Effect of Supersonic Flow Temperature on the Diffusion Combustion of Hydrogen

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1 Introduction

Combustion in the chamber at supersonic cocurrent input of the central hydrogen jet to the stream has its features [1-10]. As experiments showed [8-10], combustion becomes intensive in pseudo-shock mode. At present, one of the problems of study of combustion processes in jets is the draft loss of engine due to impairment of combustion process at the Mach numbers of the flight more than 8-10. In this case the temperature of the flow braking exceeds 2000K, heat input of combustion of fuel material is not sufficient, and "quiet" diffusion combustion takes place. Decrease of the period of ignition delay degrades the process of hydrogen mixing with air at initial zone of the flow, and limiting factor for combustion may be the process of fuel mixing with oxidizer. The given problem is studied below by the analysis of calculating data of the process in the combustion chamber at coaxial input of hydrogen jet in supersonic airflow.

2 Mathematical model of the flow

Development of round supersonic jet of hydrogen in coaxial supersonic stream in the combustion chamber is considered. Cold hydrogen jet with the temperature T_1 flows to the hot air flow with the temperature T_2 and they mix. Lets' consider boundary layers on walls of the nozzle and combustion chamber very thin due to high gas velocities. Mixing zone begins from the nozzle edge, reacting mix of gases is forming which self-ignites, and diffusion combustion of nonmixed gases of hydrogen jet and coaxial stream begins in the chamber.

The flow is supposed to be supersonic cylindrical chamber axis-direction, gas is considered as viscous, heat-conductive, chemically reacting, and the flow mode - as turbulent. For flow characterization the system of parabolized Navier - Stokes equations averaged by Reynolds is used [3,5,11,12]. Rate of hydrogen combustion in the air is characterized by multistage mechanism, including 18 chemical reactions, in which concentrations of eight active substances H, O, OH, H_2O, O_2, H_2, HO_2, H_2O_2 participate [13]. Nitrogen, which is present in the air, is inert and does not interact with other components of the mix.

Turbulent viscosity coefficient υ_t is found from (k-ε) - model turbulence for compressible flow [14].

Influence of turbulence on velocity of chemical reactions was considered using the model of unmixedness [15,16], which approximately defines damping influence of pulsations of substances concentration on the velocity of chemical reactions.

Boundary conditions of the equation system in initial section of jet and flow are set in the form of constant values of required variables. On the axis of combustion chamber conditions of symmetry are correct. Boundary conditions on the wall of combustion chamber are defined from conditions of reflection and rule of the wall

[11,12]. Applying of the rule of the wall allows circumventing calculation of all thin near-wall area that considerably reduces required calculation time.

Equation system together with boundary conditions is solved by numerical method [11].

For verification of mathematical model and solution method experimental data of combustion of hydrogen round supersonic jet in coaxial supersonic stream [17] were used. Calculations were made at the following operating conditions of the jet (M_1=2.0, T_1=251K, $C^0_{H_2}$=1.0) and the flow (M_2=1.9, T_2=1495K, $C^0_{H_2O}$=0.281, $C^0_{O_2}$=0.241, $C^0_{N_2}$=0.478). Pressures of the jet and flow were equal ($P_1=P_2$) and off-design degree was equal (n=1). Fig.1 shows distributions of concentration of vapors of water, oxygen and nitrogen in the section x/d_1=8,76, where ignition of reacting mix takes place.

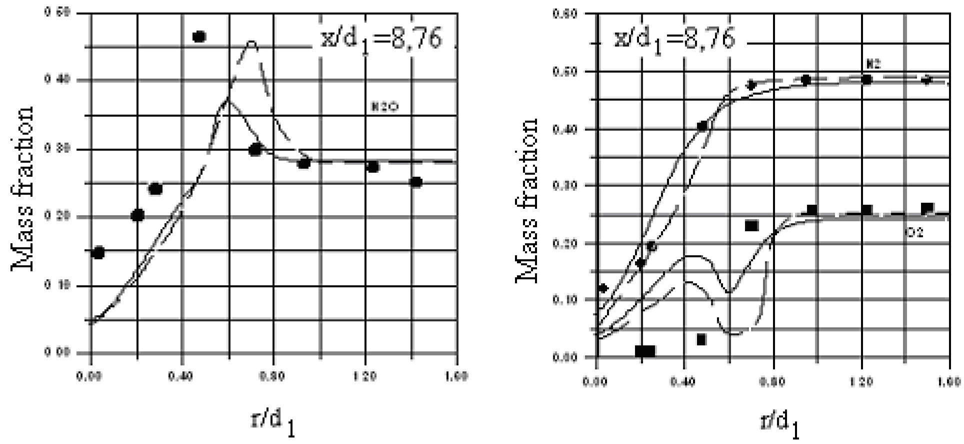

Fig. 1 – Distributions of concentration C_{H_2O}, C_{O_2} and C_{N_2}
(— calculations of the Authors; ---- calculations [16], points - experiment [17])

Numerical calculations of concentrations of vapors of water C_{H_2O}, oxygen C_{O_2} and nitrogen C_{N_2} (see Fig. 1) illustrate ignition of reacting mix and coordinate with experimental and calculating data [16,17].

3 Discussion of calculation results

On the Fig. 2 fields of concentration of radical OH and temperature T are given in operating conditions of hydrogen jet (M_1=1.4, T_1=251K, $C^0_{H_2}$=0.4, $C^0_{N_2}$=0.6) and airflow parameters (M_2=2.2, $C^0_{O_2}$=0.232, $C^0_{N_2}$=0.7679, C^0_{OH}=0.0001). Off-design degree of the jet was equal n=0.7. Stagnation temperatures of the flow were different: T_{02} =1920K for the cases (Fig. 2 a, c) and T_{02} =2500K – for the cases (Fig. 2 b, d).

At temperature value of the flow stagnation T_{02} =1920K self-ignition begins at the distance x/r_1=130 (r_1 – jet radius, r_1=1mm), and combustion practically ends at x/r_1=250. Self-Ignition takes place in paraxial zone of the jet, and general burning-out is observed in the same place (Fig. 2 a, c). Self-Ignition delay leads to sufficiently full mixing of hydrogen with air, and reacting mix is formed with heat and kinetic conditions for chemical reactions. In this case, calculation data of the field of concentration of radical OH and temperature T show that determining factor of diffusion combustion is the velocity of chemical reactions. Increase of the temperature of the flow stagnation T_{02} =2500K leads to that hydrogen self-ignites, beginning from the periphery of the jet (Fig. 2 b) and at the distance x/r_1=60. In high-temperature flow processes of dissociation begin to be very important. Additional activated radical OH appear (Fig. 2 b), in particular, after heat decay of molecules H_2O – end product of chemical reaction. Radicals OH produce early self-iginition of hydrogen. In the given regime decrease of the length of delay more than twice decreases the time of mixing of the jet and airflow. Therefore the process is limited by mixing (Fig. 2 d), and "quiet" diffusion combustion is realized. Calculation data are in qualitative accordance with the experiment [4,6].

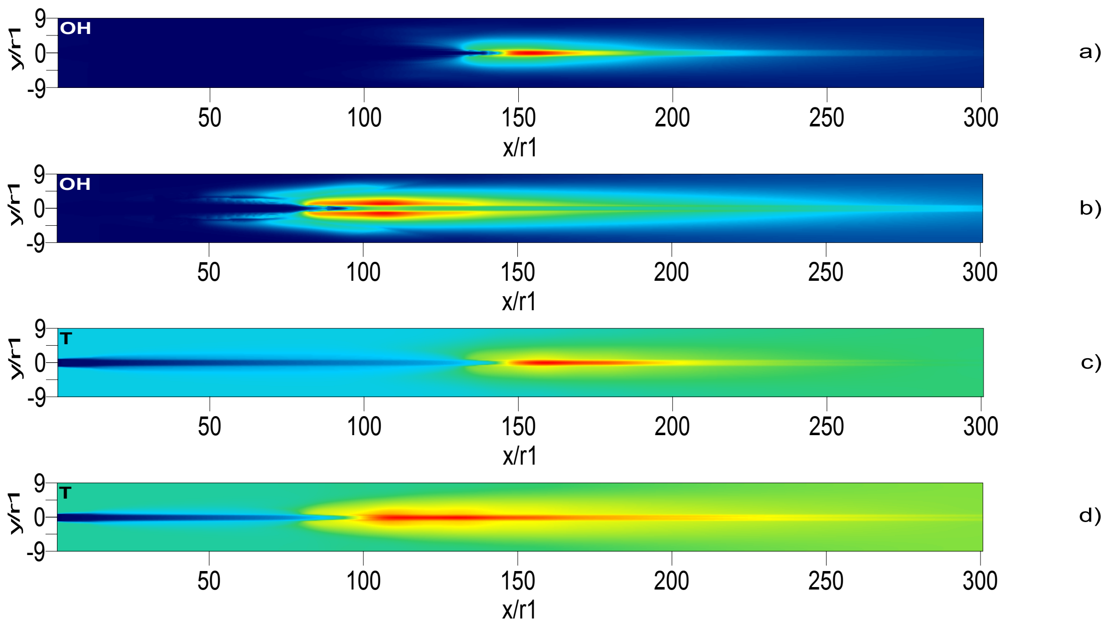

Fig. 2 – Fields of concentration of radical OH and temperature T at hydrogen combustion in supersonic flow

4 Conclusion

From the results of the research it is possible to draw the following conclusions:

1 Calculation data describe effect of the temperature of supersonic flow on diffusion combustion of non-mixed gases at overexpansed regime of outflow of circular hydrogen jet in cylindrical chamber of combustion.

2 Calculations determined borders of stable combustion of hydrogen in coaxial supersonic flow, flame structure in dependence on operating conditions. It was showed that overexpansed regime of outflow is the most favorable for mixing and combustion of non-mixed gases.

3 It was found that at the value of the temperature of flow stagnation T_{02}< 2000K the determining factor of the process is velocity of chemical reactions. Increase of stagnation temperature T_{02}>2500K produces inert behavior of diffusion combustion od non-mixed gases.

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