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ASSESSMENT OF THE AUTHENTICITY OF A SEMIEMPIRICAL TURBULENT COMBUSTION METHOD IN AFTERBURNER OF A GAS TURBINE ENGINE

Об'єктом дослідження є робочий процес у форс жній к мері згоряння турборе ктивного двоконтурного двигун зі змішув нням потоків. Дослідження були спрямов ні н розробку комплексної методики розр хунку форс жно-вихідного пристрою форсов ного турборе ктивного двоконтурного двигун з ур хув нням нерівномірності коефіцієнт н длишку кисню т турбулентності потоку.

Для розр хунку процесу сумішоутворення використовув л сь модель роздільної течії г зової т рідкої ф з з ур хув нням впливу кінцевих швидкостей переносу між ф з ми. Для розр хунку г зової ф зи використовув вся чисельний метод, з снов ний н використ нні ейлерово-л гр нжевого підходу, який дозволяє розр хув ти тривимірну стиснену нест ціон рну течію у форс жно-вихідному пристрої. Потік г зу т повітря описується рівняннями Н в'є-Стокс , розподілених з Рейнольдсом, і одноп р метричною моделлю турбулентної в'язкості. Диференці льні рівняння рідкої ф зи вирішув лися методом Рунге-Кутт . Облік турбулентного горіння викон но з допомогою н півемпіричної теорії.

Основним пок зником робочого процесу у форс жній к мері згоряння є коефіцієнт повноти згоряння, від якого з лежить тяг двигун н форсов ному режимі роботи. Для оцінки ефективності горіння розр ховуються поля швидкостей, темпер тури, тиску, м сової ч стки кисню, п рів п лив т пульс ційної швидкості. Ці величини визн ч ються шляхом чисельного моделюв ння двоф зного потоку. В роботі використовується модель роздільної течії г зової т рідкої ф з з ур хув нням впливу кінцевих швидкостей переносу між ф з ми. М ючи д ні чисельного розр хунку т н півемпіричну модель визн чен повнот згоряння п лив в з лежності від коефіцієнт н длишку повітря т довжини зони горіння. Використ н в д ній роботі методик дозволяє розр хув ти повноту згоряння п лив в форс жній к мері згоряння, результ ти розр хунків збіг ються з експеримент льними д ними з похибкою не більше 7 %. З зн ченнями повноти згоряння визн ч ється тяг сопл н форсов ному режимі роботи двигун .

Ключові слова: *г зодин мічні розр хунки, ві ційні двигуни, турборе ктивні двоконтурні двигуни, форс жно-вихідний пристрій, робочий процес.*

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1. Introduction

The main direction of development of modern gas turbine engines is to increase the parameters of the working process in the design operating modes. The urgent task is to increase the efficiency of the working process of engine elements, in particular, afterburner combustion chamber (ACC). This task requires complex gas-dynamic calculations and experimental studies [1, 2]. At aviation enterprises of Ukraine, much attention is paid to the issue of further improving the efficiency of existing aviation gas turbine engines by creating more economical and reliable modifications, as well as mastering the production of promising aircraft engines [3]. As it is known, aircraft engines have a wide variety of schemes. But at the present stage, the most developed turbojet engines (TE), which are divided into two groups: with mixing and without mixing flows. Forced turbofan engines (TEF) have advantages over unforged ones in an extended range of applications in terms of altitude and flight speed. In connection with the tendency to reduce the TEF axial dimensions, the boundaries between the mixing chamber, afterburner and the output device become conditional, since the processes characteristic of these elements proceed until the gas escapes from the nozzle. Therefore, it is advisable to consider these elements together, and call their combination the afterburner-output device (AOD). The main directions of development of modern gas turbine engines remain increasing the efficiency of the working process in the design operating modes, as well as reducing the mass of the main engine elements [1]. In connection with the rapid increase in the parameters of gas turbine engines in recent years, the energy saturation of the working fluid has sharply increased, which has led to a decrease in the geometric dimensions of the engine flow section and, in particular, afterburners. But reducing the length of the ACC leads to a decrease in the completeness of combustion. Therefore, the organization of the workflow in the ACC is an urgent task.

Thus, *the object of research* is the working process of the afterburner of the TE combustion chamber with flow mixing. And *the aim of research* is development of a comprehensive methodology for calculating the TEF AOD taking into account the unevenness of the coefficient of oxygen excess and turbulence of the flow.

2. Methods of research

Empirical methods are currently the main ones in the AOD development. AOD development of the optimal form requires long and expensive experiments [3]. The presence of unevenness in speed, pressure, temperature, kinetic energy of turbulence has a significant effect on the flow and mixing of gas flows. And the uneven distribution of oxygen and fuel has a significant effect on the formation of the air-fuel mixture. In order to organize the AOD optimal workflow, additional information is required on the distribution of all these parameters in the afterburner. To develop effective AODs, it is necessary to consider the characteristics of the spatial flow by calculating a complex three-dimensional picture of the flow and mixture formation. In this regard, numerical methods for calculating the spatial flow in the TEF AOD with mixing flows are of particular importance [4, 5].

Engine AOD is an axisymmetric channel with vertically arranged petals of the flame stabilizer, a cylindrical mixing chamber, turbine coke and nozzle [3]. The longitudinal section of the calculated area of the AOD is shown in Fig. 1, *a*, the cross section is in Fig. 1, *b*.

To assess the effectiveness of the workflow, an efficiency indicator is proposed – a relative increase in traction during forcing. It allows to summarize two private indicators of the efficiency of the workflow: the completeness of combustion and the recovery coefficient of the total pressure. To determine it, it is necessary to have a comprehensive methodology for calculating nozzle thrust [6].

A comprehensive methodology for calculating the nozzle thrust of turbojet engines is based on the use of the semi-empirical theory of turbulent combustion and the numerical calculation of three-dimensional fields of two-phase flow parameters that determine the turbulent combustion process. The non-uniformity of the flow parameters is taken into account by breaking the flow into several streams, in each of which the distribution of parameters is considered uniform.

To evaluate the combustion efficiency, it is necessary to have fields of velocity, temperature, pressure, mass fraction of oxygen, fuel vapor and pulsation velocity. These values can be determined by numerical simulation of a two-phase flow. In the work, a model of the separate flow of the gas and liquid phases is used taking into account the influence of finite transfer rates between the phases [7].

First, the gas phase flow is calculated using a numerical method, which is based on the use of the Eulerian-Lagrangian approach and allows one to calculate a three-dimensional compressible flow described by the Navier-Stokes equations averaged by Reynolds. As a result of the calculation of the equations of the gas phase, the fields of velocity, temperature, pressure, and kinetic energy of the turbulence of the gas stream are found.

Based on the results of a numerical calculation of the gas phase, droplet trajectories are calculated, as well as the change in their size and temperature along the trajectory using the Runge-Kutta method. It is believed that fuel is injected into the AOD in the form of spherical droplets, the size distribution of which obeys the Rosin-Rammler law. Source terms are calculated that take into account the contribution of evaporating droplets to changes in the concentration of fuel vapor. Given this contribution, the calculation of the vapor concentration field is performed. After a numerical calculation of the gas phase, taking into account the influence of fuel vapors, oxygen transfer is calculated.

As a result, the fields of oxygen concentration and fuel vapor are found and the coefficient of excess oxygen is determined. The presence of flow parameter fields allows to take into account their influence on the turbulent combustion process. To do this, the computational domain is divided into trickles, in each of which the parameters of the turbulent flow and the coefficient of excess oxygen are considered constant, but change during the transition from flow to flow. Under the accepted assumptions, a semi-empirical theory of turbulent combustion, which is developed for homogeneous air-fuel mixtures, can be applied for each trickle.

Due to the great difficulties of modeling the turbulent combustion process [8–10] and the difficulty of solving this problem by the numerical method at present, it is advisable to calculate the combustion efficiency by the semi-empirical method. To take into account the influence of the non-uniformity of the flow parameters and the air-fuel mixture, the computational domain is

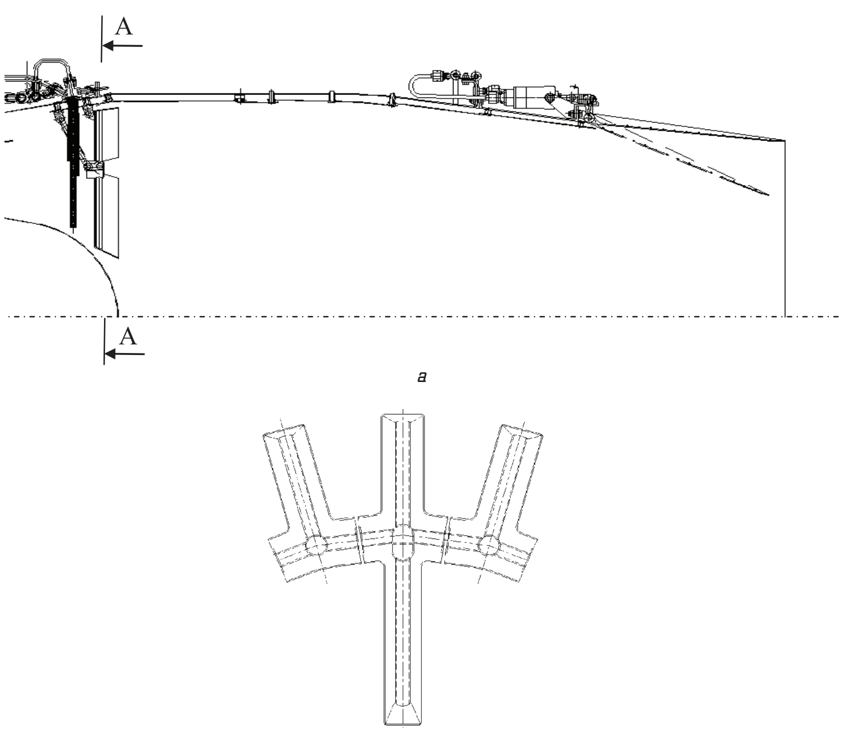


Fig. 1. The calculated area of the afterburner: *a* – longitudinal section; *b* – cross section

divided into trickles, where a uniform distribution of all parameters across the flow within each trickle is taken.

The input data are the results of a numerical calculation of a two-phase flow – the coefficient of excess oxygen and the pulsation component of the flow velocity. The presence of the flow parameter fields allows one to determine the effect of the oxygen excess coefficient on the turbulent combustion process. Under the assumptions made, for each trickle, the semi-empirical theory of turbulent combustion can be applied, which is developed for homogeneous air-fuel mixtures [11, 12].

According to this theory, there is a universal dependence of the coefficient of completeness of combustion [12–14]:

$$\eta_c = f\left(\frac{x}{L_z}\right),$$

which is approximated as a polynomial [15]:

$$\eta_c = 0.588\bar{x} - 1.948\bar{x}^2 + 8.125\bar{x}^3 + 28.386\bar{x}^4 + \\ + 110.435\bar{x}^5 + 116.189\bar{x}^6 - 39.986\bar{x}^7,$$

where $\bar{x} = x/L_z$; x – coordinate, which is measured from the front border of the flame front; L_z – length of the combustion zone.

The length of the combustion zone is determined [7]:

$$L_{cz} = B\frac{l}{\varepsilon_0}\ln\left(1+\frac{u'}{u_n}\right),$$

where $B = 1...4$ – experimental coefficient, which depends on the coefficient of excess oxygen and the degree of gas heating during complete combustion of fuel:

$$B = f\left(\chi, \frac{T_c^*}{T_f^*}\right);$$

ε_0 – free flow turbulence intensity:

$$\varepsilon_0 = \frac{u'}{u};$$

u' – ripple speed; u_n – normal flame propagation speed:

$$u_n = 0.06\left(\frac{T}{100}\right)^{2.24}\left(0.5 - \frac{m_n}{mO_2}\right).$$

Knowing the position of the combustion zone and the coordinate of the outlet boundary x_{AOD}, using the universal dependence, one can determine the completeness of combustion in a flow. Obviously, for each flow the ratio of sizes (x_i/L_{z_i}) is different. To determine x_i, it is necessary to know the coordinate x of the front boundary of the flame front and the coordinate of the AOD exit section x_{AOD}.

The front boundary of the flame front is determined by the angle of its inclination, which is calculated by the formula [12, 13, 16] (Fig. 2):

$$\sin\alpha = \frac{u_f}{\vec{u}}.$$

The turbulent flame propagation velocity is determined by the formula [13, 16]:

$$u_f = 2.5(u')^{0.9}(u_n)^{0.1}.$$

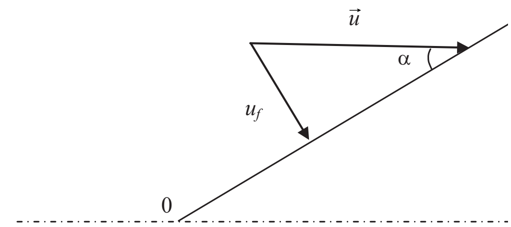


Fig. 2. Determination of the angle of inclination of the flame front

After determining η_{c_i} for each flow, the amount of heat supplied and the gas parameters p_c, T_c, c_c at the outlet of the afterburner-output device are calculated according to known one-dimensional methods [1, 2].

3. Research results and discussion

3.1. The reliability assessment of the calculation of the turbulent flame propagation velocity. In [12, 17], the effect of flame stabilizers on the main combustion characteristics is experimentally investigated. Fig. 3 presents a comparison of the experimental data [12] with the results of calculating the flame propagation velocity, where a stabilizer with an opening height of 30 mm with an opening angle of 60° is used.

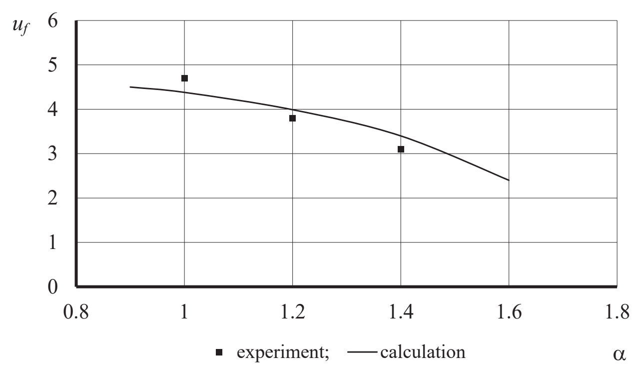


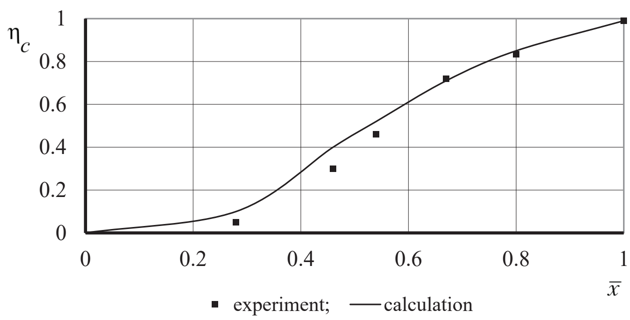
Fig. 3. Flame propagation velocity

The calculation is carried out at a constant initial temperature T=473 K, flow velocity u=50 m/s and for various values of the coefficient of excess air. Analysis of the calculation results shows that the standard deviation of the calculated data from the experimental data is about 10 %. This result can be considered satisfactory, since the angle of inclination of the flame surface changes by less than 0.5°.

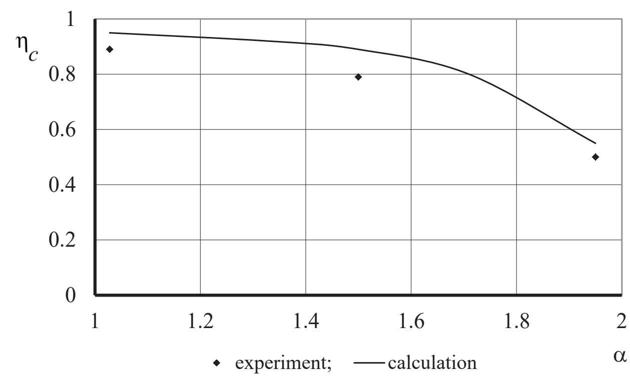
3.2. The reliability assessment of the calculation of the coefficient of completeness of combustion of fuel. Since the coefficient of completeness of combustion is one of the main indicators of the efficiency of the working process in the AOD, the calculated data are compared with experimental [13, 15] in a different range of the mixture composition and along the length of the combustion zone (Fig. 4).

Good agreement between the calculated and experimental data is obtained when evaluating fuel burn-out along the length of the combustion zone. The calculation is performed at: flow velocity u=90 m/s, T=300 K, stabilizer height=35 mm, air excess coefficient=1.2.

A comparison of the results shows that the maximum deviation of the calculated data from the experimental data is no more than 7 %.



a



b

Fig. 4. Comparison of calculated and experimental data on the completeness of fuel combustion, depending on: *a* – length of the combustion zone; *b* – coefficient of excess air

Fig. 4, *b* shows a comparison of calculated and experimental data on the completeness of fuel combustion, depending on the coefficient of excess air when using the universal burn-out curve. The calculation is performed at: flow velocity 63 m/s, T=573 K, stabilizer height=40 mm, turbulence intensity=5 %. The calculation results differ from the experimental data by no more than 8 %.

4. Conclusions

Based on theoretical studies, the results of evaluating the reliability of an integrated method for calculating the efficiency of a workflow in the TEF AOD for a semi-empirical method for calculating turbulent combustion are presented. It is proved that for the calculation of afterburner-output devices, it is possible to use a comprehensive methodology for calculating the efficiency of the TEF workflow. The two-phase flow is calculated numerically, and the combustion process in the AOD is semi-empirical. The reliability of the calculation of the turbulent flame propagation velocity and the coefficient of completeness of combustion of the fuel is estimated. The results of calculations of the turbulent flame propagation velocity are compared with experimental data. An analysis of the results shows that the standard deviation of the calculated data from the experimental data amounted to 10 %. The results of calculations of the coefficient of completeness of fuel combustion are also compared with experimental data. An analysis of the results shows that the maximum deviation of the calculated data from the experimental data is no more than 7 %.

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