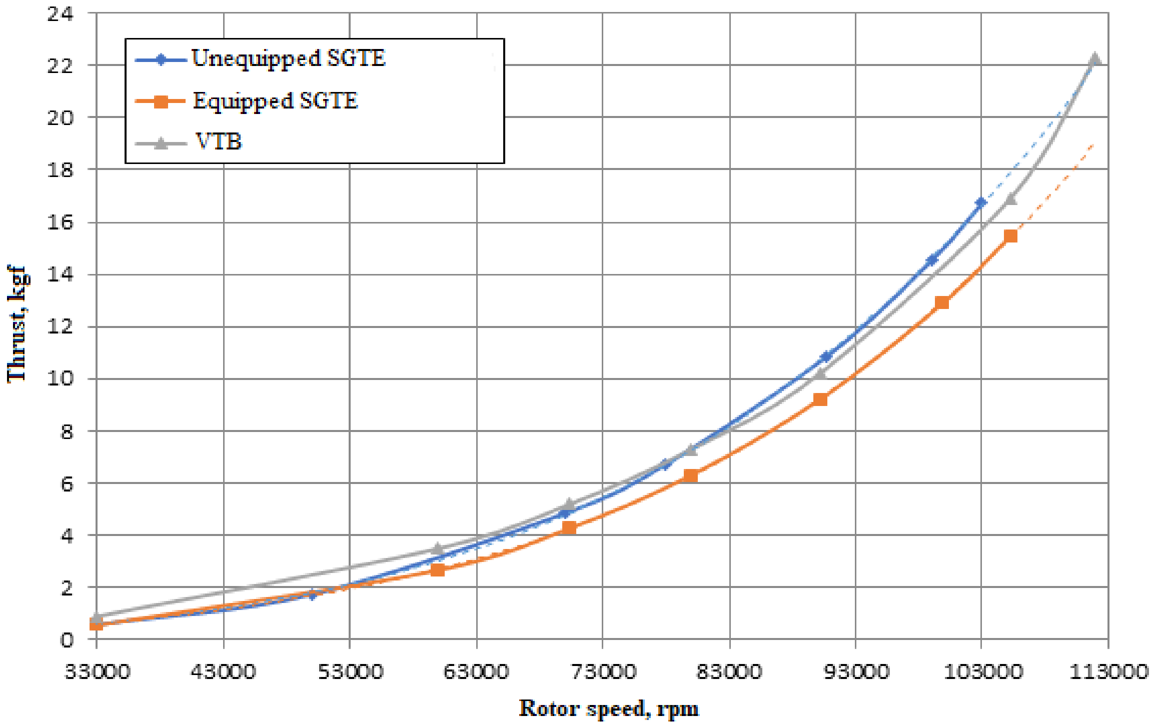

Figure 10. Dependence of engine thrust on rotor speed.

Figure 11 presents a comparison of the fuel consumption of the equipped and unequipped engines. They differ slightly in fuel consumption, the unequipped engine has a fuel consumption of 3% more than the equipped one. The fuel consumption of the equipped engine was used as a boundary condition for mathematical modeling, except the point 112000 rpm, where the fuel consumption declared by the manufacturer was used.

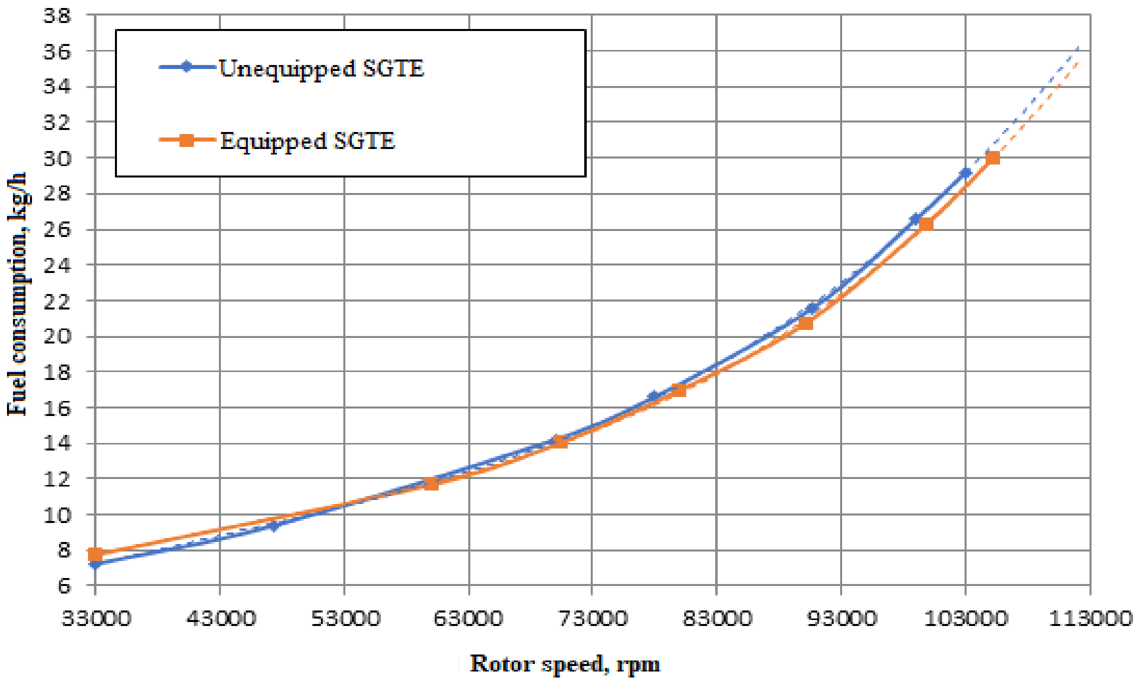

Figure 11. Dependence of fuel consumption on rotor speed.

Figure 12 presents a comparison of the measured and simulated degree of pressure increase in the compressor. The estimated P*k is higher than the measured one by about 8%, which can be caused by the following reasons:

The modeling error of the compressor;

Blockage of the compressor flow section by equipment;

Non-measurement of the total pressure of the sensors caused by a non-zero angle of attack of the flow on them.

Given that the height of the channel at the outlet of the compressor straightening device is extremely small (about 5 mm), and its unevenness can be significant. This indicates more about the difficulties of measuring the total pressure field (measured using only two sensors) in small flow parts of turbomachines, than about modeling errors. Additionally, this conclusion can be confirmed by the measured total pressure behind the compressor practically do not differ from the measured total pressure in front of the combustion chamber (the difference is less than 2%, while the total pressure loss on the combustion chamber in such a design should be about 5 ... 7%). This also indicates an underestimation of the measured total pressure behind the compressor.

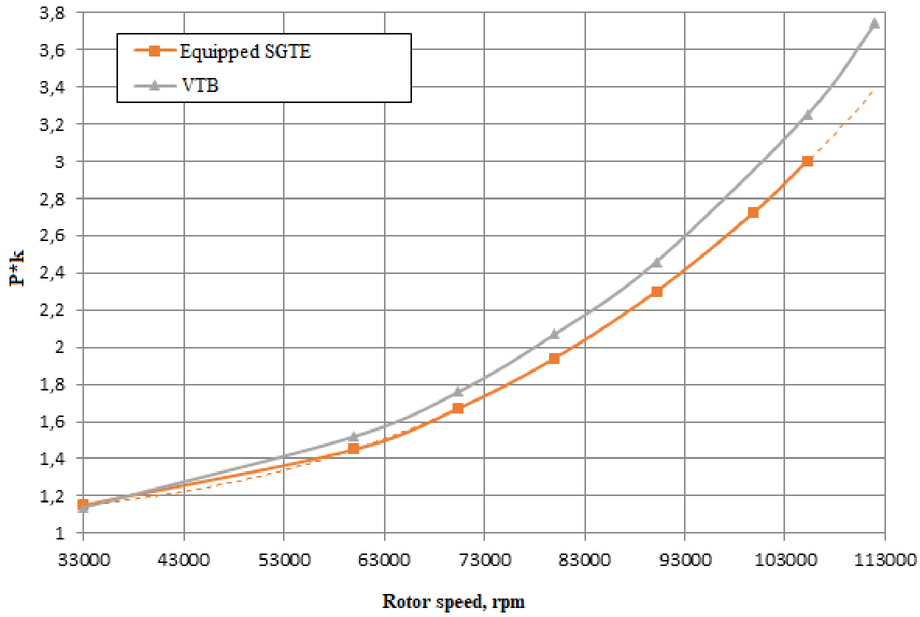

Figure 12. Dependence of compressor pressure increase on rotor speed.

Figure 13 shows a comparison of the measured and simulated air temperature behind the compressor. The results of the simulation and experiment are quite close, the difference is about 1 % (about 4...5 degrees K) except the "Low gas" mode (33000 rpm), where the measured temperature exceeds the calculated one by 7 degrees K (the difference is about 2%). Taking into account that the temperature unevenness behind the compressor is extremely small, the accuracy of measurements and modeling can be considered high.

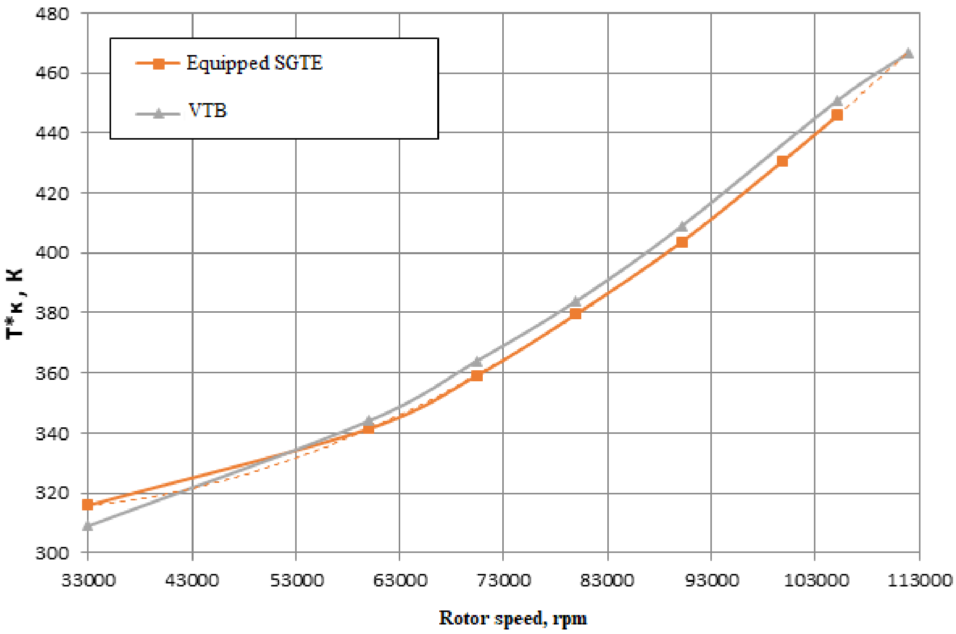

Figure 13. Dependence of the air temperature behind the compressor on the rotor speed.

Figure 14 presents a comparison of the measured and simulated degree of pressure drop behind the turbine. As soon as the channel height becomes acceptable (at least 10 mm), and the number of total pressure sensors increases (from 2 to 4 behind the turbine), the measurement results become more reliable, and the difference between simulation and experiment does not exceed 1 %.

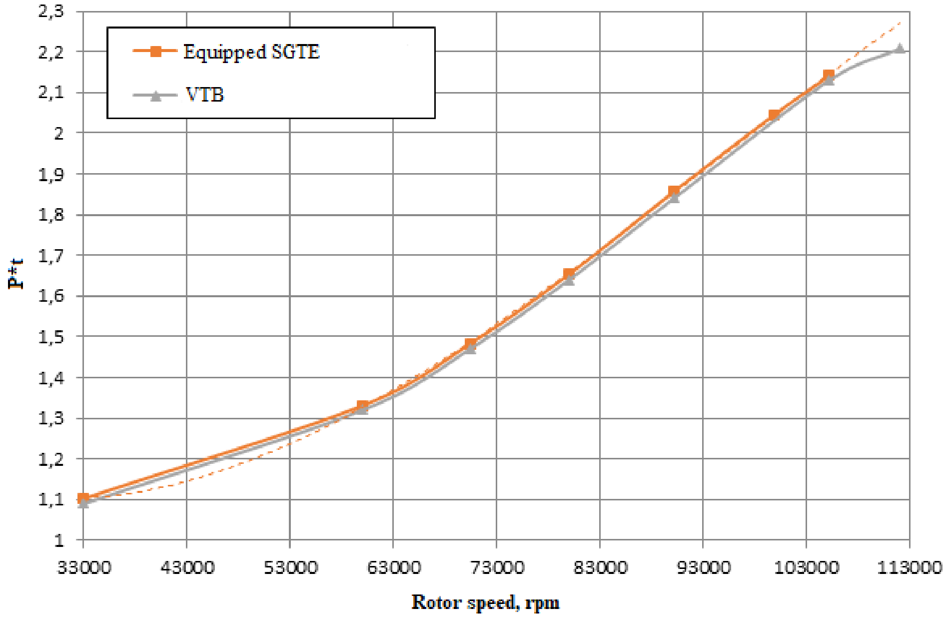

Figure 14. Dependence of decrease in turbine pressure on the rotor speed.

Figures 15 and 16 show a comparison of measured and simulated gas temperatures before and behind the turbine. The measured total gas temperature in front of the turbine is incorrect, since it exceeds the measured total gas temperature behind the turbine that cannot be. The comparison of the measured and simulated temperature behind the turbine shows that the calculated temperature is about 15% higher than the measured temperature, which can be caused by the following reasons:

- The modeling error of the combustion chamber;
- Failure or incorrect operation of part of the temperature sensors before and behind the turbine during test runs, when the fuel does not burn in the combustion chamber and burns out in the turbine and nozzle;
- It should be noted that the temperatures in the “hot part” of the turbine engine were measured by chromel-alumel thermocouples, which could easily be damaged during numerous experimental engines start due to temperature overshoot in the turbine and nozzle. The results of this experiment show that it is highly desirable to use substantially more expensive platinum-rhodium thermocouples.

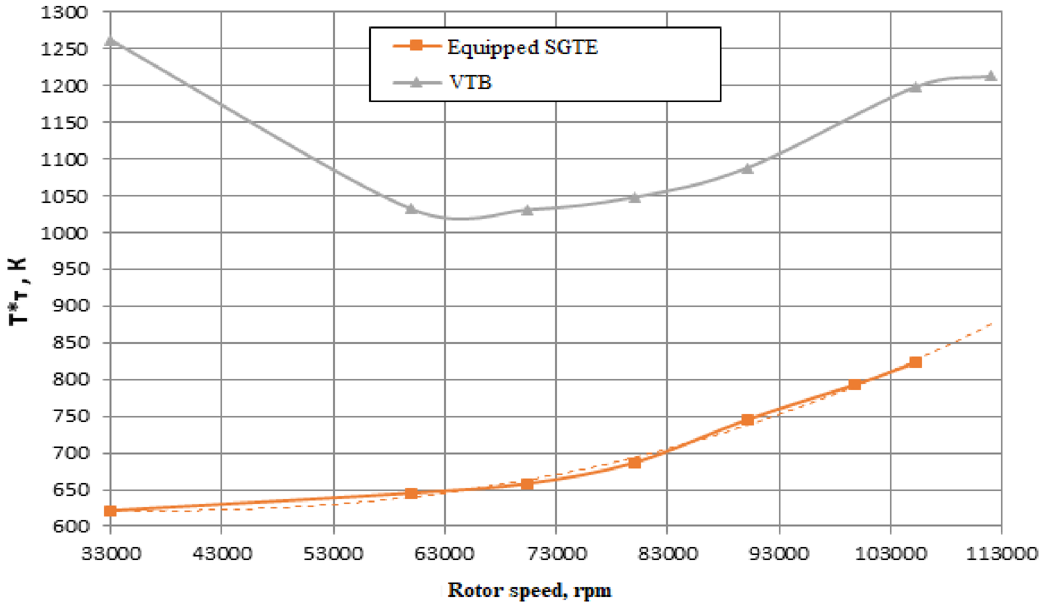

Figure 15. Dependence of the gas temperature in front of the turbine on the rotor speed.

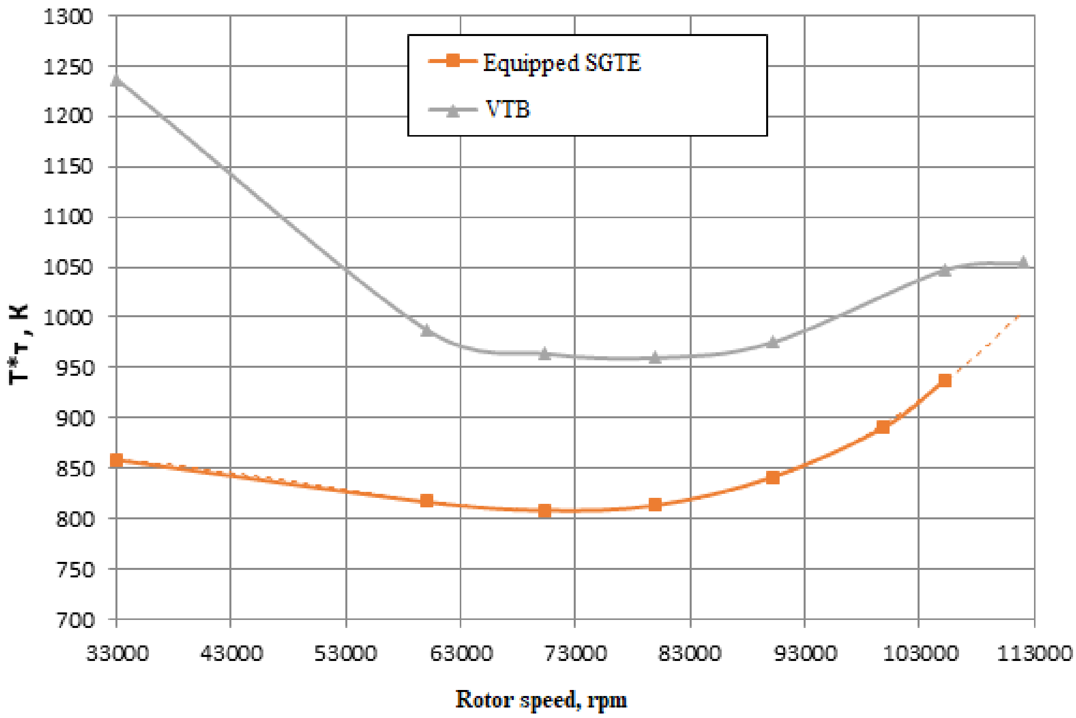

Figure 16. Dependence of the gas temperature behind the turbine on the rotor speed.

All results at the maximum engine operating mode (112,000 rpm), including extrapolation of the experimental curves, as well as calculated data and manufacturer data are summarized in Table 3. The following conclusions can be drawn from the table:

- the computation data on the degree of pressure increase in the compressor are in agreement with the manufacturer's data, which indirectly confirms the thesis about the shortage of the total air pressure behind the compressor;

- the levels of the calculated and measured gas temperatures at the turbine outlet, taking into account the measurement error and the data declared by the manufacturer, can be considered satisfactory
- extrapolation of the fuel consumption measurement curves in the experiment is in agreement with the manufacturer's data, taking into account the measurement accuracy;
- the difference in thrust measurement / calculation compared to the manufacturer's data was about -5 ... 6%. Given the growth of the calculated thrust curve when changing the operation mode of SGTE from 105,000 to 112,000 rpm (see Figure 10), it can be noted that the forecast curves for the experimentally measured engine thrusts are likely not correct and for the maximum mode the measured thrust of the unequipped engine would be close to that declared by the manufacturer.

Table 3. Comparison claimed/pilot/current characteristics of the Jetcat P200-RX engine at maximum thrust.

Parameter	Manufacturer data	Unequipped engine	Equipped engine	VTB
Full thrust, kgf	23.45	~22	~19	22.28
Outflow gas temperature, K	1023	-	~1010 ± 34	1054
Degree of pressure increase	3.7	-	~3.4 ± 0.1	3.74
Fuel consumption, kg/h	34.2	~36 ± 4	~35 ± 4	34.2

5. Conclusion

The work, performed on the numerical and experimental study of the parameters of the working path of SGTE, results in the following main conclusions:

- Under conditions where the main prerequisites for the experimental measurement of parameters are favorable (sufficient channel heights, a sufficient number of sensors, the absence of extreme temperatures and high irregularities), a comparison of the experimental and simulation results are in agreement (within 1 ... 2%) that is evident from the comparison total air temperature behind the compressor, differential pressure of the gas on the turbine and engine thrust;
- Measurement of parameters in difficult conditions (small channel heights, large non-uniformity of parameters, temperature "spikes", and a small number of sensors) leads to significant uncertainties in determining the parameters of the SGTE path and the inability to separate modeling errors and experimental errors. It is seen from the results of gas temperature measurements behind the combustion chamber and the turbine;
- Despite the incomplete success of the tests (which attributed to their difficult conditions because of the rather small overall dimensions of the research object), it can be confidently said that modern modeling techniques make it possible to reliably predict the key parameters of the main SGTE components. Besides, virtual tests allow partially replacing the full-scale ones under conditions when the experimental measurement of the necessary parameters is difficult.

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