Combustion, Explosion, and Shock Waves, Vol. 35, No. 5, 1999

Investigation of the Structure of a Diffusion Hydrogen Plume in a Supersonic High-Enthalpy Air Jet

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UDC 536.46

Translated from *Fizika Goreniya i Vzryva*, Vol. 35, No. 5, pp. 3–5, September–October 1999.
Original article submitted March 19, 1999.

The results of investigation of the plume structure in the case of diffusion combustion of hydrogen in a cocurrent supersonic high-enthalpy off-design air jet are presented. Based on the registration of radiation within the wavelength range of 260–350 nm across and along the flame, a three-dimensional tomographic reconstruction of the plume was obtained, which confirmed the interrelation between the gas-dynamic structure and combustion intensity. A possibility of existence of combustion regimes with periodically repeated cycles of complete extinction and subsequent ignition of hydrogen in accordance with the barrel-shaped structure of the off-design jet is established experimentally. The existence of local peripheral regions of combustion is noted, which can indicate the presence of vortex structures. In the three-dimensional representation (obtained under the assumption of axial symmetry of radiation), these vortex structures have the form of annular zones. In a real flow, helical structures are possibly formed at the plume periphery.

The results of investigation of the plume structure in the case of hydrogen combustion in a supersonic high-enthalpy off-design air jet are presented. The complexity of the three-dimensional plume structure is determined by the mixing dynamics, comparable values of the time required for a gas molecule to pass through the characteristic elements of the gas-dynamic flow structure and the total time of ignition delay and hydrogen combustion, and by the interrelation of the combustion intensity and gas-dynamic flow structure.

It was found previously (see, for example, [1]) that the burning of hydrogen injected into a supersonic off-design air jet has a clear periodic character and is related to wave structures (barrels) in the air jet. The combustion intensity determined from radiation of the excited OH radical can vary along the plume by several times. However, the radiation was registered in those measurements only along the flame axis with integration in the plane perpendicular to the flow direction, which limited the possibilities of studying the flame structure in the radial direction. In addition, the process may proceed in a special manner, which is related to variation of the characteristic time of combustion in off-design jets. The estimates and experiments show [2] that a strong change in pressure and temperature in the "barrels" of the jet can lead to a decrease in the characteristic time of combustion, such that complete extinction of the plume occurs in flow regions with low parameters. These regimes were not observed experimentally in previous studies.

In the present paper, we describe preliminary results of investigation of the combustion process with the use of an ÉFA-360UF opticomechanical scanner, which can register two-dimensional images of flame radiation within the wavelength range of 260–380 nm, which corresponds to the radiation of an OH molecule [3]. The registration was performed on an IBM PC personal computer with 8-digit transformation, image dimension 128 × 128 points, time of frame scanning 0.3 sec, interval between the frames 2 sec, and time of line scanning 3 m/sec. The information was preliminarily processed using the TVGS-2.0 program package [4] and standard graphical tools of the WIN-

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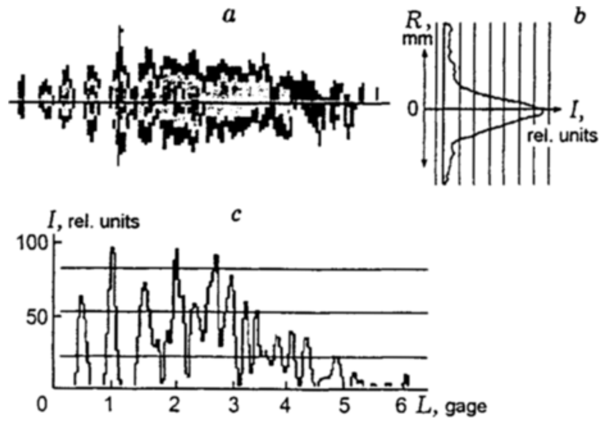

Fig. 1. Two-dimensional integral (a), transverse (b), and downstream (c) distributions of the combustion intensity for the regime $G_{H_2} = 2.7$ g/sec.

Fig. 2. Three-dimensional reconstruction of local distributions of the combustion intensity for the regime $G_{H_2} = 4.6$ g/sec.

DOWS system. To exclude random noise, the raw information was smoothed by an adapted median filter.

The experiments were conducted on a facility described in [1] with a ramjet injector aligned with the axis of the air nozzle. The Mach number at the nozzle exit was 2.2. The stagnation temperature was 2000 K in all the regimes and the stagnation pressure was $6.8 \cdot 10^5$ N/m^2, which corresponds to the nozzle pressure ratio $n = 0.64$. With these parameters, the air jet becomes slightly narrower; a moderate central shock wave approximately 5 mm in diameter (the nozzle diameter is 50 mm) appears at a distance of 30 mm from the nozzle exit. After that, a number of periodic structures (barrels), each about 90 mm long, are formed. Thus, within the region of observation (450–500 mm), there could exist 5 or 6 stable gas-dynamic structures responsible for flame stabilization and periodic variation of the combustion intensity. The parameters of the air flow and, hence, the initial gas-dynamic structure of the flow in all experiments remained constant, the hydrogen exhaustion velocity did not exceed the speed of sound, and the flow rate of hydrogen G_{H_2} varied within 1.5–5 g/sec.

The two-dimensional distribution of the radiation intensity I is shown in Fig 1a, and the axial distribution is plotted in Fig. 1c. In this regime ($G_{H_2} = 2.7$ g/sec), the radiation intensity between the maxima in the initial part of the plume dropped to zero, i.e., periodic cycles of complete extinction and subsequent ignition occurred. These peculiarities were not observed in previous experiments. Note that the frequency of the peaks is greater than the frequency of the "barrel-shaped" structures of a supersonic off-design jet. The experiments showed that peaks (local maxima) of lower intensity but higher frequency are observed on the background of the main plume. Possibly, these local maxima are not related to the zones of pressure increase in the flow core. A panoramic registration of radiation of the entire plume showed the presence of alternating combustion zones of moderate intensity at the plume periphery (Fig. 1b).

To obtain a more illustrative and reliable information, a three-dimensional image of the plume was reconstructed. The experimental data were interpreted as a set of integral radiations, and local distributions were assumed to be axisymmetric in each vertical cross section of a three-dimensional emission object. Abel's transformation formed the basis of the algorithm of three-dimensional tomographic reconstruction [5]. It is known that this transformation can be used only for axisymmetric input projections. To obtain symmetric projections from the data registered, a special method of symmetrization was developed. Two approaches are used in this method for choosing the point relative to which the right and left wings of the distribution are averaged. The first approach includes symmetrization of a projection relative to its maximum. In the second approach, the point of symmetrization coincides with the center of mass of the middle part of the wings of the one-dimensional projection. One of these approaches is chosen automatically by minimizing the norm of deviation of the right wing of the projection from the left one; the credibility of reconstruction was tested by model numerical experiments.

The results of three-dimensional tomographic reconstruction of one combustion regime shown in Fig. 2 confirm the interrelation between the gas-dynamic structure and the combustion intensity (the dark regions correspond to a higher intensity of radiation). We can also see annular combustion regions whose emergence is apparently related to the above-noted local maxima in the distribution of intensity along the plume (see Fig. 1). It should be noted that the technology of obtaining raw information did not allow us to register the temporal evolution of peripheral combustion zones; therefore, we cannot draw any conclusions about the reason of their origin and stability of existence. They can be steady or unsteady structures, and also helical vortex structures, which yield annular combustion zones after axisymmetric processing.

Thus, the studies conducted allow the following conclusions.

• In the case of hydrogen combustion in a high-enthalpy supersonic flow, the existence of a regime with periodically repeated cycles of complete extinction and subsequent ignition has been reliably registered for the first time.

• Panoramic registration and three-dimensional processing of the plume images confirmed the interrelation between the gas-dynamic structure and the combustion intensity and revealed the presence of structures of the type of annular (vortex) or, possibly, helical combustion zones at the periphery of the main plume.

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