DESIGN OF ROCKET ENGINE FOR SPACECRAFT USING CFD-MODELING

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Due to the constant tightening of the international requirements for ecology and safety of space rocketry the creation of rocket engines using ecologically fuels, such as oxygen and hydrogen, is actual.

Creation rocket engine (RE) with small thrust for system of orientation and starting of spacecraft is associated with a large amount of development tests. Use of modern Computational Fluid Dynamic (CFD) modeling of engine workflows will reduce the amount of development tests.

This paper describes designing process of rocket engine with thrust 25 N for system of orientation and starting of spacecraft instead of prototype with defect of burnout chamber which was not fixed during of development tests. The new version of the engine was designed with the reduced pressure in the chamber in comparison with prototype that according to experts provide absence of burnout. However, additional research into the cause of burnout chamber with CFD-modeling of workflows were performed to completely exclude this possibility.

At the first stage CFD-modeling of workflows in the mixing head of RE, mixing the fuel components, combustion and supersonic flow through the chamber was performed in the program ANSYS CFX. There are input data for modeling:

- chemical kinetics - the set of combustion reactions, consist of 24 reactions [1, 2, 3] with the corresponding rate coefficient [4, 5];
- properties of chemical compounds and elements which make up the intermediate results of elementary reactions in mechanism of the oxygen-hydrogen combustion: H, H_2, O, O_2, OH, H_2O, HO_2, H_2O_2 were taken from the library of ANSYS CFX.

The geometric model of the internal tract of engine was designed in SolidWorks. The full-circle grid model of engine was performed with ANSYS Meshing. Grid model consists of 6 million hexagonal cells additionally shredded in critical section and atomizers with *Element Quality* not less than 0,34 and *Skewness* less than 0,69, which satisfies the requirements of most CFD-solvers [6].

The boundary conditions were taken from the experiment, which detects burnout camera of prototype.

The simulation was performed in stationary type using the k-ω turbulence model [7]. Chamber wall of engine was simulated as non-reactive and adiabatic. Diffusion combustion model was selected Eddy Dissipation Model (EDM) limited mixing speed of the components of fuel. Ignition was simulated by high temperature at the precombustion chamber wall (3000 K).

Convergence of the solution was estimated by mathematical residuals that needs to be minimal, and the integral parameters of the rocket engine that needs to be constant for fully convereged solution, namely:

- mass flow (Fig. 1);
- specific impulse in vacuum and the axial velocity at the nozzle;
- average temperature in the critical section;
- engine thrust in vacuum.

Adequacy of CFD-model was also tested by the mass fraction of the main reaction product. The resulting mass fraction of water vapor in the critical section differs from the ideal of less than 0,9% and at the nozzle – less than 0,3%.

Comparison results of CFD-model with experimental data shows that the specific impulse in vacuum corresponds to an ideal with an accuracy of 1.5%. This relatively high error is apparently associated with a large inequality in the combustion chamber, which was not considered the ideal impulse. This inequality is the main reason of burnout in the experimental engine. Fig. 2 shows an area of increased wall temperature in combustion chamber visualized by CFD-model. Shape, size and positions of burnout corresponds with the place of burnout in the experimental prototypes.

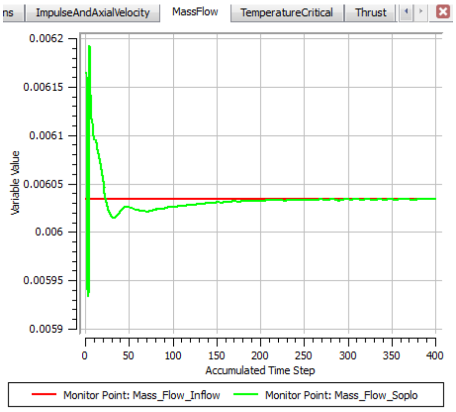

Fig. 1 – Convergence of the solution by mass flow

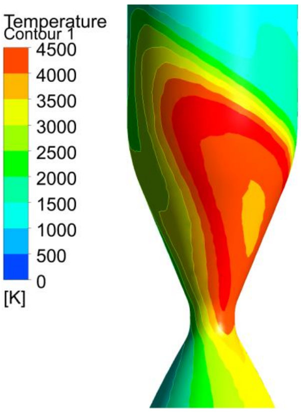

Fig. 2 – Temperature distribution on the inner surface of chamber

Thus, the created CFD-model adequately reflects the processes occurring in the gas-dynamic channel of rocket engine. It should be noted that CFD-model does not take into account losses of incomplete combustion that overstates the value of the temperature of the combustion products in comparison with experiment. It goes to the reserve of heat resistance when assessing the performance. This CFD-model was subsequently used for research different variants of the projected geometry engine.

As an experiment, and then the CFD-calculation show burnout camera of prototype, the new engine with low pressure in the chamber in accordance with the technical specifications (Table 1) was designed by conventional methods [8, 9, 10, 11, 12]. To avoid at the future possible problems with burnout due to inequality in flow chamber, CFD-research of this engine using the above adequate model has been performed.

Table 1 – Basic input data for design project of new engine

Propellants	Gaseous oxygen and hydrogen
Engine thrust in vacuum, P_V	25 N ± 0,7 N
Specific impulse in vacuum, $I_{S.V}$	4470 m/s ± 20 m/s
The pressure in the combustion chamber, p_K	0,5 MPa
The mass ratio of the components, K_m	4,9
The intensity of turbulence of fuel at the inlet of the mixing head	10%
Pressure at the nozzle, p_a	283 Pa

Fig. 3 shows that the fuel components are fully reacted after 1/3 of length of the cylindrical part of the combustion chamber and further wall temperature is above 3500 K, which undoubtedly lead to burnout. CFD-modeling of more than 50 variants of the camera with various activities to address the high temperature near the walls was conducted for create workable variant of the geometry engine. Activities include the following:

1. Change the axial length of the cylindrical part and shape subcritical part of nozzle.
2. Protection of the wall layer of fuel from premature blur.
3. Reducing uneven flow in the chamber.
4. Changing the mixing scheme.

In the numerical experiment, it was founded that reducing the axial length of the chamber does not exclude high temperature in subcritical part of the nozzle. Changing the entering angle at critical section from 60 ° to 90 ° reduces the temperature at walls of subcritical part of nozzle by 200 K.

In order to protect the walls layer coaxial swirling jets of hydrogen from premature blur the screen was used (Fig. 4, Pos. 1), which coped with its task, but only for a camera with a long cylindrical portion. In normal length of the chamber there was a great unevenness, which is a continuation after the prechamber ignition.

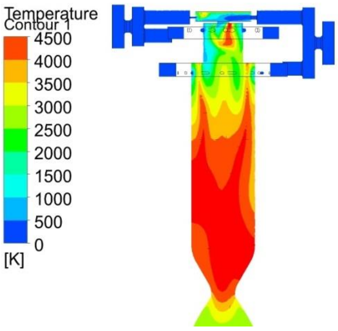

Fig. 3 – Temperature distribution at the longitudinal section of engine base variant

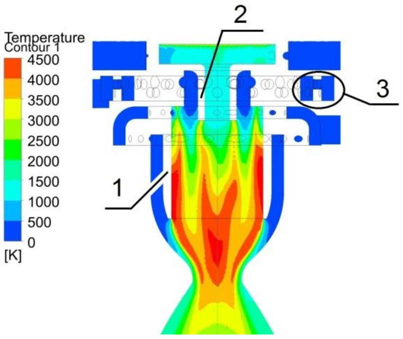

Fig. 4 – Temperature distribution at the longitudinal section of engine with additional fuel belt with centrifugal atomizers: 1 – screen, 2 – spout, 3 - redistributive grille

To reduce the unevenness after prechamber ignition was added cylindrical spout (Fig. 4, Pos. 2), and radial jet atomizers of ignition replaced by centrifugal ones. Diameter of atomizers of oxidant was increased and redistributive grille was created [13] in the collector of oxidant (Fig. 4, Pos. 3). Also attempts to make redistributing collector as snail swirler, but due to the technological complexity of making these proposals have not been developed.

For stabilizing the combustion process away from the walls of the cylindrical part of the chamber was an attempt to add additional fuel belt in the following versions:

1) between the main belts of fuels with inkjet or centrifugal atomizers (Fig. 4);
2) over the main belts of fuels with centrifugal atomizers (Fig. 5).

CFD-modeling of these mixing schemes was showed that stabilization of combustion is observed in all three versions, but in the first mixing scheme there was high temperature of the screen, which could lead to its burnout. And on the second scheme was achieved stabilization of combustion with the lowest of calorific intensity at chamber interior wall of the engine. This scheme was adopted to elaboration of engine design.

During the elaboration of design the issues of layout inlets fuel and oxidant were investigated. CFD-simulations showed that the characteristics of the engine at steady state does not depend on the position of the inlets. Inlets were placed at the angle of 45 ° to each other, taking into account the layout.

Thus, the best form of gas flow path of the engine was determined: the scheme of mixing fuel with additional belt over the main ones with centrifugal atomizers at all belts, the use of the screen, spout and redistributive grille, chamber with entering angle 90° to the critical. It is allowed us to obtain acceptable flow pattern (Fig. 6) with a maximum temperature of gases 2100 K on the inner surface of the chamber at the critical section. This will ensure a high probability of engine workability with the camera of niobium alloy coated with disilicide with a melting point of 2760 K. Specific impulse in vacuum was 4489 m/s which corresponds to the technical task (Table 1).

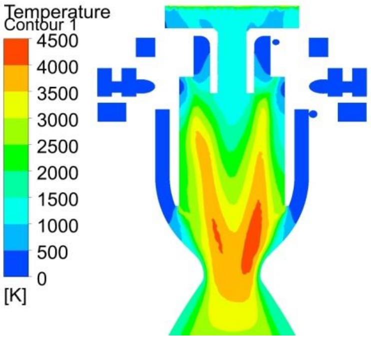

Fig. 5 – Temperature distribution at the longitudinal section of engine with additional fuel belt over the main ones

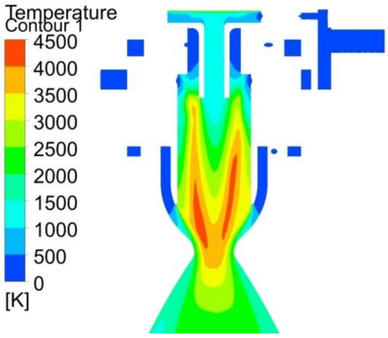

Fig. 6 - Temperature distribution at the longitudinal section of projected engine final variant

Conclusion

Rocket engine with thrust 25 N was designed. Workable of engine and compliance its parameters with technical specification were proved by numerical simulation using CFD-model, which adequacy was confirmed by comparison with experimental data. This CFD-model can be used for further research workflows of rocket engines operating on gaseous oxygen and hydrogen to reduce the volume of development tests.

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