# Structure Of Flame Front Of Hydrogen Jet Combution In A Supersonic Air Stream

**U.K. Zhapbasbayev, Z.A. Mansurov**
Al-Faraby Kazakh National University

Corresponding author, U.K. Zhapbasbayev: nich7@kazsu.kz

## Introduction

Experimental analysis of diffusion combustion of hydrogen in non-isobaric supersonic stream of high-enthalpy air showed alternation of zones of intensive hydrogen burning with zones of the burning delay, caused by gas-dynamic flow structure (Vorontsov etc. 1999). Various ways of fuel injection and increase of stagnation temperature of airflow more than 2600K greatly influence slowing-down length of hydrogen ignition and internal structure of a flame (Zabaikin etc. 1999, Vorontsov etc. 2003). At that, recording of OH-radical radiation to the length of the flame allows defining burning intensity and completeness of combustion (Vorontsov etc. 1999, Zabaikin etc. 1999). Discovered alternation of intensive burning zones with zones of burning delay may influence the efficiency of work process under organization of supersonic combustion of hydrogen in combustion chambers and demands detailed study. Results of numerical calculations for experimental data definition (Vorontsov etc. 1999, Zabaikin etc. 1999, Vorontsov etc. 2003) are suited in the given work.

## Mathematical model and numerical method

Flow of the system of supersonic plane hydrogen jets is examined in supersonic airflow. From plane slots with the altitude $h_1$ located at the distance $2h_3$ from each other hydrogen jet discharges parallel into supersonic airflow. OX axis is directed along the plane of symmetry of the flow, and OY axis is perpendicular to it. Since the system of plane jets is repetitive, we can separate a band with a width L bounded by the planes of symmetry and consider task solution in this region, replacing neglected part by conditions of symmetry along boundary planes.

The flow in the entire region is accepted as supersonic, gas is considered as viscous, heat-conducting and chemically reacting, and flow regime - as turbulent. To describe the flow, system of Reynolds-averaged parabolic Navier-Stokes equations was used (Zhapbasbaev etc. 2001).

Turbulent viscosity $\mu_t$ is determined using $(k - l_\omega)$ model of turbulence, where kinetic energy of turbulence $k$ is found from differential equation of kinetic energy of turbulence and confounding way $l_\omega$ - according empirical dependence obtained from experimental data (Krasheninnikov 1972):

$$l_\omega = (u_{\max} - u_{\min}) / (\partial u / \partial y)_{\max}$$

Here, $u_{max}$, $u_{min}$ – maximal and minimal values of longitudinal velocity in each jet section accordingly, $(\partial u / \partial y)_{\max}$ - maximal value of derivative in each jet section.

Combustion rate of hydrogen in the air is described by a multistage mechanism (Dimitrow 1977) including reversible chemical reactions with participation of concentrations of six active components: H, O, OH, $H_2O$, $O_2$ and $H_2$. Influence of pulsation effect on velocity rate of chemical reactions was considered using modified Spiegler's incompatibility model (Spiegler etc.1976), which approximately determines damping influence of concentration pulsations on the rate of chemical reactions. Though this model is considered to be the most simplified, however, its using provides best agreement of calculation and experiment results (Gromov etc. 1987).

Finite-difference expressions for convective terms and terms with pressure gradients in longitudinal direction were obtained with left-side differences due to the positivity of eigenvalues of the Jacobi matrix $A = \partial F/\partial U$, and in transverse location - with upstream differences considering eigenvalues of the Jacobi matrix $B = \partial G/\partial U$ according to splitting scheme of flow-vector (Steger etc. 1981). Viscous shift voltages and heat flow were described by central differences. Difference analogs of gas dynamics equations set are solved by of matrix execution method (Anderson etc.1984).

To verify generalized mathematical model of hydrogen combustion the problem of outflow of pre-wall plane hydrogen jet into supersonic stream was analyzed in accordance with experimental conditions (Burrows etc. 1971). Considering that boundary conditions have no great influence on the length of induction zone and pressure distribution along the wall in thin boundary layer, slipping condition was laid down in calculations instead of adhesion condition. Distributions of the temperature and concentration of hydrogen, oxygen and steam molecules in outflow face of the canal are satisfactorily in line with experimental data (Burrows etc. 1971).

**Discussion of calculation results**

Main mode parameters of the flow are: $n=p_1/p_2$ – off-design degree of the jet, $M_1$ and $M_2$ - the Mach numbers of the jet and flow, $T_1$ and $T_2$ - temperatures of the jet and flow, $\alpha$ - excess air factor. Regime parameters in the present studies are: of the jet - $M_1$=1,45, $T_1$=254K, n=0,7, $C^o_{H_2} = 1{,}0$; of the flow - $M_2$=2,2, $C^o_{O_2} = 0{,}232, C^o_{N_2} = 0{,}768, \alpha = 1{,}42$. Air braking temperature was taken as $T_{o2}$=1850K and 2600K. The effect of these parameters on ignition and combustion patterns was studied in numerical experiment.

Distribution of OH hydroxyl concentration shows how flame-front surface is formed (see Fig. 1).

It is evident that ignition of hydrogen-air mixture starts at the distance $x/h_1 = 30$ length gage from exhausting start point (see Fig. 1, a). The ignition leads to that hydrogen jet mixes with airflow, producing a homogeneous reacting mixture, which does not ignite due to low temperature of hydrogen jet. As a result of mixing of cold jet with hot flow, the temperature of hydrogen-air mixture increases up to 900K thus providing kinetic conditions for reacting mixture ignition. The flame-front has a complex configuration. Homogeneous reacting mixture fully burns out in internal part of the front. Outside flame front is in mixing layer and shows diffusion character of interaction between fuel jet and oxidizer flow. Form of the flame front is determined under the effect of disturbance waves. In rarefaction zones the mixture accelerates and in compression zones it becomes slower, diffusion flame front has cellular structure in accordance with a wave structure of the flow. Diffusion flame front has finite thickness, zone of chain reactions is not localized on a thin surface. OH hydroxyl concentration has maximal value in the flame front.

a

b

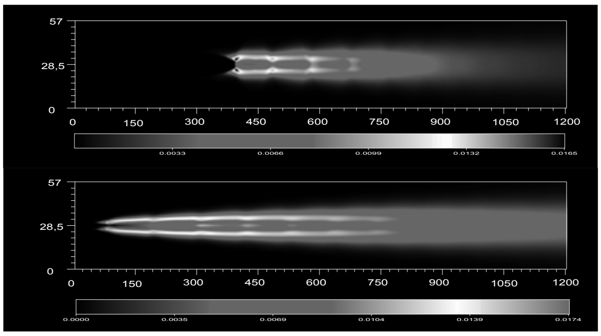


**Figure 1.** Calculated distribution OH concentration.
a – $T_{2o}$ = 1850 K, b – $T_{2o}$ = 2600 K.

a

b

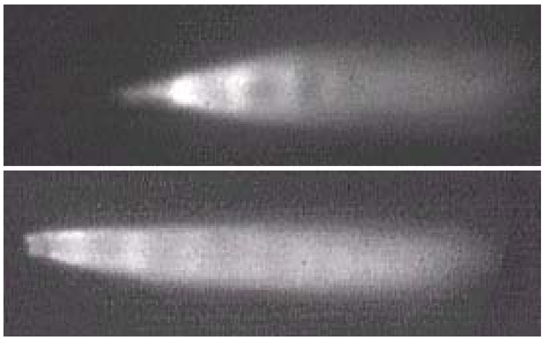

**Figure 2.** Experimental data OH concentration.
a – $T_{2o}$= 1850 K; b – $T_{2o}$= 2600 K.

Study of the structure of combustion zones at great change of airflow temperature represents is of a great interest. Fig. 2 shows measurement results of reradiation of OH-radical at braking temperature change from 1850K up to 2600K (Vorontsov etc. 1999).
Both experiments and calculations show change of the character of hydrogen burning out at change of air braking temperature. Zones with high intensity of combustion, as well as ignition places are displaced into external area of mixing layer. In comparison with average level of temperatures 1500-2000K, when ignition takes place basically in paraxial part of the jet after shock waves and main combustion processes too, at high temperatures (≥2500K) hydrogen ignites, beginning from the periphery of hydrogen jet. However, qualitative concurrence of the structure, showing character of combustion in supersonic flow at various temperature levels is very high.

**Conclusions**

The obtained calculation data reveal wave structure of the flow and describe mechanism of diffusion combustion of non-mixed gases in non-isobaric mode of injection of plane supersonic hydrogen jet system into a concurrent supersonic airflow.
Presence of active particles in the flow leads to initiating of combustion of reacting system in the mixing zone. The diffusion jet has a cellular barrel-like shape in accordance with the wave structure of the flow. Calculation data on the flame-front structure are in qualitative agreement with the theory of diffusion combustion of non-mixed gases.

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