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ON THE NEED TO MAINTAIN HOMOGENOUS TEMPERATURE FIELD WITHIN THE WORKING AGENT AT THE INTAKE OF A JET ENGINE TURBINE

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Abstract

The paper presents results from numerical experiments with use of the computer model of the SO-3 engine designed for simulations. The model has been purposefully modified to take account of the assumed non-homogeneity of the temperature field within the working agent at the turbine intake. It turned out that such non-homogeneity substantially affects dynamic and static properties of the engine are considered as an object of control since it leads to a lag of the acceleration time and to increasing in fuel consumption. The summarized simulation results demonstrate that the foregoing properties of a jet engine are subject to considerable deterioration in pace with gradual increase of the assumed non-homogeneity of the temperature field, The simulations made it possible to find out that variations of the temperature field non-homogeneity within the working agent at the turbine intake lead to huge fluctuation of the turbine rpm for the idle run, which enables a new look to the role of the so-called idle run valve and importance of that component within the supply and control system of the SO-3 engine.

***Keywords**: Turbine jet engine, simulation model, working agent temperature field*

1. Introduction

The deliberations in this study provide only a partial explanation for its title. The next important issue that should be the matter of subsequent studies of the author in the near future is the highly probable relationship between non-homogenous distribution of the temperature field at the turbine intake and pulsation of the engine torque that leads to premature wear of jet engines and shortens their service lives.

2. Specific properties of a turbine engine as a non-linear object

All versions of the simulation model for the SO-3 engine that have already been published by the author [4, 7] comprise considerable number of non-linear parameters. In particular, these include static characteristics of the compressor and the turbine. The theory of control says that in case when at least one component in the computation structure is non-linear, the entire structure is non-linear as well. Thus, a turbine jet engine, considered as an object of control, is a dynamic nonlinear object [1, 9].

Such an important feature of a turbine engine, resulting from that fact that the engine is a non-linear dynamic object, is the impact of the temperature field non-homogeneity within the working agent at the outlet of the combustion chamber onto the acceleration time and performance at steady conditions. Some properties shall be the matter of detailed discussions in the subsequent parts of this paper.

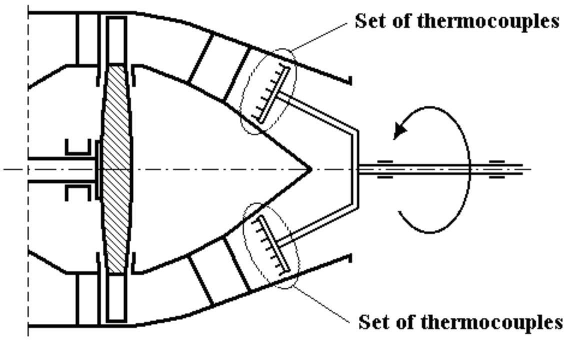

Fig. 1. Diagram of an appliance for measurement of the temperature field non-homogeneity within the working agent in the engine jet nozzle

Procedures of handover tests of engines at manufacturing plants as well as routine tests after overhauls include measurements of the temperature field. In most cases, due to practical reasons, the temperature field non-homogeneity is measured within a cross-section of the jet nozzle duct with use of dedicated equipment. The reasons for non-homogeneity may be various and in practice, the phenomenon is very difficult for total eradication [2]. The most common method that can be applied consists in appropriate calibration and selection of a matching set of working injectors. Fig. 2 shows an example graph that depicts non-homogeneity of temperature field across the jet nozzle of a prototype K-16 engine (slightly altered version of the K-15 engine). The image was acquired by means of the measuring testbench shown in Fig. 1. The testbench is made up of two sets of thermocouples, with 7 units in each set, deployed between the inner and outer walls of the jet duct within its cross-section. The measurements are taken by simultaneous readouts from all 14 thermocouples at a time for various angle positions of the entire arrangement selected by its revolution around the longitudinal axis.

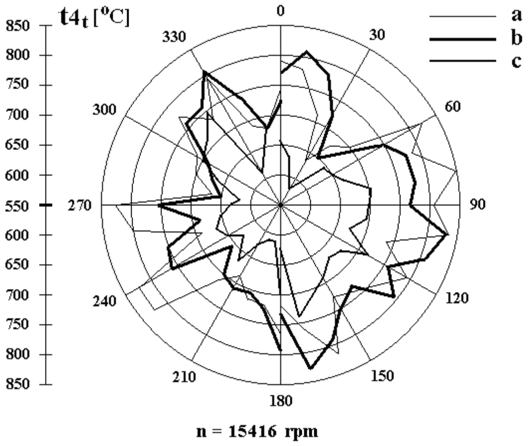

Fig. 2. Example results for measurements of the temperature field non-homogeneity within the working agent inside the jet nozzle of the K-16 engine; a – nearby the outer wall, b – in the middle of the gas duct radius, c – nearby the inner wall

The measurement results depicted in Fig. 2 indicate that non-homogeneity of the temperature field for the cross-section of the working agent flux is surprisingly large and subject to some fluctuations in spite of the constant rpm of the rotor. The size of such fluctuations can be expressed as discrepancies of temperatures measured for the same measurement points but after elapsing of time necessary for displacements of the measurement arrangement by the angle of 180° (see temperature differentials for 'azimuths" of 0° and 180°).

The simulation model for the SO-3 engine presented in the past output of the author [4, 7] involves description of the working agent parameters within selected cross-sections of the gas duct with use of the 'zero-dimensional' approach. Thus, such a description is incapable of considering such nuances as 3-D nature of the working agent flow, in particular through the so-called 'hot part' of the engine.

3. Plan for a numerical experiment with use of a simulation model

The idea of this paper consists in suggestion to modify the structure of the engine model with the aim to achieve a kind of a simple mathematical dummy that enables simulation of the temperature field non-homogeneity within the working agent at the combustion chamber outlet, where the simulation is carried out with use of basically zero-dimensional description of the working agent flow.

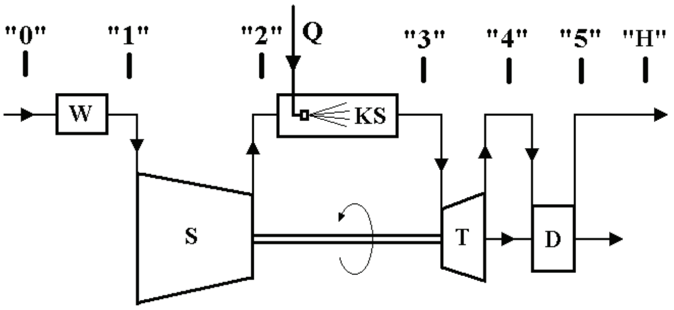

Fig. 3. *The basic principal diagram of a turbojet engine (W – engine intake, S – compressor, KS – combustion chamber, T – turbine, D – nozzle jet, Q – fuel expenditure)*

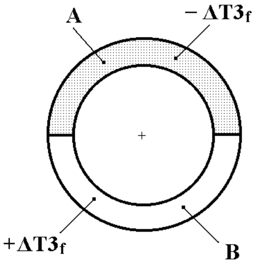

Fig. 4. *Conventional breakdown of the cross-section area for the outlet duct of the combustion chamber (or the intake duct of the turbine)*

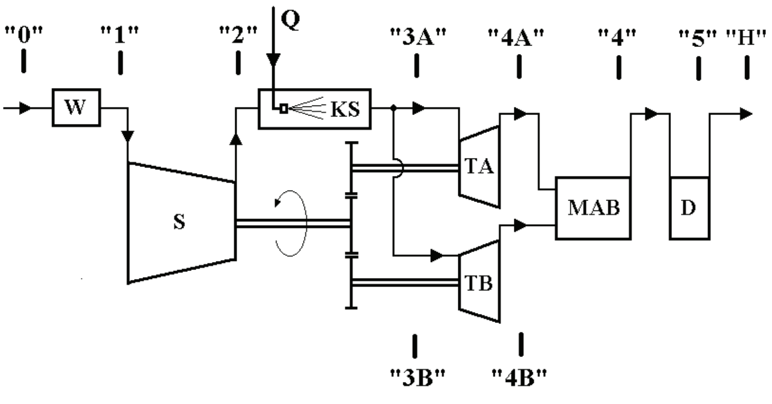

Fig. 5. *The schematic diagram for the engine model – a mathematical dummy for simulation of the temperature field non-homogeneity within the working agent at the turbine intake (W – engine intake, S – compressor, KS – combustion chamber, TA – turbine (part 'A'), TB – turbine (part 'B'), MAB – mixing area, D – nozzle jet, Q – fuel expenditure)*

Figure 3 depicts the general structure of the engine. This diagram was used as the outset point to develop the simulation model already described in [4, 7]. Fig. 4 and 5 depict upgraded version of that model where both the turbine and the combustion chamber are split into mutually equal parts. Each of the TA and TB turbines has the same efficiency characteristic curve, whilst the flow characteristic curves are equivalent to a half of the working agent flux.

With regard to the split combustion chamber, the assumption was made that a different temperature of the working agent should be measured at the outlet of each turbine half, which is the result of random and difficult to explain fluctuations of the temperature field. The conventional diagram split in that way into two mutually equal cross-section areas of the outlet duct of the combustion chamber is shown in Fig. 4.

4. Results from the numerical experiment carried out with use of the simulation model

The upgraded model for the SO-3 engine as described above was then combined with the model for the automatic control circuit [7], not shown in the drawing. The control circuit enables execution of simulated control for transition processes and generation of selected steady states. Two types of numerical experiments were carried out. The first type assumed investigation into how the non-homogeneity of the temperature field affects transition processes within the engine. The second series of investigations was dedicated to check impact of the temperature field non-homogeneity onto static characteristics of the engine.

The transition processes were triggered by quick subsequent accelerations and decelerations, starting for the idle run of the engine up to nearly the maximum thrust with due care to avoid tripping the limiter for the maximum engine rpm. The experiments were carried out with the presumed values of the $\Delta T3_f$ parameter that represents the measure of non-homogeneity of the temperature field distribution at the outlet of the combustion chamber (or at the turbine intake). Examples of obtained results are depicted in Fig. 6 to Fig. 8.

The selected static characteristic curves of the engine are shown in Fig. 9 to Fig. 11. These curves were plotted for the engine operation under normal atmospheric conditions on the ground (Ma = 0, H = 0) and for flights at the speed of Ma = 0.4 under normal atmospheric conditions at the altitude of 6 km. For that purpose, the own-developed method proposed by the author was applied, referred to as scanning of the engine status space and described in details in [7]. That method, verified in [7] for determination of static characteristic curves for the K-15 engine, prevails over the conventional one, typically used for the same purpose because it enables collection of great many points with measurement results, which is shown in Fig. 9 to Fig. 11.

4.1. Simulation of selected transition processes

Results from simulation of transition processes for the case in which the engine runs under normal ground conditions are shown in Fig. 6 to Fig. 8. Excitation of the transition processes was carried out by input waveforms of fuel expenditures for three 3 values of the $\Delta T3_f$ parameter as shown in Fig. 6. The presented graphs have two distinctive features:

- initial and final values of fuel expenditures are identical for all three values of the $\Delta T3_f$ parameter,
- durations of the acceleration processes substantially differ from each other depending on the value of the $\Delta T3_f$ parameter.

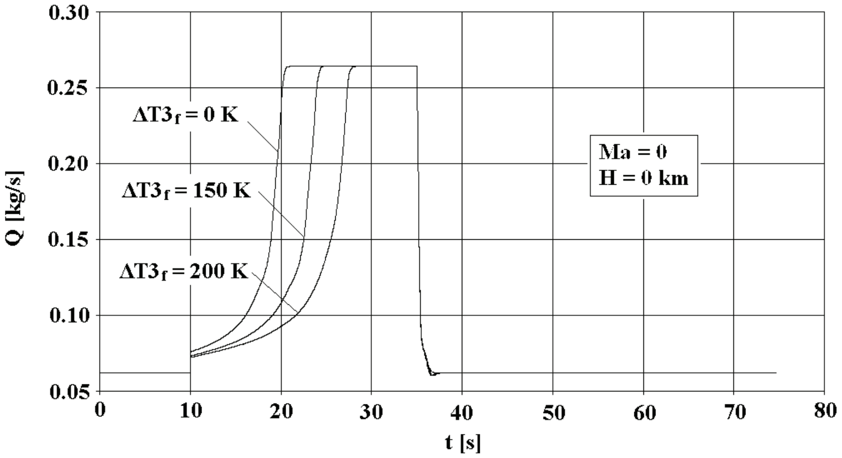

Fig. 6. *Timings for fuel expenditures during acceleration and deceleration of the jet engine within the range from idle run to the area slightly below full thrust without tripping the limiter of the maximum rotor rpm, under normal ambient conditions on the ground and for various settings for the* $\Delta T3_f$ *parameter*

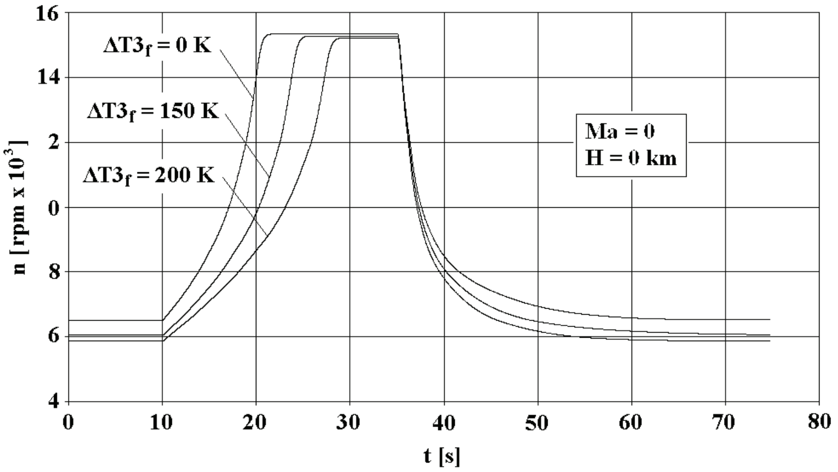

Fig. 7. *Timings for the rotor rpm during acceleration and deceleration of the jet engine within the range from idle run to the area slightly below full thrust without tripping the limiter of the maximum rotor rpm, under normal ambient conditions on the ground and for various settings for the* $\Delta T3f$ *parameter*

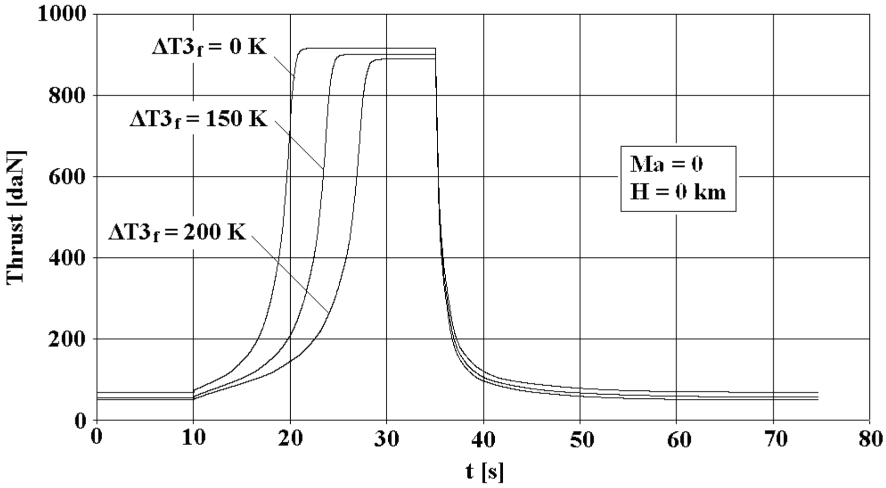

Fig. 8. *Timings for the engine thrust during acceleration and deceleration of the jet engine within the range from idle run to the area slightly below full thrust without tripping the limiter of the maximum rotor rpm, under normal ambient conditions on the ground and for various settings for the* $\Delta T3f$ *parameter*

Figure 7 to Fig. 8 depict timings for responses of the engine model to excitations applied as timing waveforms of fuel expenditures as shown in Fig. 6. The presented results feature with some distinctive properties:

- values of all engine parameters presented in graphs plotted for steady states clearly depend on the value of the ΔT3f parameter in spite of the fact that the fuel expenditure observed for steady states and shown in Fig. 6 is exactly the same for all values of the ΔT3f parameter,
- duration of the acceleration and deceleration periods are substantially different for all monitored engine parameters (n, Thrust, Cj) and depend on the value of the ΔT3f parameter,
- the foregoing results indicate the need for thoroughly examine impact of the ΔT3f parameter onto static characteristic curves of the engine.

4.2. Selected static characteristics

As mentioned before, static characteristic curves for the engine model were determined with use of the own-developed method, called by the author scanning of the state space. Among other applications, the method was also used [7] to find out static characteristic curves of the K-15 engine. The key advantage of the method is the possibility to obtain great many points with measurement results for steady states, where the scanning time is much shorter than it takes place when the conventional method is applied. However, the method has also a drawback, since it can be applied for determination of static characteristic curves merely for single-rotor engines with small volume of the jet nozzle duct, i.e. for such engines where dynamic behaviour thereof can be described by means of the 1st order non-linear differential equation [4, 7]. It is the condition, that is fulfilled by the SO-1 engine and its simulation model disclosed in this paper.

The typical property of all other static characteristic curves that are shown in Fig. 9 to Fig. 11 is the fact they substantially differ from each other for various values of the $\Delta T3_f$ parameter.

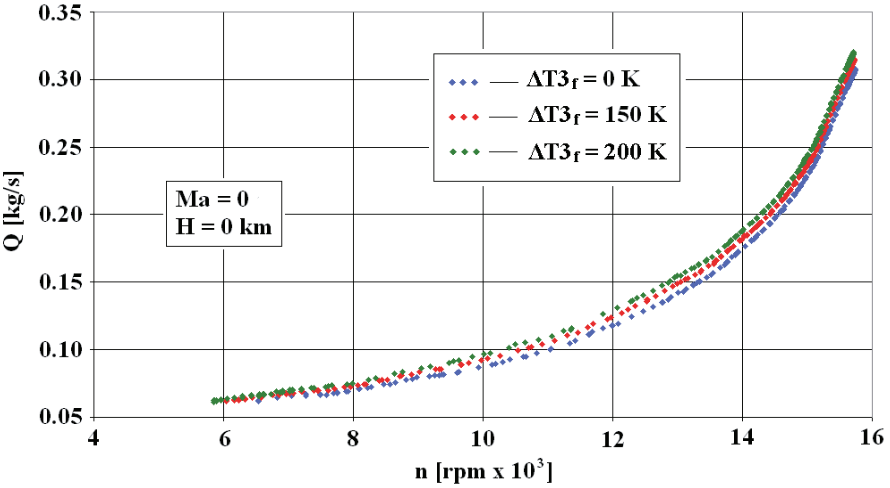

Fig. 9. Static characteristic curves plotted for the jet engine in the coordinate system Q = f(n) for various fixed values of the ΔT3f under normal ambient conditions on the ground

It is worth paying attention that static characteristic curves plotted for the engine for the flight at the altitude of *H = 6 km* feature elevated rotor rpm within the range of idle run, which can be seen from comparison between Fig. 9 and Fig. 10. It is the distinctive property of all avionic turbojet engines and it was correctly reproduced in the simulation model for the SO-3 engine applied to these studies.

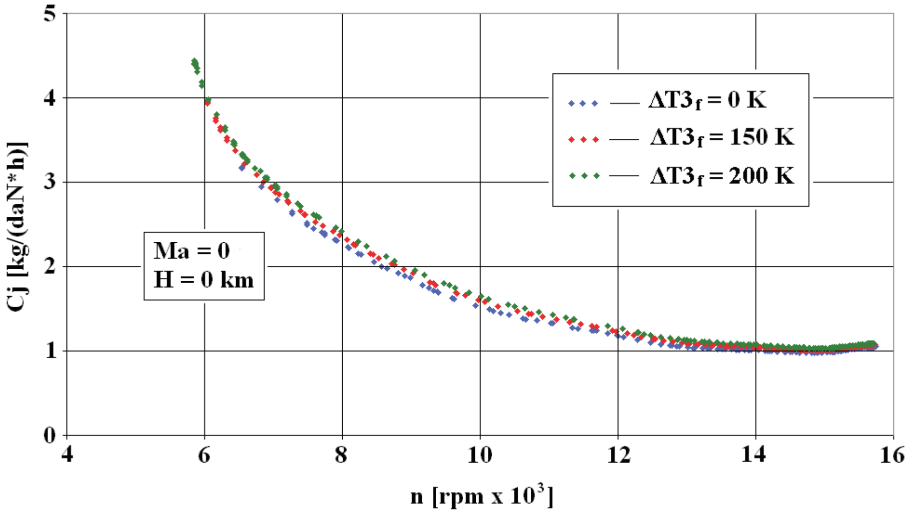

Fig. 10. Static characteristic curves plotted for the jet engine in the coordinate system Cj = f(Q) for various fixed values of the ΔT3f under normal ambient conditions on the ground

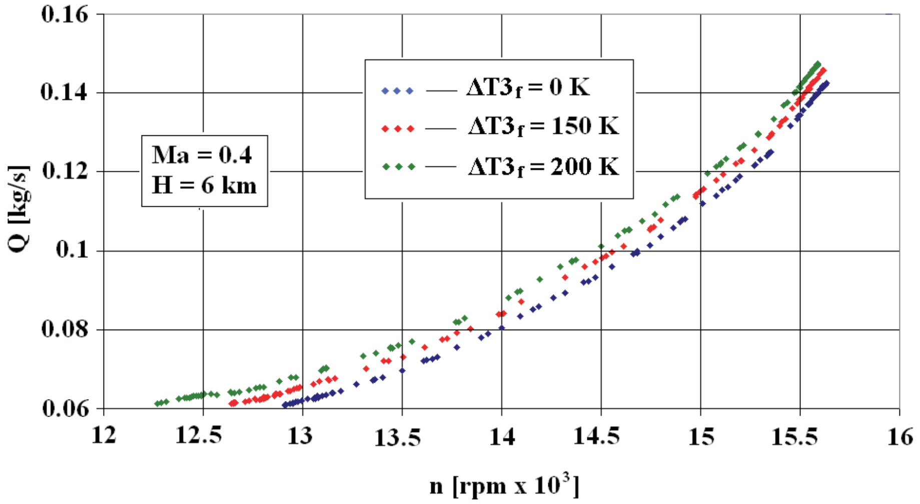

Fig. 11. Static characteristic curves plotted for the jet engine in the coordinate system Q = f(n) for various fixed values of the ΔT3f for the flight at the speed of Ma = 0.4 at the altitude of H = 6 km under normal ambient conditions

5. Conclusions

1. The investigations enabled to find out substantial impact of temperature field non-homogeneity onto deterioration of both dynamic and static properties of the SO-3 engine. The non-homogeneity leads to a lag of the acceleration time (see Fig. 6 to Fig. 8), which is the crucial parameter for suitability of the engine for use. In addition, other performance parameters of the engine in its steady state, such as specific fuel consumption per thrust unit and total fuel consumption in time, are considerably higher. It is the phenomenon that can be spotted both for operation of the engine on the ground (Ma = 0, H = 0) and at flight (Ma = 0.4, H = 6 km).
2. Results from investigations on a real object [6] confirm the impact of the temperature field non-homogeneity within the working agent at the turbine intake onto entire duration of the engine acceleration process under ground conditions. The impact of the mentioned temperature field onto specific and total fuel consumption in steady states, although

revealed by experiments carried out within the scope of these studies, is still awaiting its experimental confirmation.

3. The phenomena described in paragraph 1 are visible when the conventional parameter that stands for non-homogeneity of the temperature field distribution is large enough, e.g. $\Delta T3_f > 100K$. Thus, one can expect that for a real engine it will be possible to apply the method disclosed in this paper to define requirements to the permissible maximum of dispersion for the temperature of the working agent.
4. When the engine is running, it is really difficult to keep the temperature field dispersions within the predefined boundaries. It is caused by unsteady flow characteristics of the set of working injectors due to deposition of carbon black and the effect of fuel 'coking'. The specific problem has already been recognized, which is evidenced by the attempt, known from literature references [8], to design an automatic system for self-adjustment of the NK-144 turbojet engine (for the Tu-144 aircraft), where the system could have been provided with modules for active correction of the non-homogeneity of temperature field by means of individual control for fuel expenditures into selected groups of working injectors. Concurrent increase in the acceleration time and growth of the total fuel consumption, spotted during the engine operation, may be a valuable diagnostic symptom that indicates faulty operation of working injectors caused by the already mentioned phenomenon of fuel 'coking'.
5. The objective of this study was achieved owing to a simple approach, where the simulation model of the turbine was halved (Fig. 4). Hence, results of the experiments carried out in such a way are more of qualitative, not quantitative nature. Application of the turbine model with partitioning of its intake ducts into more than two parts would enable reproduction of non-homogenous distribution of the temperature field in the way that is more coherent with operation of a real engine.
6. The core reasons for all phenomena described in this study are the non-linear nature of the turbine and the jet nozzle subassembly. In particular, the subassembly is deprived of the additivity (superposition) property [1]. However, it must be mentioned that the static characteristic curve for the SO-3 engine is definitely non-linear [4, 7] for the entire range of the engine rpm, i.e. from idle run up to full thrust. Consequently, the simulation model developed for that engine and used for experiments described in this paper is also non-linear. It results from the fact that the maximum compression factor for the SO-3 engine is relatively low ($\pi \approx 4.7$), which leads to subcritical flows in the turbine gas duct for nearly whole operation range of the engine. One can expect much less impact of fluctuations in non-homogeneity of the temperature field onto operation parameters of the engine in the case of the turbojet engine with the much wider range of the engine rpm with the critical flow of the working agent through guiding vanes and the outlet cross-section of the turbine. However, this statement should be referred to with great care and considered as a scientific hypothesis that deserves further investigations.
7. Besides the turbine and jet nozzle subassembly of definitely non-linear nature, the engine comprises also other non-linear components, such as static characteristic curves of the compressor. However, the impact of those non-linear components onto engine operation was not analysed in this study by means of the same method as the impact of the non-linearity attributable to the turbine and the jet nozzle subassembly. The author intends to carry out such an analysis in the near future.
8. With regard to the finding, that duration of the acceleration process substantially depends on non-homogeneity of the temperature field expressed by the $\Delta T3_f$ parameter it is necessary to say a few words about the design error that occurs in the ASS-1C1 automatic control unit with its cross-section. The unit makes up an important part of the supply and control system for the SO-3 engine and incorporates the structural subassembly called as 'idle run valve'. According to the intention of designers, the valve should stabilize fuel

supply to the engine when it is operated in the idle run mode, since it reduces to the minimum possible degree the disturbing effect of the dry friction force between the follower and the guiding sleeve. However, results of this study demonstrate that fluctuations of the engine rpm shall occur even when the fuel supply (expenditure) is constant for the entire range of the engine rpm and when the detrimental impact of the mentioned force of dry friction is completely eliminated.

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