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THE PECULIARITIES OF APPLYING CAD/CAE SYSTEMS FOR THE PRIMARY COMBUSTION CHAMBER FLAME TUBE CYCLE LIFE PROLONGATION OF THE TACTICAL MILITARY AIRCRAFT AFTERBURNING TURBOFAN JET ENGINE

Abstract: *In this article, the computational simulation of the workflow in the primary combustion chamber flame tube of the afterburning turbofan jet engine (ATJE) on the tactical military aircraft was carried out. The geometric model of a flame tube was created and adapted to perform the interrelated calculation of the thermal and stress-strain behaviour of the walls of the flame tube influenced by the operational loads during the computational simulation of the workflow. Quantitative and qualitative analysis of the simulation results was conducted, and the connection between the peculiarities of the workflow and the characteristic damage of the flame tubes, detected during the operation, was established. The possibility of using modern CAD/CAE systems to solve the scientific tasks towards maximizing the cycle life potential of the main and primarily important components of the ATJE on the assessment basis of their damage exhaustion degree was determined.*

Keywords: cycle life, computational simulation, CAD/CAE systems, flame tube, workflow, thermal and stress-strain behaviour

1. Introduction

Global trends in solving the issue of maximizing the use of operational reserves of the ATJE of the tactical military aircrafts are targeted at constant improvement of the means and methods of individual assessment of their technical condition based on the in-depth study as well as considering the loading conditions and the further grounded reasons for the possible increase (prolongation) of the cycle life. Whereas, a certain proportion of damage to the engine components, which in turn determines a certain quantitative measure of their cycle life exhaustion, corresponds to every loading cycle of the engine during the flight or ground testing. The above fact has also been taken into account.

In this regard, the actual scientific task of the research is as follows: the study aimed at establishing the scientific, methodological and organizational conditions to maximize the use of the operational reserves of the ATJE through prolonging their specified cycle life (SCL) and switching to the operation in accordance with their cycle life technical condition.

Pursuant to the Overhaul Manual (OM), the prominent construction feature of the ATJE is the that they are equipped with components that possess lower SCL values than the overall value of the engine cycle life as a whole. Figure 1 shows the structure and dependence of the ATJE SCL on the SCL of its main and cycle life limiting components.

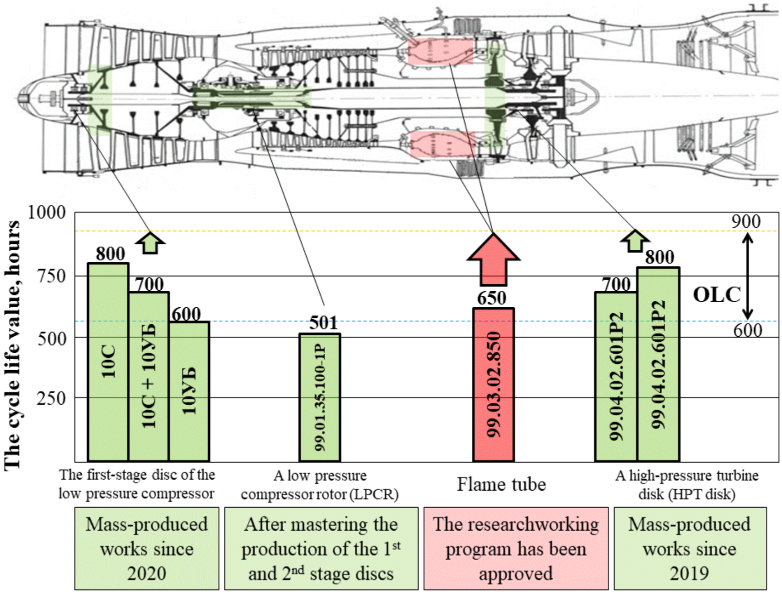


Fig. 1. The scheme of the structure and ratio of the ATJE SCL from the SCL of its main and cycle life limiting components

In accordance with the results of the research and studies carried out in the previous years by the State Research Institute of Aviation (SRIA), State Enterprise Lutsk Repair Plant "Motor" (SE LRP MOTOR) and State Enterprise (SE) "Ivchenko-Progres", the tasks of computational and analytical assessments of the possible prolongation of the SCL of the HPT disk as well as the non-reinforced disc of the 1st-stage of the LPCR have been accomplished; lists of additional procedures which are to be performed on them during the second overhaul, as well as procedures aimed at assessing their remaining cyclic life cycle and the actual technical condition during the extended period, have been developed. Nevertheless, the task of equipping the planned second overhaul of the ATJE with the primary combustion chamber flame tubes (PCC FT) with the appropriate remaining SCL to ensure the exercising of a regular overhaul life still needs to be addressed. In addition, PCC FT without improved cooling demonstrates limitations not only in the value of the SCL of 650 hours, but also in operating cycle life at increased modes (maximum operating mode (M) + afterburner operating mode (A)) depending on the setting of the electronic controller (EC) for the combat (C) or training-combat (TC) modes 72.5 hours, only 13 of which are taken by the M+A for C (Fig. 2).

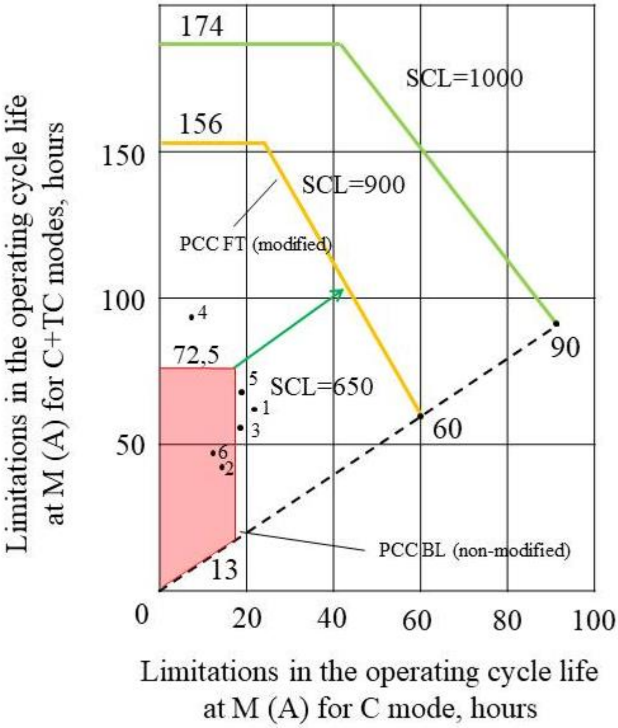


Fig. 2. Ranges of limitations of the ATJE operation life for the M+A for C and C+TC modes and PCC FT without improved cooling and with improved cooling

PCC FT is one of the complex and essential components of aviation gas turbine engine (GTE), the excellence of which influences the main characteristics of the engine, its reliability and cycle life [6]. Schematic diagram of the organization of the workflow and the principal elements of the ATJE PCC is shown in Fig. 3.

The creation of the PCC, which will have to meet the basic requirements and provide the necessary performance characteristics within the framework of a given cycle life is accompanied by a significant amount of experimental research, since the processes within the PCC FT tend to be difficult to calculate theoretically. Therefore, in modern aircraft engine construction at the stages of design, modification, operation and repair, the workflow peculiarities of the PCC processes are studied by using the methods and models of computational gas dynamics [4, 9], namely: the practical implementation of modern automated design systems, which includes not only CAD (computer-aided design), but also CAM (computer-aided manufacturing) and CAE (computer-aided engineering) systems. The computation part of the CAE system packages is based on multiple methods for calculating differential equations, namely the finite element method, the finite volume method, etc. Modern CAE systems are used in collaboration with CAD while integrating into the hybrid CAD/CAE systems [5].

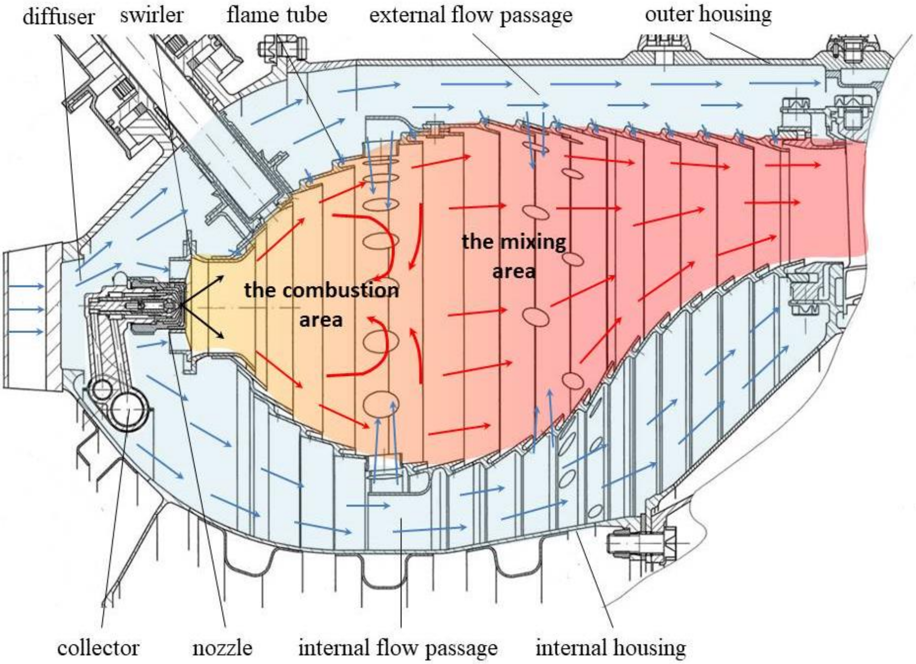


Fig. 3. The scheme of the organization of the workflow and the main design elements of the ATJE PCC

The development of multiple methods for solving the tasks of thermal and stress-strain behaviour (SSB) of complicated structural elements in the domain of aerospace engineering enabled to perform the analysis, with the use of the ANSYS software complex [3], which implements the connection between the study of thermal and stress-strain behaviour and the hydrodynamic calculation in the form of the Fluid-Structure Interaction (FSI) technology. ANSYS CFD is used as a hydrodynamic software package, and ANSYS Mechanical is applied for thermal and stress-strain behaviour calculations. Different schemes of relationships between the corresponding units within the unifying platform of the software package are used depending on the task. Some examples demonstrate their capabilities, including the simulation of the entire range of tasks related to the organization and workflow in the PCC, defining the thermal behaviour of the FT and determining its stress-strain behaviour and thermal resistance on its basis [10, 14].

2. Experimental study

The basic algorithm lies in the basis of the research methods used in modern approaches to the computational simulation of the workflow in PCC, regardless of the variety of special software complexes and their focus. It includes the following steps:

- creating a geometric model of the elements of the PCC design and determining the physical limits of the gas flow;
- constructing the finite element grid with its subsequent adaptation depending on the PCC area type (the area of a solid body, the volume of gas environment, the boundary layer area) and determining the size of the finite elements depending on the complexity of the constructive performance of the computational domain;
- determining the simulation criteria (the continuity equation, the conservation of momentum, the conservation of energy, the condition), setting the limiting conditions (setting parameters of the operating environment) and performing the simulation (calculation of differential equations) using iterations;
- performing visualization and analysis of the results obtained.

Implementing the computational simulation method requires an overall understanding of the nature of the PCC workflow. The complexity of the mathematical simulation of the PCC workflow is due to the need to interpret the interrelated physical and chemical processes within the gas stream. According to study [1], which analyzed the results of the most fundamental research on the physical and chemical aspects associated with the combustion process, the basic principles of organizing the workflow were defined, and the dependence relationship between the workflow peculiarities and the design features of the PCC was established.

The simulation of the PCC FT workflow was carried out at the maximum operating mode of the engine to solve the given task. The scheme of the project is shown in Fig. 4.

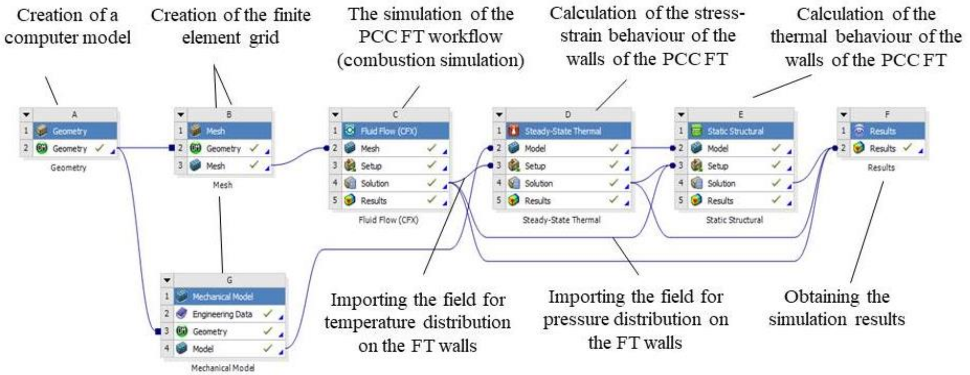
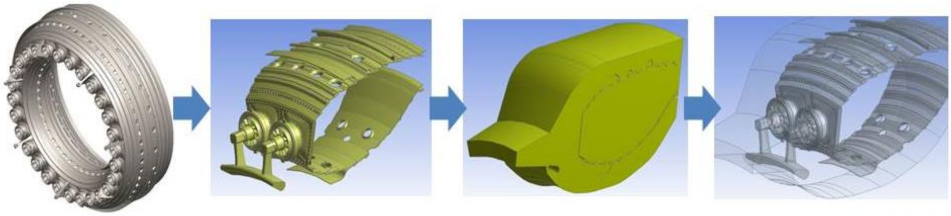


Fig. 4. The schematic project of the computational simulation of the PCC workflow

Computational simulation of the PCC workflow requires creating and combining several geometric models and conducting a one-way simulation of the interconnected calculation (1-way FSI) to determine the thermal and stress-strain behaviour of the walls of the PCC FT. As exhibited in the drawings, a geometric model of the FT and a geometric model of the gas environment, limited by the PCC body, were created. A sector with two nozzles out of 28 ($\angle 12{,}85^\circ$) was chosen to simplify the calculations, provided that the symmetry of the model is ensured. The algorithm for creating the computer model of the PCC FT for simulating the workflow is shown in Fig. 5.



1. The geometric model of a PCC FT

2. A PCC FT sector (includes 2 out of 28 nozzles to provide for the symmetry conditions)

3. The geometric model of the gas environment, which is limited by the PCC body

4. A collaborative model with an interface task aimed at establishing the relationship between the environments

Fig. 5. An algorithm for creating the computer model of the PCC FT for the work simulation

Real data from bench testing of the ATJE was used as input flow gas-dynamic parameters. The PCC workflow occurs under the diffusion combustion in a turbulent flow.

In such a case, during the computational simulation, the flame structure is determined based on the solution for the diffusion equation (1) according to the kinetic mechanism of combustion and the energy transfer equation - the flamelet model (a thin front model applied to flame) of the diffusion combustion by N. Peters (RWTH, Aachen, Germany) [13].

$$\rho\frac{\partial T}{\partial t}=\rho\frac{\chi}{2}\left(\frac{\partial^2 T}{\partial Z^2}+\frac{1}{c_p}\frac{\partial c_p}{\partial Z}\frac{\partial T}{\partial Z}\right)+\frac{1}{c_p}\left(\sum_{k=1}^{N}h_k\dot{m}_k+q'''_R-H\right) \tag{1}$$

where:

t - time;

Z - mixture fraction;

T - temperature;

χ - scalar dissipation rate;

ρ - density;

c_p - specific heat capacity at constant pressure;

$\dot{q}'''_R$ - rate of radiative heat loss per unit volume;

N - number of chemical species;

h_k - enthalpy of species k;

H - accounts for the enthalpy flux by mass diffusion.

The actual use of kerosene with its real characteristics in the computational simulation significantly complicates the calculation while considering the variability of the component composition of fuel, which depends on the raw material and a large number of hydrocarbon components. Therefore, an assumption was made for the calculation and experimental study of the combustion process to use the so-called "substitute" of kerosene as a fuel model. In order to generate the combustion library, the CFX-RIF tool [2] was used, which includes the scheme of the combustion kinetic reaction of the "substitute" for the Jet A aviation kerosene (surrogate) as a two-component fuel with mass fractions of (60% n-C10H22 and 40% TMB-C9H12 respectively).

Fuel and air are to be found in different thermodynamic states, which makes it essential to describe the conditions of mixing the liquid fuel and air, and to build a phase transition model. For this purpose, a homogeneous binary blend was created to determine the relationship between the saturated vapour pressure at a specific temperature and is described by the Antoine equation (2).

$$\log_{10}(p)=A-\frac{B}{C+T} \tag{2}$$

where:

A, B, C are the experimentally obtained constants.

The computational simulation of the turbulence of the PCC workflow [7, 8, 12, 15] involves the use of the Reynolds equation (3) (RANS (Reynolds-averaged Navier-Stokes), which was developed based on the averaged Navier-Stokes equation (the equation of motion for a viscous fluid) according to Reynolds, to be the principal approach.

$$\rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \rho \overline{f_i} + \frac{\partial}{\partial x_j}\left[-\bar{p}\delta_{ij} + \mu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \rho\overline{u_i' u_j'}\right] \tag{3}$$

where:

$\rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j}$ - change in the amount of movement of the working unit volume due to a change in the averaged speed component;

$\rho \overline{f_i}$ - averaged value of the external forces;

$-\bar{p}\delta_{ij}$ - averaged value of the pressure;

$\mu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$ - viscosity forces;

$-\rho\overline{u_i' u_j'}$ - Reynolds stresses (turbulent stresses), which involve the losses and redistribution of energy within a turbulent flow.

Currently, the two-equation turbulence models were developed and widely used based on the RANS approach since they make a compromise between the numerical accuracy of calculations and the computing capacity. Shear Stress Transport (SST) (4) was chosen as the turbulence model since it involves the transfer of the turbulent stress and enables a more accurate prediction for the flow split value at high-pressure gradients;

$$\begin{gathered}
\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \beta'\rho k\omega + P_{kb} \\
\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j \omega) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + \alpha\frac{\omega}{k}P_k - \beta\rho\omega^2 + P_{\omega b}
\end{gathered} \tag{4}$$

Under the operating conditions of the PCC, the walls of the FT are heated due to the radiation in the combustion area and convection from the gas flow. The part of the heat from the radiation flow constitutes the predominant component since the heat transfer in the areas, which are protected by a curtain of cooling air, occurs exclusively through radiation. The P1 model, equation (5), was chosen as a radiation model, which is a simple case of the P-N model (spherical harmonics method) where the spectral intensity of radiation is represented by a series of spherical functions [11]. In the first approximation of this method, the P1 model is the common version of the approximation of the diffusion equation;

$$q_r = -\frac{1}{3(\alpha + \sigma_s) - C\sigma_s}\nabla G \tag{5}$$

where:

q_r - radiation flux value;

α - absorption coefficient;

σ_s - dissipation coefficient;

∇G - incident radiation value;

C - coefficient of the linear anisotropic phase function.

The fields of temperature and pressure distribution on the walls of the PCC FT were obtained (Fig. 6) during the computational simulation of the workflow.

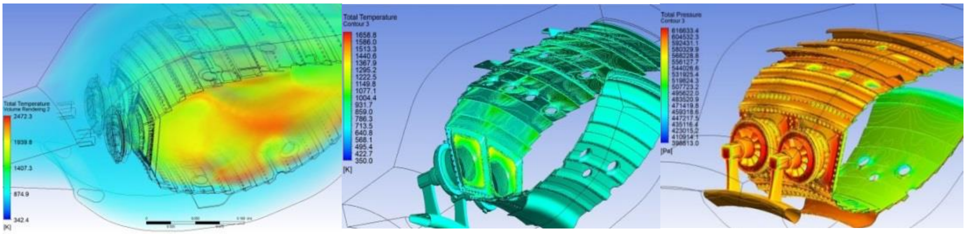
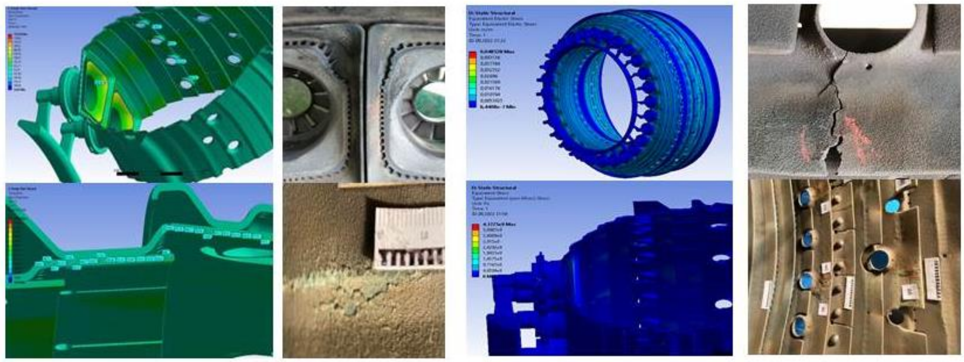


Fig. 6. The temperature and pressure distribution on the walls of the PCC FT

Importing the results makes it possible to perform a calculation-experimental study of the thermal (Fig. 7a) and stress-strain behaviour of the walls of the PCC FT of the ATJE, taking into consideration the real influence of the maintenance factors and identifying a connection between the nature of the workflow and the detected damages and defects of the PCC FT (Fig. 7b).



a b

Fig. 7. The results of the PCC FT simulation: a shows the thermal behaviour; b – the SSB

3. Summary

The obtained results of the numerical calculations for the workflow, thermal behaviour and SSB of the walls of the PCC FT make it possible:

- to identify the critical sections and perform the design optimization;
- to make a reasoned decision regarding the setting or prolongation of the FT cycle life based on the assessment of the degree of damage exhaustion under the conditions when the designer and manufacturer neglect their obligations regarding design supervision;

- to provide the aircraft repair enterprises with recommendations regarding the modification of the FT structure during the overhaul, thus avoiding the expensive and long-term experiments aimed at determining their limiting condition.

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