TRANSACTIONS ON AEROSPACE RESEARCH
eISSN 2545-2835, VOL. 275, NO. 2/2024, 33-43
DOI: 10.2478/tar-2024-0010

NUMERICAL SIMULATION OF WORKFLOW FOR EVALUATING FLAME TUBE THERMOCYCLIC DURABILITY

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ABSTRACT

This paper explores strategies for extending the operational lifespan of flame tubes in turbofan engines – a critical component for maintaining engine efficiency and reliability, in line with global trends aimed at maximizing the use of laid reserves of aircraft engine performance. Utilizing a combination of advanced computational simulations and empirical research, the study meticulously analyzes the internal processes within the flame tube of the AL-31F turbofan engine. A detailed geometric model and finite element grid were created and adapted to simulate various operating conditions and assess their impact on the flame tube's performance. Special attention is given to understanding the thermal and mechanical stresses that influence its durability and serviceability. The results, compared against experimental data, validate the simulations and are crucial for identifying critical sections prone to damage, thereby facilitating enhanced decision-making regarding maintenance schedules and overhaul practices. This approach not only aims to minimize downtime and reduce maintenance costs but also extends the service intervals for critical engine components, thereby improving thermocyclic durability based on the damage mechanisms identified.

Keywords

turbofan engine; time between overhaul; numerical simulation; flame tube, workflow; thermal and stress-strain state; thermocyclic durability.

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Received 09.12.2023 • Revised 15.01.2024 • Accepted 29.04.2024

INTRODUCTION

One of the structural and technological features of aircraft turbofan engines is that they include certain resource-limiting parts, with overhaul periods shorter than the designated overhaul period of the whole engines themselves. A prominent issue arises, therefore, in optimizing the utilization of these components to fully realize the engine's potential between maintenance cycles. The potential replacement of such parts is often constrained by prohibitive costs, in the range of 100,000–150,000 USD, as well by the technical challenges associated with their domestic production. One prominent such resource-limiting part for a turbofan engine as a whole is the flame tube of the main combustion chamber.

At the same time, global trends in addressing the maximal efficiency and longevity of aircraft engines and their resource-limiting parts focus on the continuous improvement of evaluation techniques. These methods are grounded in in-depth analyses of their technical condition on the basis and detailed evaluation of their load conditions, and facilitate well-founded decisions on the feasibility of extending the time between overhauls.

A pressing and unresolved issue in the field is the effective execution of scheduled overhauls for aircraft engines, with a particular focus on the flame tubes of main combustion chambers. Achieving a balanced and strategically managed overhaul timeline is crucial for the planning of future maintenance intervals. Thus, the objective of this paper is to explore strategies to extend the operational life of flame tubes – a topic of significant scientific and practical importance.

LITERATURE REVIEW

The flame tube is one of the most complex and critically important parts of the turbofan engine, upon which the engine's main characteristics, reliability and maintenance intervals between overhauls depend [1]. Figure 1 illustrates the basic workflow organization and the main design elements of the aircraft engine's combustion chamber.

Designing a main combustion chamber that meets essential requirements and provides the desired performance over specified maintenance intervals between overhauls requires considerable experimental research, as the processes occurring in the flame tube are only minimally amenable to theoretical calculations. In Ukraine, features related to the operation and repair of aircraft engines are investigated within the context of scientific and technical support, particularly the integration of modern automated design systems. The variability of engine operation during flight greatly complicates the application of theoretical methods to describe the workflow in the combustion chamber and increases the cost of conducting full-scale experiments.

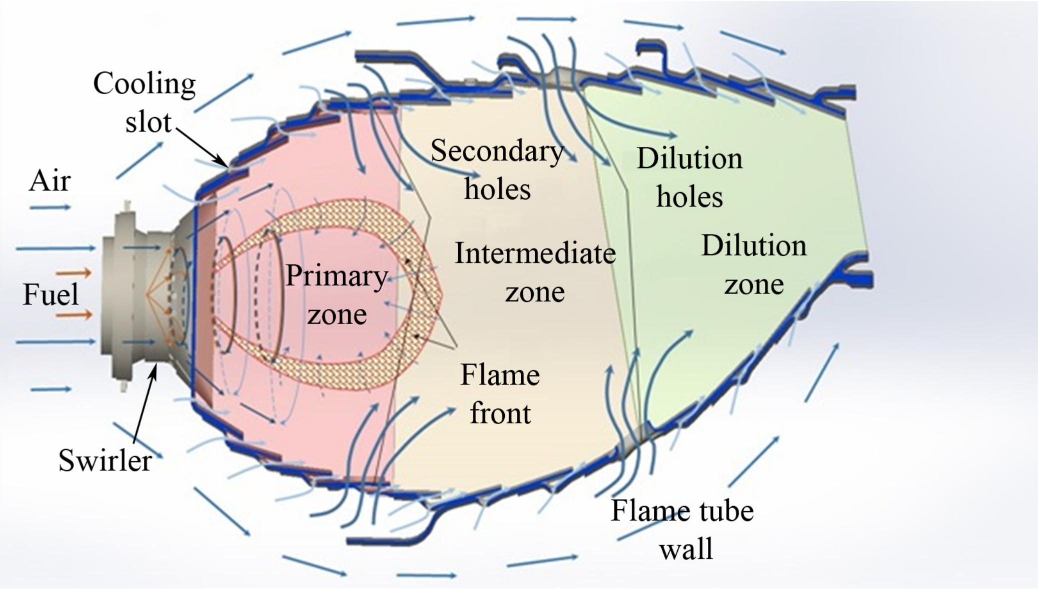


Fig. 1. Workflow organization scheme and main design elements of the flame tube

Therefore, in modern aircraft engine design, refinement, operation and repair, the distinctive characteristics of the processes in the combustion chamber are investigated using methods and models of fluid dynamics [2-4]. These include the practical implementation of modern automated design systems (AutoCAD, ADEM, Unigraphics, SolidWorks, ProEngineering, Ansys), which encompass not only CAD (computer-aided design), but also CAM (computer-aided manufacturing) and CAE (computer-aided engineering) systems. The computational aspect of CAE system packages is based employs multiple methods for solving differential equations, including the finite element method and finite volume method [5].

These systems make it possible to determine the shape of the distribution of the temperature field along the flame tube walls, which result from the complex interaction of spatial currents and physical and chemical processes. Recently, the advancement of numerical methods for solving problems of stress-strain states of complex structural elements in the field of aerospace engineering has facilitated detailed analysis using ANSYS software packages [6].

ANSYS allows for the simulation of physical processes to solve nonlinear and non-stationary spatial problems under specific boundary conditions. These conditions reflect operational influences, facilitate the modification or creation of geometry of research objects, and also incorporate the effects of contact interactions between elements and environments through Fluid-Structure Interaction (FSI) technology. Depending on the specific requirements, different schemes are utilized to integrate the corresponding modules within the unified platform of the software package. Their capabilities are demonstrated when modeling the full range of tasks related to the workflow organization in the combustion chamber, including the evaluation of the flame tube's thermal state, its stress-strain states and thermal strength [7].

This study aims to simulate the internal processes of the flame tube in the main combustion chamber and evaluate how its resource parameters affect the serviceability of aircraft engines. In specific, the objectives are to:

- model the workflow within the flame tube;
- analyze the impact of its resource parameters on engine serviceability.

EXPERIMENTAL STUDY

The same basic algorithm underlies the research methods used in modern approaches to the computational simulation of the workflow in a flame tube, across various specialized software systems with differing focus. This algorithm includes the following steps:

- creating a geometric model of the elements in the flame tube design and defining the physical limits of the gas flow;
- constructing a finite element grid and adapting it depending on the type of area within the flame tube (solid body, fluid environment volume, boundary layer), while determining the size of the finite elements depending on the complexity of the computational domain's design performance;
- determining the simulation criteria (the continuity equation, the conservation of momentum, the conservation of energy, boundary conditions), setting parameters of the operating environment, and performing the simulation through iterative calculation of differential equations;
- performing visualization and analysis of the results obtained.

At the first stage (Fig. 2a), using the appropriate software, a computer 3D model of flame tube turbofan engine AL-31F was created, without improved cooling. Based on the original design documentation, this element was created in the form of an assembly of its individual constituent elements (wall parts, nozzles, swirlers, and other elements). This made it possible to represent, on a 1:1 scale, all the design features of flame tube, as well as to reliably determine the connections between the elements.

The next step, to reduce the use of computer RAM and significantly bring down the time of calculations, a sector that includes 2 nozzles out of 28 (Fig. 2b) was chosen.

To simulate the area of the workflow, a model of the fluid domain was built, limited by the combustion chamber walls (Fig. 2c).

Combining models b and c, a joint 3D model of the flame tube and the fluid domain was created (Fig. 2d). At the same time, the boundary between the two media was defined to further ensure the accurate representation of the interactions between the fluid and solid parts of flame tube.

The primary factor influencing the reliability of simulation results is the parameterization of the finite element mesh. Fig. 3 illustrates a model of the finite element grid for the flame tube sector, developed for simulating the workflow process and for calculating thermal and stress-strain states. This model was created using ANSYS and consists of two distinct parts. These are interconnected via a specialized grid deformation mechanism to ensure alignment at the interface between the domains.

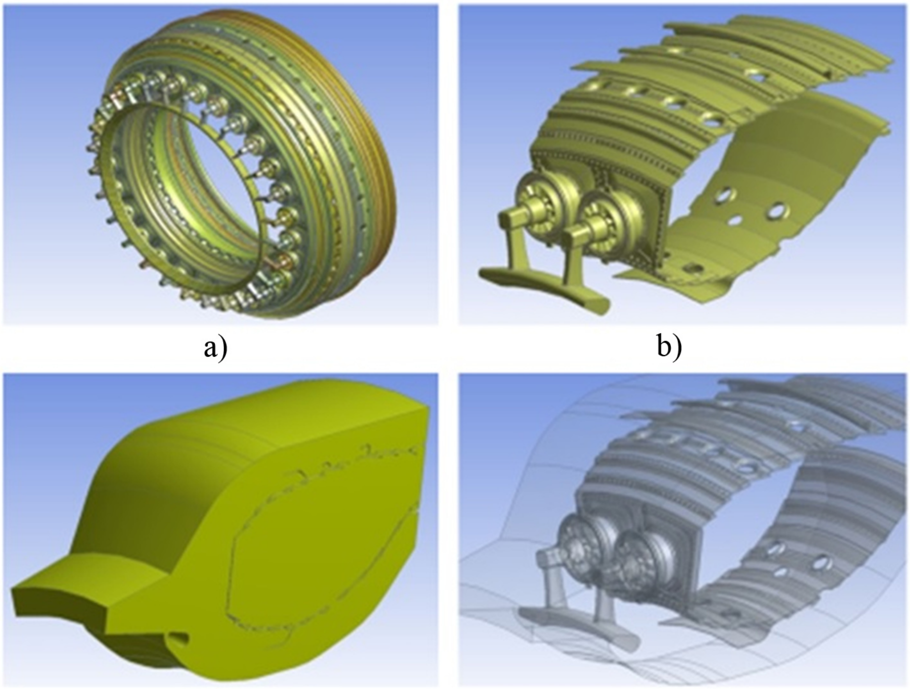

a)
b)
c)
d)

Fig. 2. 3D model of flame tube turbofan engine AL-31F

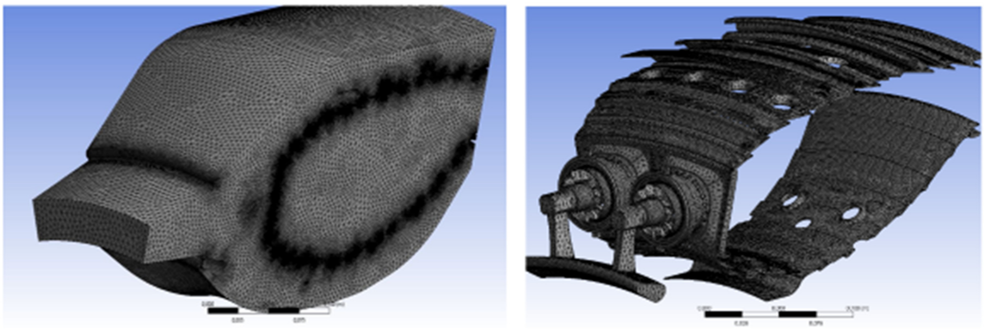

a)
b)

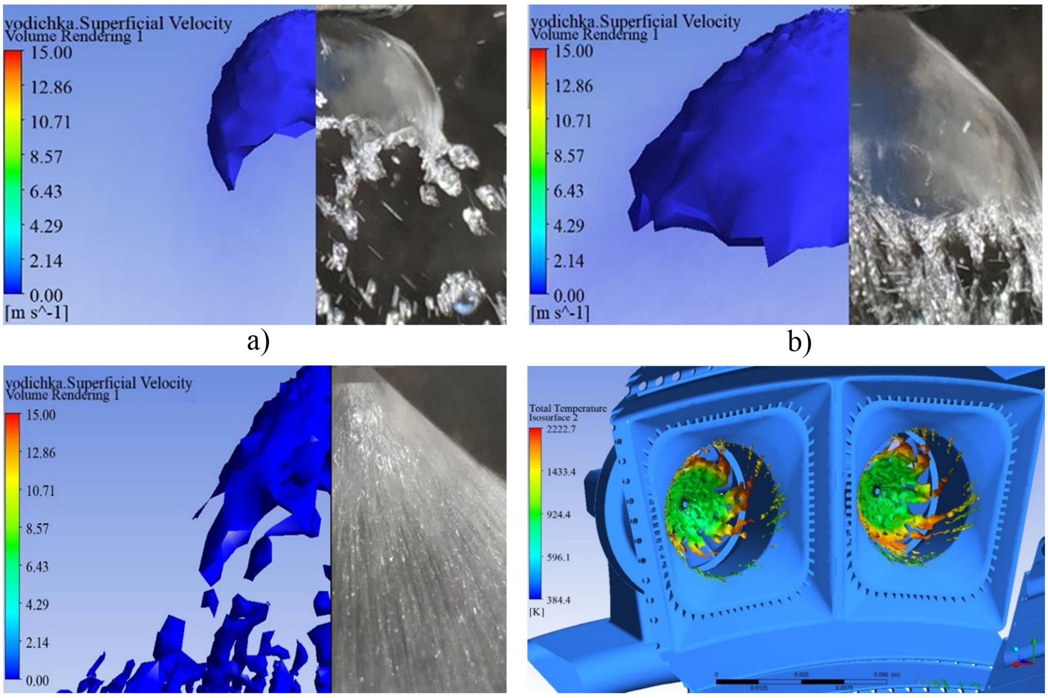
Fig. 3. Model of the finite element grid of the flame tube sector turbofan engine AL-31F

Fig. 3a shows a model of the finite element grid for the fluid domain, which includes 5,331,124 design nodes and 28,050,634 finite elements. Fig. 3b depicts a model of the finite element grid for the flame tube walls, which includes 47,274,787 design nodes and 30,768,575 finite elements. Given the modern requirements and capabilities of existing hardware and software systems, in terms of the overall number of finite elements, this grid is considered high-quality and robust enough for conducting numerical simulations and obtaining reliable results.

Numerical simulation of the workflow, particularly in determining the temperature distribution field on the flame tube walls, plays a dominant role in the implementation of the overall project of calculating and experimentally studying the thermal and stress-strain states.

RESEARCH RESULTS

In order to ensure compliance of fuel spraying parameters, the theoretical calculations and simulation results [8] were cross-verified with experimental data obtained based on the results of hydraulic pouring of AL-31F nozzle (Fig. 4). A comparison between the visualization of the numerical modeling of liquid leakage from the cascades of the fuel nozzle and the liquid flow during the physical modeling of the nozzle revealed a consistency in spray angles, which differ by values from 3 to 8 degrees.



a) b)

c) d)

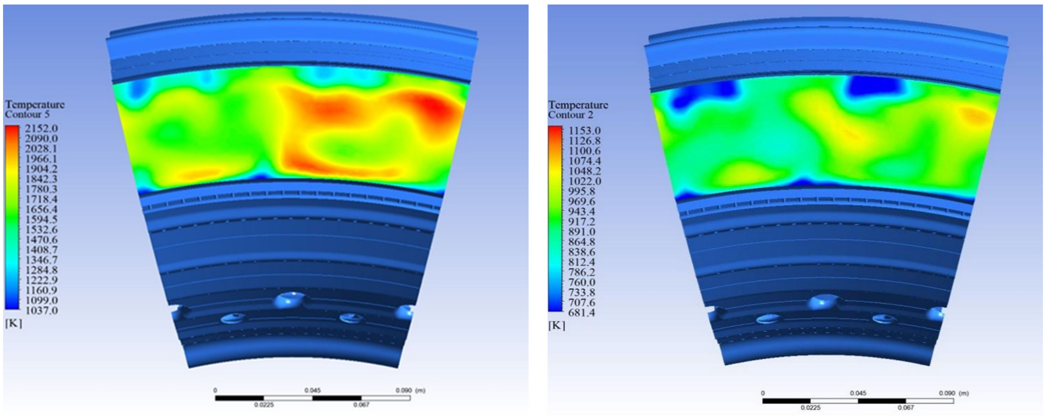
Fig. 4. Visualization of the results of numerical and physical simulation of the flow from the secondary circuit of the nozzle at the mass flow rate of the liquid: a) 0.002 kg/s; b) 0.003 kg/s; c) 0.004 kg/s; d) parameters of fuel spraying in Max mode at simulation of combustion process.

There is also agreement in terms of the breakup of the conical liquid film into individual drops, as is confirmed by the beginning of the atomization process at the same distance from the outlet section of the nozzle.

Experimental methods do not make it possible to establish the quantitative distribution of fluid dynamic parameters in the flame tube field. In most cases, such experimental measurements only provide a qualitative assessment of the nature of the combustion process. This is due to restrictions on the number of possible places where sensors can be installed, since the presence of measuring instruments can itself affect the nature of fluid flow in the combustion chamber.

Therefore, to verify the workflow in flame tube, the results of numerical simulation are compared with the obtained parameters of radial unevenness of the temperature field at the output section of the combustion chamber.

Fig. 5 shows the calculated results of the distribution of the temperature field at the outlet from the combustion chamber.



a) b)

Fig. 5. Results of numerical simulation workflow: a) dry trust rating; b) forward idle thrust rating

DISCUSSION OF RESULTS

To verify the results of the simulation of the working process in a flame tube, the calculated and experimental values of the diagram of radial temperature unevenness were compared to the results of bench tests of the engine in the dry trust rating mode, adjusted for resource utilization (Fig. 6) [9, 10].

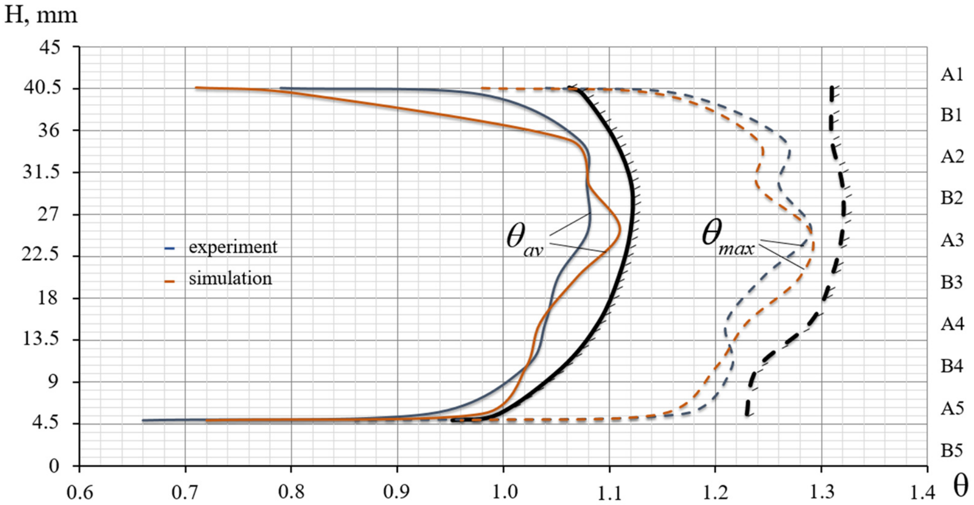
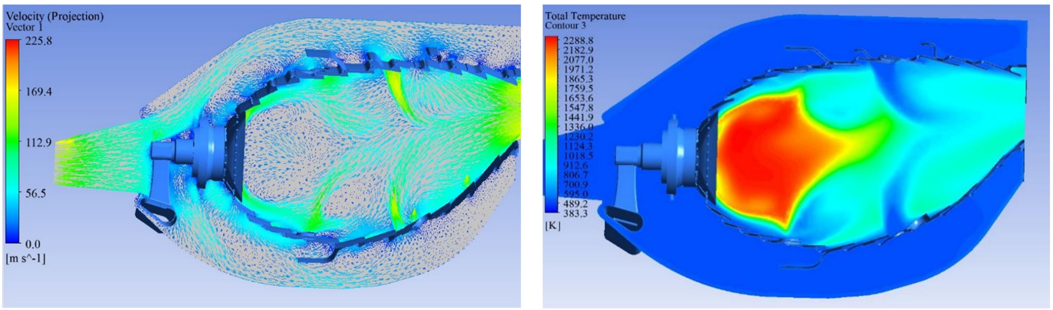


Fig. 6. Comparative evaluation of the diagram of radial unevenness of the temperature field at the outlet from the combustion chamber

The analysis revealed that the maximum discrepancy observed in the area of the A3-B3 plane of the initial section of the flame tube is $\Delta\theta_{av}$ = 0.017 for the mean and $\Delta\theta_{max}$ = 0.035 for the maximum value of the non-uniformity diagram. These findings affirm that the simulation results are both adequate and reliable, since the discrepancy ranges from 6 to 11%. It should also be noted that the simulation results displayed in cross section (Fig. 7) are also deemed satisfactory.



a) b)

Fig. 7. Distribution of velocity vectors and temperature field along the length of flame tube

Analysis of gas flow velocity vectors clearly indicates the creation of a reverse current zone, which, in accordance with theoretical principles, forms a combustion zone and ensures continuous and complete combustion of fuel. Examining the distribution of temperature fields in the section along the axis of the nozzle, it should be noted that there are no breaks in the cooling sheet formed as a result of the organization of cooling during the movement of the flare into the mixing zone. Thus, it can be argued that the numerical simulation of the workflow in the flame tube is performed with satisfactory accuracy.

A key feature of modern hardware and software systems used in numerical simulation is the ability to interpret the results of calculations in three-dimensional formats. This study mapped the distribution of temperature along the aircraft engine flame tube walls (Fig. 8), which made it possible to establish a connection between the nature of the workflow in the main combustion chamber flame tube and the main damage detected during their overhaul.

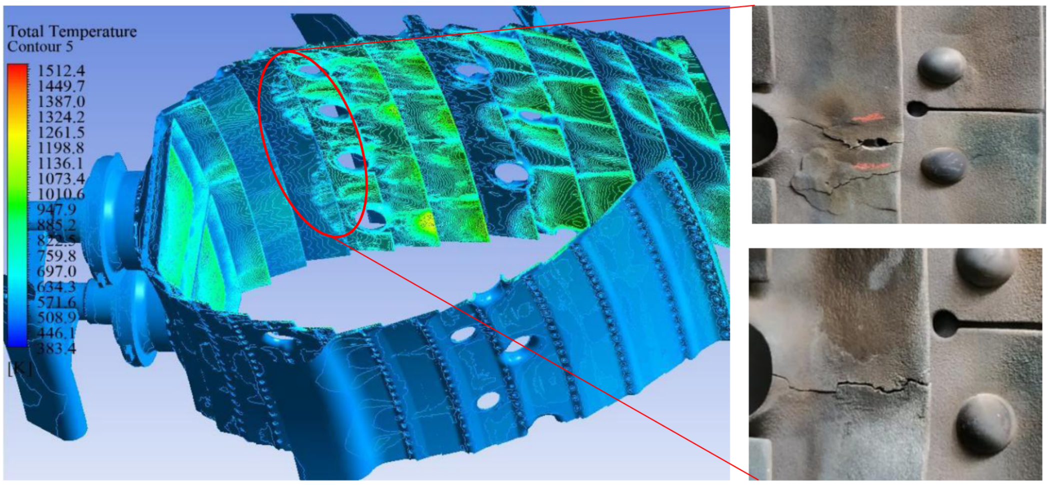


Fig. 8. Temperature distribution and typical flame tube walls damage

The main defects are naturally occurring and predominantly occur around the large holes for secondary air supply. This can be explained in terms of the unevenness of the temperature field, since the flow of air flowing through the main holes into the inner region of the flame tube has great penetrating power. Near the emerging zone of intense combustion at the boundary of two vortex burners, this nature of the workflow leads to local violations of fluid flow conditions and, as a result, reduces the cooling efficiency in specific areas. Thus, the results of numerical simulation of the workflow are crucial for identifying critical sections of the flame tube structure, providing essential information for further study into mechanisms of damage formation and accumulation on the flame tube walls.

The identified locations of maximum temperature values are pivotal for assessing the thermocyclic durability of the material in which fatigue damage is most likely to occur, which in turn is confirmed by the results obtained.

CONCLUSIONS

The results of numerical simulations of the workflow, thermal and stress-strain states of the walls of the main combustion chamber flame tube allow for the following actions:

- identifying critical areas and performing structural optimization;
- making informed decisions regarding the installation or extension of the service life of a gas turbine, based on an assessment of the extent of damage, in cases where the developer and manufacturer do not fulfill their obligations for technical support;
- providing recommendations to aviation repair enterprises for refining the flame tube structure during major maintenance, avoiding costly and time-consuming experiments to determine their limit state.

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