Some Calculated Research Results of the Working Process Parameters of the Low Thrust Rocket Engine Operating on Gaseous Oxygen-Hydrogen Fuel

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Abstract. The paper presents the calculating results of the combustion products parameters in the tract of the low thrust rocket engine with thrust $P \approx 100$ N. The article contains the following data: streamlines, distribution of total temperature parameter in the longitudinal section of the engine chamber, static temperature distribution in the cross section of the engine chamber, velocity distribution of the combustion products in the outlet section of the engine nozzle, static temperature near the inner wall of the engine. The presented parameters allow to estimate the efficiency of the mixture formation processes, flow of combustion products in the engine chamber and to estimate the thermal state of the structure.

1. Introduction

The gas-dynamic parameters distribution in engine tracts is relevant for any low thrust rocket engines. The parameters determine the perfection of working processes in the combustion chamber and nozzle, which affect the thermal state of the structure and form the main (energy) parameters of rocket engines.

Until recently, most of the problems in the engines development were solved, mainly, by the experimental method, which was accompanied by the need to simulate operating conditions, high labor costs of manufacturing prototypes, experimental stands, fuel storage facilities, and thus the high cost of the experimental infrastructure. Engine development by this technology lasts a considerable period of time (up to 7 ... 10 years). The information received has clear limitations: the research is not carried out in the entire area of the change in the determining parameters. As a result, usually, only integral characteristics are determined, and at the last stage the thermal state of the structure is determined.

At present, numerical methods of investigation are becoming increasingly important for solving a number of problems for creating engines. It helps to reduce the development time, improve design quality and reduce the volume of experimental development.

Mathematical modeling is related to the object under study through the calculation domain, the initial and boundary conditions, but it is subject to the influence of specific factors that are absent in physical modeling, such as the replacement of a continuous domain by discrete one, replacement of differential equations describing physical processes by a system of algebraic equations, the using a number of limitations and assumptions.

Experimental methods are still indispensable at all stages of engine development: acceptance and approbation of technical solutions, assessment of the compliance of product parameters with the technical task requirements, engine development.
A promising direction is the integration of the results obtained in mathematical modeling to the computer design of low thrust rocket engines and further into the PLM system of the propulsion system and the spacecraft.

2. Calculations and result analyses
The computer environment ANSYS CFX is used to study the stationary spatial turbulent multicomponent chemically reacting flow of the working fluid in the sub-, trans- and supersonic regions.

Calculated studies of the low-thrust rocket engine working process (with thrust $P \sim 100$ N) were carried out using a mathematical model based on a software package [1], including the basic equations of conservation of mass, momentum, energy, concentration of fuel components in the form of Navier-Stokes. To simulate turbulence, a model based on Reynolds stresses (RSM) [2] was used, modernized for the "wall law" for the flow structure and heat-mass transfer in the near-wall region.

A diffusion combustion model (EDM) [3] with a simple chemical reaction has been chosen, since the mixing rate of fuel components is a limiting and not the rate of kinetic processes.

Effective Prandtl and Schmidt numbers are assumed to be equal «1».

Heat transfer on the wall of the engine chamber corresponds to the conditions of impermeability, the walls themselves are non-reactive and adiabatic.

The paper studies the following: the structure of the flow, the parameters of the low-thrust rocket engine working process, determining its efficiency and reliability, the main (energy) characteristics of the engine, and the thermal state of the engine structure.

Proceeding from this, it is reasonable to consider in the gas-dynamic distribution path of the engine (combustion chamber) the following three parameters: firstly, the total temperature of the combustion products as the main energy parameter, secondly, the axial velocity of the combustion products in the outlet section of the engine nozzle as a parameter that determines the specific impulse of the engine and, thirdly, the temperature of the combustion products in the engine region wall that determines the thermal state of the structure.

The realization of the described technology will be illustrated by the data obtained in the calculation of the low-thrust rocket engine (with thrust of 100 N) on gaseous oxygen-hydrogen fuel.

In order to ignite the fuel mixture in the combustion chamber of the rocket engine, an efficient, reliable and reliable electric spark ignition system was selected.

For the organization of the working process, one of the effective ways of mixing gaseous oxygen and hydrogen in the combustion chamber of the engine was selected, which based on the interaction of co-axial coaxial twisted gas flows of fuel components organized in several cascades [4].

The cooling of the engine chamber walls was solved with the help of gas curtains, the main parameters and design of which were selected using materials [5].

It is convenient to present the calculated results in the form of the parameters distribution patterns characterizing the quality of the working process in the longitudinal section of the engine chamber flowing part and in the characteristic cross sections, and in the distribution diagrams of the determining quantities.

Figure 1 shows the combustion products flow structure in the form of the streamlines distribution along the engine chamber flowing part.

The supply of gaseous oxygen and hydrogen is mainly carried out through tangential channels and effective mixing of the components takes place in the pre-chamber and the combustion chamber, as can be seen from the characteristic curvature of the flow lines. As the flow develops the flow lines of the combustion products become more ordered. The mechanism of turbulent mixing of gaseous oxygen and hydrogen flows is manifested in the area of the prechamber and the combustion chamber. It is characteristic for developed swirling currents; therefore, its use is an additional factor of influence on the completeness of the fuel combustion in the chamber without reducing the nozzle efficiency [6].
The total temperature distribution of the combustion products in the rocket engine chamber tract is an important factor of the working process efficiency evaluation in the low thrust rocket engine. The results are shown in figure 2.

It should be noted the presence of extended zones of high temperature in the pre-chamber and the combustion chamber, starting from the section of supplying the main fuel components. The figure shows the presence of specially organized wall zones with a reduced temperature of the combustion products along the engine chamber, which are generally lower than the permissible wall temperature; an admissible wall temperature is $T_{\text{wall available}} \leq 2000$ K.

It can be seen that the intracameric processes are quite full, but the reserves for improving the mixing pattern are obvious. In support of what has been said, figure 3 shows the total temperature distribution of the combustion products in the final section of the combustion chamber.
From the of the energy parameters formation viewpoint of the low thrust rocket engine the numerical values and shape of the braking temperature diagram are interesting as a result of the processes of mixture formation and fuel conversion during combustion of fuel components. The requirement for the total temperature distribution is that in the central region of the chamber the temperature values should be approximated to the maximum for the accepted components mass ratio, and in the rocket engine wall area the temperature values do not exceed the wall temperature permissible for the selected structural material. Proceeding from this, the profile of the total temperature should ideally have a parabolic shape, facing its convex part in the direction of the combustion products flow.

The obtained combustion products total temperature distribution in the final section of the combustion chamber requires correction at least in part of the fuel redistribution between the stages of the mixture formation scheme.

The maximum specific thrust impulse in the rocket engine depends on the size and shape (completeness) of the axial velocity component distribution of the combustion products in the exit section of the nozzle. In this sense, the deformation of the velocity distribution from the minimum section of the nozzle to its cut is important. In the outlet section of the nozzle, the axial velocity component should tend to its maximum corresponding to the accepted degree of expansion of the combustion products in the nozzle.

Omitting the analysis of the reasons for the change in the total velocity and its components in the supersonic nozzle, let us consider the outlet section of the nozzle (Figure 4), where the diagrams of the flow velocity of the combustion products are presented. The axial velocity component of the combustion products has a characteristic distribution that directly affects the engine specific impulse formation. In the central region of the nozzle cross section, the oxygen-hydrogen fuel combustion products velocity reaches values $U \sim 4300$ m/s. In the region of the wall of the nozzle, a substantial decrease of the velocity is observed.

In general, the obtained velocity diagram meets the requirements for the desired distribution in the cross-section at the exit from the RDMT nozzle with a geometric expansion ratio $F_{\text{nozzle}} = 250$.

The most important indicator of the low thrust rocket engine is the thermal state of the structure. At the calculation stage, this is largely facilitated by the temperature (total temperature) localization of the combustion products in the engine chamber wall region. These results it is convenient to present on the wireframe engine model. Figure 5 shows the combustion products temperature distribution in the area of the rocket engine wall as the basis for evaluating the low thrust engine thermal state with a single-layer chamber wall construction.
Figure 4. The total (axial) velocity distribution of the combustion products in the engine output section

Figure 5. The combustion products temperature distribution in the engine chamber wall region

Comparing the values of the combustion products temperature with the permissible wall temperature of the selected structural material, it is necessary to find a compromise solution: either to replace the construction material (with higher values of $T_{\text{wall \ available}}$) or to provide a lower temperature near the wall of the engine chamber, introducing changes in the mixture mixing scheme.

The obtained calculation information allows not only to determine the parameters and characteristics of the object under study, but also to outline ways to improve the working process and engine design.

High potential opportunities for the organization of an effective work process were laid down in the adopted scheme of RDMT on the basis of coaxial, swirling gas streams of rocket fuel components providing sufficiently high values of turbulence energy both local and integral. For the engine under
investigation, the values of the specific thrust pulse at the level $I_{\text{specific \, vacuum}} \sim 4200 \, \text{m/s}$ ($\phi_{\text{spec. \, impulse}} \sim 0, 85$) were obtained by calculation.

The methods for the engine improving are based on providing a more uniform and energy-consuming the total temperature distribution in the combustion chamber output section due to the working process intensification proper in the engine combustion chamber, and by increasing the prechamber flow rate and by using traditional methods of increasing the combustion chamber relative length. The thermal state problems of the engine structure should be solved by optimizing the gas curtains parameters.

3. Conclusion
The work shows that using a high-level mathematical model, taking into account real processes in low-thrust rocket engines, makes possible to determine a parameters set that allow to determine the low thrust rocket engine work process efficiency, to evaluate the integral parameters and the engine characteristics, depending on the determining factors. Analysis of calculated information makes it possible to outline ways to improve the engine working process both in the direction of improving the mixture formation quality and in the direction of ensuring the engine structure thermal state by bringing the combustion products temperature at the wall layers in line with the structural materials permissible temperature. It should be noted that the problem of the low thrust rocket engine design shape by models similar to that used in this work is solved by choosing the investigated variants by the efficiency criteria of the working process and by ensuring the engine structure thermal state.

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