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3-D STRUCTURE OF HYDROGEN FLAME IN SUPERSONIC HIGH-ENTHALPY FLOW

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Abstract. The purpose of this document is to provide an example of how authors must format their papers. The summary should be a self-contained and explicit overview of the paper with a clear statement of the principal conclusions reached. It should be at least 100 words, but must not exceed 150 words in length. It must be single spaced, 10pt, even justified across the full width of the page.

The experimental results of investigation of the flame structure in the case of hydrogen combustion in supersonic high-enthalpy air jet are presented. The complexity of the three-dimensional by the mixing dynamics, comparable values of the time required for a gas molecule to pass through the characteristic elements of the gasdynamic flow structure and the hydrogen combustion time, and by the interrelation of the combustion intensity and gas-dynamic flow structure. The main purpose of experimental investigation was to study the dynamic of hydrogen mixing and combustion in a high-enthalpy air stream in the presence of wave structures inherent in supersonic flows, and also to determine dimensions of combustion zones. Such studies are necessary for developing physical models adequately reflecting the gasdynamic and thermophysical phenomena that accompany the combustion process under conditions of high flow velocities and temperatures.

When studying combustion in supersonic flow, averaged parameters of the jet are usually used, and the influence of shock waves on the flame is hardly even taken into account. This approach is related to objective difficulties in measuring parameters in supersonic high-temperature reacting flows. In these conditions the most informative method for studying of inner regions structure is image registration on wave-lengths of radiation of intermediate reaction products [1].

The experiments were performed on a supersonic combustion test bench [2] with electric arc heating of air that allow a temperature of 2500 K and higher to be achieved at continuous running. The air flows out through axisymmetric supersonic (M = 2.2) nozzle in to ambient atmosphere (Fig.1). Hydrogen was delivered cocurrently through an injector fixed coaxially with the air nozzle. Self-ignition of hydrogen in hot air then occurs.

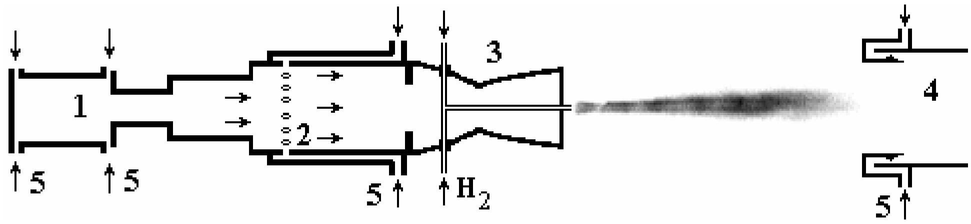

Figure 1. Schematic of a supersonic combustion test bench. 1 – electric-arc heater; 2 – precombustion chamber (mixing chamber); 3 – nozzle unit; 4 – exhaust system; 5 – air feed.

Flame radiation in the visible and ultraviolet spectral regions was registered. In hydrogen-air turbulent flames, a combustion process is most adequately described by radiation of excited OH molecule, which is the intermediate product of hydrogen oxidation and exhibits a small time of luminescence ($\sim10^{-8}$sec [3]). Note that this time is much less than the characteristic time taken for the gas to traverse the elements of the flame gasdynamic structure ($\tau\sim10^{-5}$sec), and registered radiation of excited OH molecules in the ultraviolet spectral region (wave length $\Delta\lambda$=280-350 nm, transition $^2\Sigma^+ - {}^2\pi$) corresponds to the intensity of heat-release (combustion) of hydrogen flame [1].

During the experiments radiation of the OH molecule was captured by an optical filter and was projected, via quartz objective, on photocathode of an electronic-optical transformer. Then image was recorded by CCD camera with an exposure time of 1/500 sec. CCD cameras were also used for a flame radiation registration in the visible and the near infrared spectral regions (λ = 0.35-1 μm). In that case a minimum exposure time was amounted 10^{-5} sec (maximum – 10^{-1} sec, for receiving averaged patterns of the flame). The high-speed camera DALSA giving 17 serial image of a visible radiation of flame in the same wavelength region carried out the registration too.

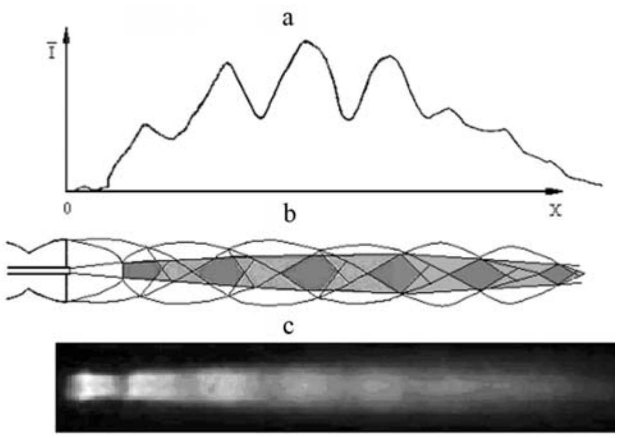

Figure 2. Hydrogen combustion unevenness in supersonic nonisobaric air jet. ***a*** – integral radiation intensity of the H_2 flame in the axial direction; ***b*** – scheme of gasdynamic structure with combustion zones of various intensity; ***c*** – 2-D distribution of radiation intensity in ultraviolet range.

It was found as a result of investigations of OH radiation in hydrogen flames that the central (paraxial) zones of combustion intensification exist. The main maxima (Fig.2,a) are connected with central zones of combustion intensification (dark places in Fig.2,b), which correspond to zones of periodic pressure and temperature rise behind shock waves in nonisobaric air jet.

It shows the difference of real flame structure from visible one, that is according to long exposures (Fig.3,a). By decreasing exposure time down to $\sim 10^{-3}$-10^{-4} sec also in the visible range it is possible to see the central zones of combustion intensification (Fig.3,b).

a

b

c

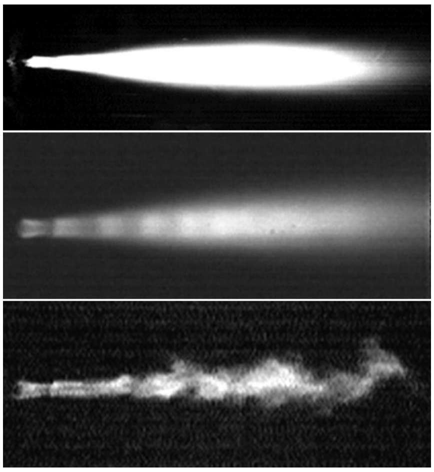

Figure 3. Flame structure in the visible wavelength range at various exposure times.
Time order: ***a*** – 10^{-1} sec, ***b*** – 10^{-3} sec, ***c*** – 10^{-5} sec.

High-speed photorecording (~ 10^{-5}-10^{-6} sec) has shown the existence of peripheral combustion zones with less intensity as well. Peripheral (external) combustion zones have a quasi-periodical structure, and their intensity increases toward the flame tip (Fig.3,c).

To clear up dynamics of generation and evolution of the detected combustion zones, the high-speed optical system was used, that has allowed a combustion process to be registered at a zero time between adjacent frames. The train of several uninterrupted frames enables to observe the processes generation of external combustion zone generation, their evolution and interaction with gasdynamic structure of an external nonisobaric jet. Experiments at exposure of 50 µsec covered the flame at full length that made it possible to analyze the processes at a large distance (about 10 size of air nozzle or 50 sizes of hydrogen injector).

It was found, that maximal generation of vortices is observed in the fourth "barrel", where combustion intensity begins to increase at the flame periphery. A separate combustion zone formed moves along the periphery of flame (possibly rotating at the same time) to the point of full extinction. At the some time, such peripheral combustion zones can increase drastically in size.

Figure 4 shows a typical evolution of the combustion process at the external flame boundary with the 50-microsecond exposure of each frame. One can see the generation of peripheral combustion zones (frames 1 and 2), its evolution (3 to 5), intensification (6 and 7) and extinction (8 to 10). Several combustion zones (of small intensity) may separate from the main flame and evolve independently. On frame 10, one can notice the appearance of a new combustion zone at the same place as previous one. Both the intensification regions and the extinction zones are located mainly in fixed periodical sites – regions of interaction between shock waves in the outer supersonic air stream and the mixing layer.

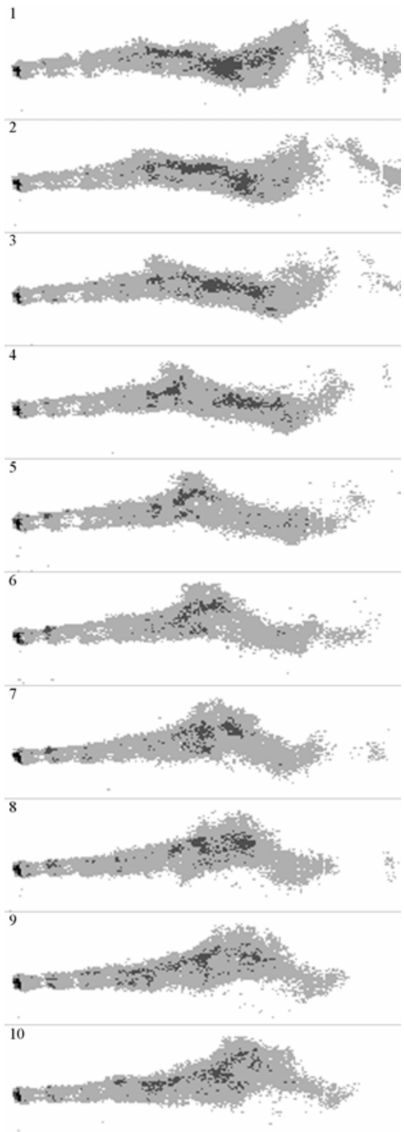

Figure 4. Evolution of peripheral combustion zone.

The successive images of the flame make it possible to estimate the travel velocity of the peripheral luminous regions. The maximum velocity in the axial direction was found to be 370-400 m/s, the value approximately four times lesser than the mean initial velocity of the air jet flow. This difference can be attributed to flow deceleration near the edge of the air jet, and also to the lagged burnout dynamics of hydrogen in the luminous zones. Each individual peripheral combustion zone is fed with an additional portion of the fuel mixture that ignites and starts emitting light. At the same time, at the opposite end of the combustion zone the reactions come to the end, with no glow observed. All this results in an apparent drop of the travel velocity of the luminous zone, although the flow velocity itself may be higher. To estimate the travel velocity more precisely, one has to take into account possible rotation of the combustion zone.

Experiments with measurements at heat-release intensity (by registering OH radiation) show that the major part of heat-release in the first 4 to 5 "barrels" in the supersonic air jet occurs in the central part of the plume (it is well seen in Fig.2). However, closer to the plume end, the combustion intensity in vortices can approach its value at plume axis. Afterburning of certain pockets of fuel and oxidizer can take place in local zones separated from the main flame. This process looks like fluctuations in the plume tail.

Thus, the wave structure, being the intrinsic feature of a supersonic stream with a particularly pronounced manifestation in nonisobaric jets, strongly influences mixing of fuel and oxidizer (i.e., mixing occurs not only due to diffusion). Incidentally, the conditions required for realization of the microvolumetric combustion mechanism in the turbulent air jet may come into effect. This, in turn, can result in the redistribution of combustion intensity over the flame region and to the decrease in flame length. This is valid not only for combustion in free space but also in a duct due to multiple reflections of shock waves from the duct walls and their interaction with the flame.

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