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PHYSICS

Diffusion Combustion of a Round Hydrogen Microjet at Sub- and Supersonic Jet Velocity

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Abstract—The experimental research results on diffusion combustion of a round hydrogen microjet flowing from a slit micronozzle at subsonic and supersonic speeds are presented. For the first time, four scenarios of diffusion combustion of a round hydrogen microjet have been identified, including supersonic combustion in the presence of supersonic cells both in air and in hydrogen. It has been found that flame stabilization for a subsonic microjet velocity of hydrogen is associated with the presence of a "bottleneck flame region" leading to the nozzle choking phenomenon, and flame stabilization for a supersonic microjet flow is associated with the presence of supersonic cells. A hysteresis of the diffusion combustion process of a plane microjet of hydrogen is found depending on the method of ignition of the microjet (near or far from the nozzle exit) and the direction of change in the rate of its outflow (growth or decrease).

Keywords: hydrogen round microjet, diffusion combustion, "bottleneck flame region," sub- and supersonic combustion, hysteresis

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INTRODUCTION

Experimental studies of diffusion combustion of a round hydrogen microjet [1–5] showed the existence of different scenarios of this process, depending on the increase in the microjet outflow velocity in the range of outlet diameters from 0.25 to 1 mm. The following scenarios of diffusion combustion of a round hydrogen microjet were found: (1) combustion of a purely laminar microjet with the presence of a long-range laminar flame; (2) the emergence of a spherical "bottleneck flame region" (BFR) with the presence of a laminar microjet in it and a laminar flame with turbulization of the microjet and flame when the laminar microjet overcomes a narrow region of the gas density gradient; (3) the turbulent flame lift-off from the nozzle; (4) cessation of combustion of the turbulent section of the microjet while maintaining combustion in the BFR, and in this situation, combustion in the BFR persists up to transonic velocities of its outflow, however, in the presence of phenomena such as "micronozzle choking" [4–6]; (5) cessation of combustion of the microjet. It should be noted that the nozzle was blocked when the hydrogen microjet velocity was close to the speed of sound in air ($U_0 \approx 331$ m/s). Stabilization of combustion of both round [1–6] and plane [7] microjets was provided in this situation by the presence of a BFR and the existence of combustion in it.

Nevertheless, we were not able to achieve supersonic diffusion combustion of a hydrogen microjet due to the choking of the BFR nozzle, which led to heating of the micronozzle output and prevented flame lift-off from the exit section of the nozzle. One of the characteristics of supersonic combustion of a jet flow, along with a number of others, is the presence of supersonic cells both in the jet and in the flame. This is demonstrated in detail in [6, 8] when a round hydrogen microjet is ignited far from the nozzle exit. In this situation, it was possible to observe the presence of supersonic cells both in the jet and in the flame detached from the nozzle exit. The results of experimental and numerical studies of the combustion of round hydrogen jets at supersonic velocities of their outflow are presented in [9–11], and those of the plane are in [12].

The purpose of this work is to investigate experimentally the features of diffusion combustion of round

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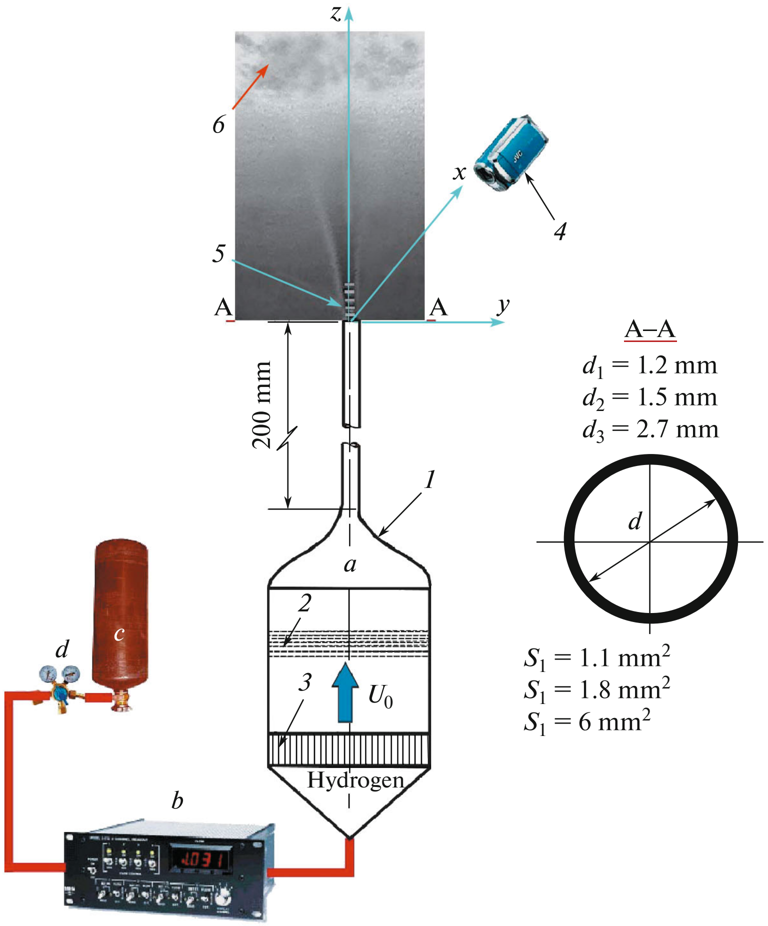

Fig. 1. Experimental scheme: *a*, nozzle apparatus; *b*, mass gas flow regulator; *c*, compressed hydrogen cylinder (100 atm); *d*, reducer. Nozzle apparatus *a: 1*, prechamber; *2*, a set of deturbulizing grids; *3*, honeycomb and microtubes 200 mm long with a round micronozzle; and *4*, digital video camera.

hydrogen microjets and to determine different scenarios of this process depending on the microjet velocity. Attention will be paid to the study of the development characteristics of this microjet at subsonic and supersonic (relative to air U_0 = 331 m/s and hydrogen U_0 = 1284 m/s) jet velocity and in the presence of supersonic cells.

RESULTS

Figure 1 shows the scheme of the experiment. Hydrogen was supplied from a cylinder at a pressure of 100 atm through a reducer to the nozzle apparatus through the MKS Instruments gas mass flow control valve, which provides a gas flow rate measurement accuracy within 0.7%.

Gas flow control was carried out by a gas mass flow controller, and hydrogen flow readings were recorded on its electronic display (see Fig. 1, *b*). In the experiment, hydrogen was supplied into the nozzle apparatus, which consisted of a prechamber with a set of deturbulizing grids, a honeycomb, and then through a cylindrical microchannel of about 200 mm long into a circular micronozzle with the sizes of its outlet shown in Fig. 1. A detailed description of the equipment used in the experiments and the research procedure are presented in [1–5].

Scenarios of Supersonic Diffusion Combustion of Round Hydrogen Microjets (d_0 = 0.5 mm and d_1 – d_3 = 1.2, 1.5, and 2.7 mm)

Experiments have shown that with a diameter (area) d = 0.5 mm (S = 0.2 mm^2), respectively, at the outlet of a circular nozzle at a flow rate of about 200 cm^3/s ($U_0 \approx$ 1000 m/s), the flame-out and the absence of combustion of a hydrogen microjet are observed. On the other hand, stable supersonic combustion was observed for both a plane (S = 0.9 mm^2) [12] and a round ($S \approx$ 3 mm^2) jet of hydrogen with the flame detached from the nozzle exit section, but with an outlet (slit) area of more than four times higher than the analogous parameter for a round microjet with an outlet diameter d = 0.5 mm (S = 0.2 mm^2). The results of these experimental stud-

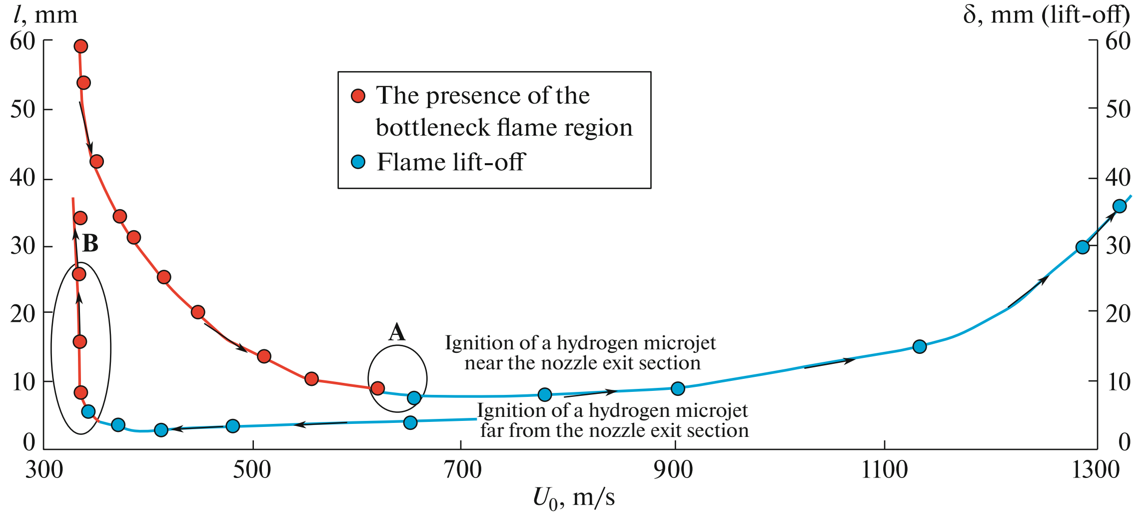

Fig. 2. Graph (hysteresis) of the dependence of the process of flame development of a round microjet of hydrogen depending on the jet velocity and the method of ignition (near/far from the nozzle exit section), the speed range of the disappearance of BFR and the beginning of flame lift-off (**A**), and the range of the rate of cessation of flame lift-off and the appearance BFR (**B**). The arrows indicate the direction of the change in the microjet velocity (increase/decrease). Nozzle diameter is 1.2 mm.

ies of diffusion combustion of a round hydrogen jet flowing out of circular nozzles with a nozzle outlet diameter $d = 1.2$, 1.5, and 2.7 mm and the cross-sectional area of the nozzle outlet $S = 1.1$, 1.8, and 5.7 mm^2, respectively, demonstrate the process of “supersonic diffusion combustion” with the presence of supersonic cells that stabilize combustion, at a jet velocity exceeding the speed of sound in hydrogen ($U_0 \geq 1284$ m/s). This research result correlates with the results of the study of diffusion “supersonic combustion” of a plane hydrogen microjet presented in [12]. From this, it can be concluded that the “supersonic diffusion combustion” of a round hydrogen microjet at jet velocities exceeding the supersonic hydrogen speed is possible when the diameter of the micronozzle outlet is within 1 mm or more.

With an increase in the microjet velocity, one can observe the appearance of a BFR, the presence of combustion in which exists up to the transonic microjet velocities, but ultimately leads to the phenomenon of choking the micronozzle due to the heating by BFR of its outlet. The range of microjet velocities of hydrogen in the presence of BFR depends on the method of its ignition (ignition): near or far from the nozzle exit section. In this case, one can observe the so-called hysteresis, which is clearly visible in Fig. 2.

Hysteresis of the Process of Development and Disappearance of BFR, Depending on the Method of Ignition of a Round Microjet of Hydrogen (Far/Near the Nozzle Exit) and with a Decrease or Increase in Its Jet Velocity

Figure 2 shows a graph of the process of development and disappearance of BFR depending on the ignition method (near/far from the nozzle exit), as well as the increase/decrease in the round microjet velocity of hydrogen. The graph clearly demonstrates the presence of hysteresis in this process. Ignition of the microjet near the nozzle exit BFR and heating of the nozzle outlet make it possible for this region to exist, until its disappearance and occurrence of flame lift-off at a sufficiently high microjet velocity ($U_0 \approx 590$ m/s). However, with a decrease in the microjet velocity, the process of inversion of the flame lift-off to its attachment with the appearance of BFR occurs at $U_0 \approx 333$ m/s, which correlates with the situation observed when the hydrogen microjet is ignited far from the section of the nozzle exit.

Thus, in this case, a hysteresis cycle can be observed. Semi-cycle **A**: the presence of a BFR, its disappearance, and flame lift-off during the ignition of the microjet near the nozzle exit section and an increase in its jet velocity (position **A**). Semi-cycle **B**: the process of inversion from the detached flame to its attachment and the appearance of a BFR with a decrease in the microjet velocity in the situation of its ignition far from the nozzle exit (position **B**).

It should also be noted that the flame lift-off from the nozzle exit section and the disappearance of the BFR, which guarantee the absence of heating of the micronozzle output, create conditions for cessation of the phenomenon of micronozzle choking and the release of combustion of the hydrogen microjet at supersonic speeds.

Four Scenarios of Diffusion Combustion of Round Microjets of Hydrogen

Thus, the results of experimental studies indicate that there are four main scenarios of diffusion combustion of round, as well as plane [12], microjets of

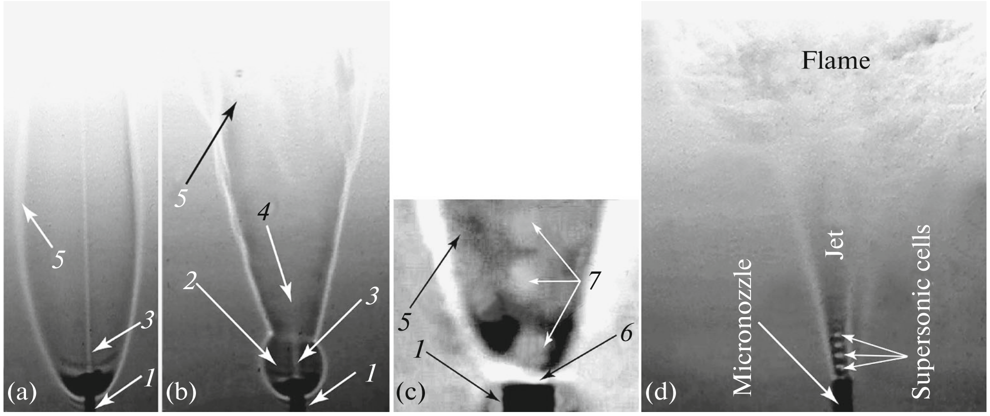

Fig. 3. Shadow patterns of four scenarios of diffusion combustion of a round hydrogen microjet depending on its jet velocity (a, $U_0 \leq 150$ m/s; b, $U_0 \geq 150$ m/s; c, $U_0 \geq 330$ m/s; d, $U_0 \geq 1280$ m/s): *1*, round micronozzle; *2*, BFR; *3*, laminar microjet; *4*, turbulent microjet; *5*, flame; *6*, flame lift-off; *7*, supersonic cells.

hydrogen, depending on its jet velocity. These are the following scenarios (see Fig. 3):

(1) Laminar combustion in the presence of a laminar microjet and a laminar flame (Fig. 3a, $U_0 \leq 150$ m/s).

(2) The emergence and development of BFR with a laminar microjet and an almost spherical flame, the presence of a narrow region of the gas density gradient, overcoming which the microjet and the flame become turbulent (Fig. 3b, $U_0 \geq 150$ m/s).

(3) The disappearance of the BFR, flame lift-off from the nozzle exit section, and “supersonic combustion” of the microjet relative to the speed of sound in air (Fig. 3c, $U_0 \geq 330$ m/s).

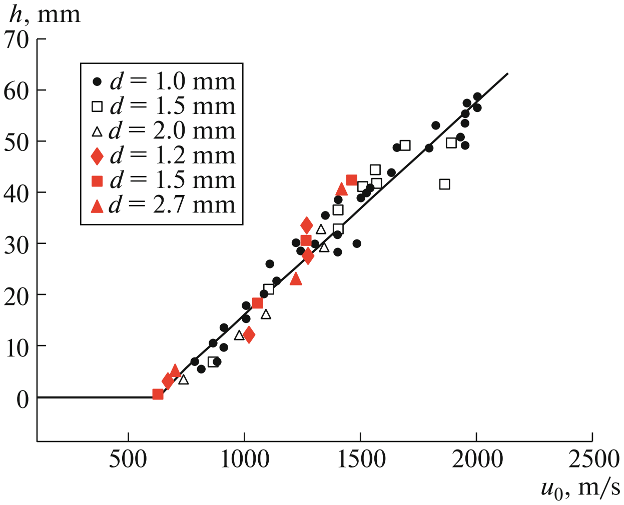

Fig. 4. A graph of the dependence of the flame lift-off value from the nozzle exit section depending on the round microjet velocity of hydrogen during diffusion combustion, symbols (●, □, △, from [10], and ◆, ■, ▲, research data).

(4) An increase in the magnitude of the flame lift-off from the exit section of the nozzle and “supersonic combustion” of the microjet relative to the speed of sound in hydrogen (Fig. 3d, $U_0 \geq 1280$ m/s).

Comparison of the Results of These Experimental Studies with Those of Other Authors

The results of experimental and numerical studies of the combustion of round hydrogen jets at subsonic and supersonic jet velocities are presented in detail in [9–11]. Figure 4 shows a graph of the dependence of the flame lift-off height from the nozzle exit for a diffusion flame of a round microjet of hydrogen on the jet velocity according to [9, 10], in which only the last scenario was investigated with the ignition of a microjet lift-off far from the nozzle.

It can be observed that, as shown in Fig. 4, the dependence is linear; the maximum speed at which the authors carried out the measurements at $d = 1$ mm is more than 1.5 times higher than the speed of sound in hydrogen; and with an increase in the diameter of the nozzle outlet, this speed decreased, but exceeded the speed of sound in hydrogen.

It should be noted that the authors of [10] do not present patterns of shadow visualization of flows, although they carried out such studies. Whether or not they observed the presence of supersonic cells during the combustion of jets at a supersonic jet velocity is nowhere noted. The results of experimental studies of the dependence of the flame lift-off value on the velocity during diffusion combustion of round microjets obtained in this work are also plotted on the graph (Fig. 4). There is a good agreement between our experimental data and the dependence presented in [10]. However, in contrast to the data of [10], our research results, indicating the “supersonic combustion” of a round microjet, are supported by one of the important characteristics of such a process, and the experimental detection of the existence of supersonic cells in a hydrogen microjet, as we assume, is the most important factor in stabilization of the flame under these conditions.

CONCLUSIONS

For the first time, four scenarios of diffusion combustion of round microjets of hydrogen are presented, including "supersonic combustion" in the presence of supersonic cells both in air and in hydrogen. It was found that flame stabilization at a subsonic round microjet velocity of hydrogen is associated with the presence of heating of the BFR nozzle, which leads to the phenomenon of "choking" the nozzle, and flame stabilization at a supersonic hydrogen microjet velocity is associated with the presence of supersonic cells. The hysteresis of the diffusion combustion process of round microjets of hydrogen was found depending on the place of ignition of the microjet (near or far from the nozzle exit section) and on the change in the jet velocity (growth or decrease). It has been found that the "supersonic diffusional combustion" of round microjets of hydrogen, both in air and in hydrogen, is realized only when the diameter of the outlet micronozzle is in the range of 1 mm or more.

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