Studying the dependence of model combustion chamber integral characteristics on the flow duct geometrical parameters during two-component mixture burning

O V Guskov\textsuperscript{1,2}, V S Zakharov\textsuperscript{1}, A V Minko\textsuperscript{1,2}
\textsuperscript{1} Central Institute of Aviation Motors named after P.I. Baranov, Moscow, Russia
\textsuperscript{2} Moscow Institute of Physics and Technology, Moscow, Russia

Abstract. This paper presents numerical simulation results of hydrogen combustion in variable flow ducts. The study was carried out in three-dimensional formulation using the chemical kinetic mechanism. Several configurations of the flow paths were examined. Relative thrust and combustion efficiency were selected as criteria for comparing the flow ducts. The results of the numerical simulation were compared with the results obtained within the framework of a one-dimensional calculation. The presented results can be used at the calculating stage of the operational process in the advanced power units.

1. Introduction

Currently, the development of high-speed transport systems on hydrogen fuel is getting a lot of attention all over the world. A large number of studies is being carried out in the world both on the formation of the general image of a high-speed aircraft \cite{1} (projects HEXAFLY-INT \cite{2-3}, LAPCAT \cite{4-5}, "Holol" \cite{6}, etc.), and on the formation of separate parts of the flow duct made by power plants of such aircraft \cite{7-8}. The key element of such vehicles is the power plant that has a high degree of aircraft integration. At the moment a pressing task is choosing such a configuration of the combustion chamber at a given length that will provide high thrust and economic characteristics. Recently, in connection with the development of high-level mathematical models and the growth of computer capacity, it has become possible to simulate combustion in a three-dimensional formulation. This makes it possible to study the structure of the flow in the combustion chamber in detail, to determine the characteristics of the operational process, and reasonably approach the choice of its geometric parameters. The aim of this study was to analyze the efficiency of the operational process depending on the heights of the characteristic points of a flat channel of constant width.

2. Problem and calculation methods

The study subject was a part of a model flow path of a high-speed jet engine, consisting of a transition channel in which the supersonic flow is transferred to a subsonic one, a combustion chamber and a part of nozzle with a critical section. The flow in the air intake device was not calculated, however, the influence of the air intake device on the flow structure at the entrance to the computational domain was modeled by specifying the boundary layer with the corresponding displacement thickness. A rectangular section transition channel with an expansion angle of 2° was chosen for this paper. Starting from the throat section (entrance to the computational domain) and ending with the entrance to the combustion chamber, the flow path is divided by a vertical bulkhead to prevent the occurrence of large-scale transverse vertexes. At the rear end of the bulkhead there were
injectors from which fuel was supplied. The height of the throat was taken as the main parameter of length; all dimensions were further referenced to this height. The configurations of the flow path with four heights of combustion chambers were considered: \( H_1 = 3 \, h \) (where \( h \) is the height of the throat section), \( H_2 = 3.8 \, h \), \( H_3 = 4.5 \, h \), \( H_4 = 5.5 \, h \). The width of the flow path was constant throughout its entire length and was equal to \( b = 4 \, h \), the length of the transition channel for all variants was \( A = 15 \, h \), and the length of the combustion chamber (from fuel injectors to the critical section) was \( L = 19 \, h \). For each height \( H \) two variants of connections between the transition channel and the combustion chamber were considered: a smooth expansion with an angle \( \theta \) and a backward-facing step. For various \( H \), the following \( \theta \) values were obtained: \( H_1 - \theta_1 = 9^\circ \), \( H_2 - \theta_2 = 16^\circ \), \( H_3 - \theta_3 = 22^\circ \), \( H_4 - \theta_4 = 30^\circ \). The designation of the aforementioned dimensions and options for the connections of the transition duct and the combustion chamber are shown in Figure 1.

![Diagram of computational domain](image)

**Figure 1. General view of the computational domain. Typical dimensions (at the top) and various connection options (on the bottom). Green color indicates entry boundary.**

In order to save computational resources the computational domain was started from the throat section. At the input boundary condition a supersonic flow with a Mach number \( M = 2.3 \) in the flow core and a boundary layer with a displacement thickness of \( \delta* = 0.01 \, h \) was specified. To correctly simulate the pseudoshock region and the flow in the volume of the combustion chamber the calculation was carried out in a full three-dimensional formulation without using symmetry conditions. There is no heat transfer between the walls and the gas. The calculation was made through a program based on solving the Navier-Stokes equations with the finite volume method. The study was carried out using the k-w SST turbulence model [9]. The air at the entrance to the computational domain was modeled with a mixture of gases: 23% - O\(_2\) and 77% - N\(_2\) (mass concentrations). For the considered flow (diffusion combustion in a subsonic flow at high temperatures) the time required to establish chemical equilibrium is determined by the time required for the energy exchange between the internal degrees of molecules’ freedom. Basically, such an exchange is required for the redistribution of vibrational energy caused by the collision of particles. The relaxation times of the vibrational freedom degrees are short, they amount to \( 10^{-4} - 10^{-6} \) seconds [10 - 11] at a temperature of ~ 1500–2000 K, which is significantly less than the characteristic times of hydrodynamic and thermal equalization between zones. Due to this, the calculation was carried out in the equilibrium approximation. The combustion was simulated using the Hanson scheme [12] and the following components: H\(_2\)O, O\(_2\), H\(_2\), OH, H, O, HO\(_2\) and H\(_2\)O\(_2\); nitrogen (N\(_2\)) which was also presented in the calculation, was considered to be inert. The fuel was supplied perpendicular to the flow from the vertical slot injector nozzles.
located near the end of the vertical bulkheads - three on both sides. Hydrogen heated to 700 K was used as fuel; the outflow velocity from the injectors corresponded to the Mach number $M = 1$. The location of the injectors is shown in Figure 2 (a-b) in red, red arrows show the direction of fuel supply (the arrows show the direction of injection), dashed lines indicate sections in which the value fields will be examined and shown in Figure 3. The excess oxidizer ratio is $\alpha = 1.5$ for all configurations.

![Figure 2](image.png)

**Figure 2.** The positioning of the sections for displaying the results. The red arrows show the direction of the fuel spray.

The calculations were carried out on unstructured grids with cubic cells constructed by the Cut Cell method. The height of the external wall cells is 0.2 mm, the size of the cells away from the walls is 3 mm. To calculate the flows, we used the AUSM splitting scheme [13] and the 2nd accuracy order reconstruction. The initial conditions in the computational domain corresponded to the steady-state flow mode without fuel supply. The criterion for the solution convergence was the establishment of close values of the air flow consumption through the throat section of the air intake device and the section of the nozzle cut.

Below are the formulas used to analyze the calculated data:

$$
\int \rho(\vec{v},\vec{n}) \cdot dF = \sum_{i=1}^{n} \rho_i(\vec{v}_i,\vec{n}) \cdot F_i - \text{gas mass flow,}
$$

$$
\int C_k \cdot \rho(\vec{v},\vec{n}) \cdot dF = \sum_{i=1}^{n} (C_k)_{i} \cdot \rho_i(\vec{v}_i,\vec{n}) \cdot F_i - \text{mass flow of k-th component,}
$$

$$
\eta_E = \frac{\sum_{k} -i_k \cdot G_k}{Hu_{H_2} \cdot G_{H_2}} - \text{fuel combustion efficiency ratio calculated on energy (for } \alpha > 1) \ [14].
$$
The fuel combustion efficiency ratios obtained as a result of numerical modeling were compared with the combustion efficiency ratio calculated by Annushkin's method [15].

3. Calculation results

Figure 3 shows the areas of hydrogen mass concentration in different sections.
Figure 3. Areas of hydrogen mass concentration, on the left - configurations with a backward-facing step, on the right - configurations with a smooth expansion. Various ducts are sorted from top to bottom by increasing heights of the combustion chamber.

The distributions shows that by the end of the combustion chamber the fuel concentration decreases along with the increase of the combustion chamber height. In the $H_3$ and $H_4$ stepped configurations there is a slight fuel injection into the transitional channel.

Table 1. Comparison of all considered configurations. On the graphs (in the third column) the green line shows mass flow rate through the inlet section, red – mass flow rate through the critical section.

| Configuration | View | Mass flow rate disturbance in the critical section | Relative force acting on the combustor in the X direction | Combustion efficiency ratio (energy) | Combustion efficiency ratio ($H_2O$) | Combustion efficiency ratio (Annushkin) |
|---------------|------|--------------------------------------------------|--------------------------------------------------------|------------------------------------|--------------------------------------|----------------------------------------|
| $H_1=3h$, backward-facing step | | | 1 | 0.854 | 0.889 | 0.82 |
| $H_1=3h$, $\theta_1 = 9^\circ$ | | | 0.977 | 0.835 | 0.875 | 0.81 |
| $H_2=3.8h$, backward-facing step | | | 1.057 | 0.88 | 0.931 | 0.79 |
| $H_2=3.8h$, $\theta_2 = 16^\circ$ | | | 1.017 | 0.871 | 0.9 | 0.77 |
| $H_3=4.5h$, backward-facing step | | | 1.085 | 0.896 | 0.94 | 0.76 |
| $H_3=4.5h$, $\theta_3 = 22^\circ$ | | | 1 | 0.838 | 0.861 | 0.75 |
| $H_4=5.5h$, backward-facing step | | | 1.147 | 0.924 | 0.971 | 0.74 |
| $H_4=5.5h$, $\theta_4 = 30^\circ$ | | | 1.061 | 0.891 | 0.939 | 0.715 |
The presented graphs show that with a satisfactory coincidence at the initial point (configuration $H_1$) the combustion efficiency ratio dependences from the combustion chamber height obtained during numerical modeling and during one-dimensional calculations are fundamentally different. Based on the results of the calculations performed, it can be concluded that the presence of a backward-facing step in the combustion chamber favorably affects both the efficiency of fuel combustion and the resulting thrust. Such a result can be explained by the formation of stagnant vortex zones behind the step which stabilize combustion. With an increase in the cross section of the combustion chamber the combustion efficiency ratio and thrust increase. At the same time, thrust and combustion efficiency values obtained for the $H_3$ configuration with smooth expansion ($\theta_3 = 22^\circ$) are lower than those of the similar configuration with $H_2$ ($\theta_3 = 16^\circ$). This is explained by the fact that the flow in the combustor had strong pulsations which can be seen in mass flow rate graphs in Table 1. For both configurations with $H_4$ an increase in pressure was observed in the combustor during which there was a breakdown of the flow in the throat (the head of the pseudoshock area reached the throat and the mass flow rate at the entrance border decreased). Thus, according to the available data it is impossible to adequately compare configurations with the highest combustor’s height to other configurations; therefore, these points are shown on the graphs in red.

4. Conclusion

The numerical simulation of the hydrogen-air mixture combustion in rectangular channels of variable cross-section was carried out. The fuel combustion efficiency ratio was estimated in two different ways. The force acting on the flow duct in the longitudinal direction was estimated. Based on the performed calculations it was concluded that the backward-facing step in the subsonic channel improves the operational process.

The numerical modeling results were compared with the data obtained by a one-dimensional method using the Annushkin’s burnout curve. It is shown that the influence of geometric parameters of the flow duct with a constant fuel supply system on the working process is significant. The technique based on the Annushkin’s burnout curve can only provide a rough integral estimate of the combustion efficiency ratio. To compare different configurations of the flow duct with a constant fuel supply system, it is advisable to use a three-dimensional numerical simulation.
5. Acknowledgments

Research is performed at the expense of the grant of the Russian scientific fund (the project №19-49-02031)

6. References

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