Combustion of round hydrogen microjet in a cocurrent air flow with nanopowder

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Abstract. In the present paper we show our recent experimental data on diffusion combustion of a round hydrogen microjet in a cocurrent flow of air mixed with nanoparticles of TiO2. The hydrogen microjet is emanated from a round micronozzle which is surrounded by a coaxial slit to produce the cocurrent flow. Combustion events found in the present conditions are similar to those observed in the previous studies on diffusion combustion of hydrogen microjets at subsonic and supersonic velocities. In a subsonic range, the so-called “bottleneck-flame region” is generated close to the nozzle exit, while in high-speed conditions the flame separates from the nozzle. At increasing velocity of both the hydrogen microjet and the cocurrent flow, the “bottleneck-flame region” is still found and the combustion becomes more intense. The “bottleneck-flame region” is suppressed at the microjet velocity approaching transonic values.

1. Introduction
Experimental results on the diffusion combustion of round hydrogen microjets [1–5] testified to a variety of combustion scenarios at increasing velocity of the microjet emanating from the nozzles with the exit diameter in the range of 0.25 mm to 1.00 mm. The following main stages of the combustion were suggested. Combustion of the microjet with an extended laminar flame was found at \( U_0 \leq 150 \) m/s. Then, combustion in conditions of laminar-turbulent transition at the generation of spherically-shaped “bottleneck-flame region” close to the nozzle exit was observed at \( U_0 > 150 \) m/s. Turbulent flame separated from the “bottleneck-flame region” at \( U_0 > 200 \) m/s. Combustion terminated in the turbulent section of microjet, however, the laminar portion of microjet was still burning. The last option applies to flow velocity of up to transonic values. In our previous experiments [5, 6] we did not manage to examine the supersonic combustion because of the nozzle choking at \( U_0 > 331 \) m/s. Finally, combustion of the microjet was completely terminated at \( U_0= 331 \) m/s. Similar features were found at the diffusion combustion of plane hydrogen microjets [2, 7]. Note that the nozzle choking takes place at the velocity of hydrogen close to the speed of sound in air, that is, \( U_0= 331 \) m/s. Combustion of both round and plane microjets is stabilized by the generation of “bottleneck-flame region”.

As it was already emphasized, in our previous experiments we failed to achieve supersonic velocities of the hydrogen microjet at preservation of its diffusion combustion. One expects that the
nozzle chocking is due to the generation of “bottleneck-flame region” resulting in the nozzle heating and preventing the flame lift-off from its exit. A feature of the supersonic jet flow is the generation of supersonic cells in conditions of the flame lift-off from the nozzle which was demonstrated in [6, 8] at ignition of the hydrogen microjet far from the nozzle exit. In the above studies, the supersonic cells were observed both in the jet and in the flame detached from the nozzle. Some experimental and numerical data on the combustion of round hydrogen microjets at subsonic and supersonic velocity are presented in [9–11].

One more issue is the effect of gas additives to the hydrogen microjet on its combustion. Experimental results on the diffusion combustion of hydrogen premixed with methane, helium, or nitrogen in round microjets are presented in [12]. As is shown, the diffusion combustion of gas mixtures is featured with the origination of the “bottleneck-flame region” similarly to that at the diffusion combustion of pure hydrogen microjet. The “bottleneck-flame region” appears as a spherically-shaped laminar area of the microjet mixing with ambient air and their combustion. When overcoming the narrow layer of high density gradient at the border of the spherical “bottleneck-flame region”, the microjet and its flame instantly become turbulent. Several stages of the diffusion combustion of hydrogen/methane mixture in a round microjet were observed. Initially, the flame becomes separated from the nozzle at combustion sustaining in the “bottleneck-flame region”. Then, the flame lift-off occurs and, finally, the combustion stops completely which is similar to the behavior of burning pure-hydrogen microjet. The above stages of combustion of the hydrogen/methane mixture were found at the microjet velocity varying from 200 to 500 m/s being much lower than the velocity range of 600 to 800 m/s in which the same phenomena were observed at combustion of pure hydrogen. The microjet combustion of hydrogen/methane mixture appears more stable than that of pure methane so that the combustion of hydrocarbon can be stabilized in a wide range of flow velocity due to hydrogen additive. Also, it was shown that to make the diffusion combustion of microjets of hydrogen premixed with methane, helium, or nitrogen more stable at flow velocity getting higher, the portion of hydrogen should be increased.

The focus of [13] was the microjet combustion of hydrogen premixed with oxygen. It was found that the oxygen additive makes the velocity range of burning microjet smaller as compared to the diffusion combustion of pure hydrogen. At increasing velocity of the microjet, the spherically-shaped “bottleneck-flame region” of laminar microjet turned into a cylindrical configuration. Note that in the above experimental studies the gas mixtures were generated upstream of the nozzle section.

The objective of the present work is investigation of the diffusion combustion of round hydrogen microjet in a cocurrent flow representing a coaxial air jet with nanopowder. The interaction of both jets is examined at their subsonic and supersonic velocities. The present results are compared with our previous experimental data on combustion of hydrogen microjets.

2. Experimental Arrangement

Experimental set-up is shown in figure 1. To generate the jet flow, two nozzles were used. Micronozzle 1 was designed as a small-sized port for injection of hydrogen in the centre of the nozzle section surrounded by a coaxial slit to produce the cocurrent flow. In the case of micronozzle 2, the coaxial slit was replaced by a set of openings equally spaced around the central port. The hydrogen microjet was generated using a vessel at 100–atm pressure; the cocurrent flow was formed through injection of compressed air. The volume flow rate was controlled by electromagnetic valves 179B from MKS Instruments. Diffusion combustion of the hydrogen microjet, occurring with and without the cocurrent air flow seeded with nanoparticles, was recorded by a digital camera and examined at acquisition of its shadow images using a schlieren method and camera Nikon D7500 providing resolution of 24 Mpix.

Experimental runs were carried out at velocity variation of the hydrogen microjet and the cocurrent flow. The volume flow rate Q (sm³/s) was controlled by precision flow meters from MKS Instruments (USA) with an accuracy of 0.7 %. Microjet velocity was calculated as U = Q/S, where S stands for the cross section of the round nozzle of hydrogen microjet or that of the coaxial slit generating the
cocurrent flow. Note that the above formula is not appropriate in supersonic conditions as far as it does not take into account a set of parameters, particularly, gas compressibility. Thus, we also used another way to determine the microjet velocity through the pressure difference $\Delta P = P_{\text{inlet}} - P_{\text{atm}}$ at the inlet of micronozzle ($P_{\text{inlet}}$) and its exit ($P_{\text{atm}}$). If so, the microjet velocity makes

$$U = \sqrt{\frac{2 \cdot \Delta P}{\rho}}$$

where $\rho$ is density of hydrogen.

**Figure 1.** Experimental sketch: 1 – hydrogen, 2 – air flow, 3, 4 – flow-meter valve, 5 – flow-meter controller, 6 – nozzle section, 7 – schlieren device; cross sections of nozzles 1 and 2 are shown in the bottom.

In what follows, the crosssection $S_1$ of the central port of round micronozzle 1 generating the hydrogen flow is calculated as

$$S_1 = \frac{\pi \cdot d^2}{4} = \frac{3.14 \cdot 0.11^2}{4} = 0.0095 \text{ m}^2$$
and that of the coaxial slit $S_2$ for injection of cocurrent flow is given by the formula

$$S_2 = \pi \left( r_1^2 - r_2^2 \right) = 3.14 \times 0.17^2 - 3.14 \times 0.14^2 = 0.0292 \text{ cm}^2 \tag{3}$$

Similarly, in the case of nozzle 2 the crosssection $S_1$ makes

$$S_1 = \frac{\pi \times d^2}{4} = \frac{3.14 \times 0.11^2}{4} = 0.0095 \text{ cm}^2 \tag{4}$$

and the size of coaxial openings $S_2$ is measured as

$$S_2 = \pi \times r_2^2 - \pi \times r_1^2 = 3.14 \times 0.249^2 - 3.14 \times 0.173^2 = 0.097 \text{ cm}^2 \tag{5}$$

3. Experimental Results

3.1. Combustion of round hydrogen microjet in the cocurrent flow of air with nanopowder in subsonic conditions

Shadow images of the diffusion combustion of round hydrogen microjet emanating from nozzle 1 are presented in figure 2. One can compare the flow patterns taken in the absence (see figure 2a) and in the presence (see figure 2b) of the cocurrent flow of air with nanopowder. In particular, figure 2b illustrates the interaction of both jets at their combustion visualized in orange. Here and in what follows, the subscripts “1” and “2” stand for the hydrogen microjet and the cocurrent flow, respectively.

![Figure 2](image)

**Figure 2.** Shadow images of the burning hydrogen microjet in the absence of cocurrent flow ($Q_1=150 \text{ sm}^3/\text{s}$, $U_1=158 \text{ m/s}$) (a) and at their interaction ($Q_1=150 \text{ sm}^3/\text{s}$, $U_1=158 \text{ m/s}$, $Q_2=110 \text{ sm}^3/\text{s}$, $U_2=37.5 \text{ m/s}$) (b); nozzle 1.
Figure 3. Shadow images of the burning hydrogen microjet in the absence of cocurrent flow \( (Q_1=102 \text{ sm}^3/\text{s}, U_1=107 \text{ m/s}) \) (a) and at their interaction \( (Q_1=102 \text{ sm}^3/\text{s}, U_1=107 \text{ m/s}, Q_2 = 18 \text{ sm}^3/\text{s}, U_2= 6 \text{ m/s}) \) (b); nozzle 2.

In a similar way, the combustion of hydrogen microjet in the case of nozzle 2 is shown in figure 3. At the diffusion combustion of pure hydrogen without additive, the flame pattern is almost transparent (see figure3a) while in the presence of cocurrent air flow with nanopowder the flame turns orange (figure 3b).

Figure 4. Shadow images of the burning hydrogen microjet interacting with the cocurrent flow \( (Q_1=200 \text{ sm}^3/\text{s}, U_1=210 \text{ m/s}, Q_2 = 200 \text{ sm}^3/\text{s}, U_2= 20.5 \text{ m/s}) \) (a) and in the absence of air-nanopowder coaxial jet \( (Q_1=200 \text{ sm}^3/\text{s}, U_1= 210\text{m/s}) \) (b); nozzle 1.

Note that at the diffusion combustion of hydrogen microjet emanating from nozzle 1, the laminar flame is observed both with and without the cocurrent flow (figure 2). The flow patterns generated by
nozzle 2 (figure 3) are somewhat different. Though the velocities of hydrogen microjet and cocurrent flow become lower, one can see the origination of “bottleneck-flame region” at the nozzle exit and the turbulent flame further downstream. The interaction of hydrogen microjet with cocurrent flow results in intense burning of the air-nanopowder mixture as is visualized in figure 3b.

3.2. Diffusion combustion of round hydrogen microjet in the cocurrent flow of air with nanopowder in high-speed conditions

Similarly to figure 2, the diffusion combustion of round hydrogen microjet emanating from nozzle 1 is illustrated in figure 4 at increasing flow velocity. In this case, the turbulent flame becomes separated from the nozzle exit. In these conditions, the “bottleneck-flame region” degenerates and the laminar diffusion combustion is no longer observed.

**Figure 5.** Shadow images of the burning hydrogen microjet in the absence of cocurrent flow (U₁ = 210 m/s) (a) and at their interaction (U₁=210 m/s, U₂= 6 m/s) (b), (U₁=107 m/s, U₂= 6 m/s) (c); nozzle 1.

**Figure 6.** Shadow images of the burning hydrogen microjet in the absence of cocurrent flow (U₁ = 150 m/s) (a) and at their interaction (U₁=175 m/s, U₂= 6 m/s) (b), (U₁=175 m/s, U₂= 9 m/s) (c); nozzle 1.
Figure 7. Shadow images of the burning hydrogen microjet in the absence of cocurrent flow ($U_1= 50$ m/s) (a) and at their interaction ($U_1=60$ m/s, $U_2= 4.5$ m/s) (b), ($U_1=70$ m/s, $U_2= 9$ m/s) (c); nozzle 1.

Further, the combustion of round hydrogen microjet at variation of flow velocity is demonstrated in figures 5–7, the main features being as follows. As it is seen in figure 5, the flame separates from the nozzle exit so that the laminar combustion is not sustained. At reduction of flow velocity, one can observe laminar flame (see figure 6). Then, the flame turns necked at the border of cocurrent flow with distinct radiation by the heated nanoparticles (see figure 7).

Thus, the present data on diffusion combustion of the high-speed round hydrogen microjet affected by the coaxial cocurrent air flow with nanopowder support the scenarios of combustion which we observed earlier in a wide range of flow velocity [1–7]. Particularly, in the case of flame separation from the nozzle exit the combustion becomes turbulent in the absence of laminar section of the microjet (see figure 5). If so, the nozzle is not heated and the stability of flame goes down at increasing flow velocity. At diminution of the velocity of hydrogen microjet, the flame attaches to the nozzle (see figure 6). In such conditions, the temperature of nanoparticles which are injected through the coaxial slit grows up to $1500^\circ$C and even higher so that the burning mixture radiates in yellow. At further reduction of flow velocity down to $50–60$ m/s (see figure 7), the laminar section of microjet combustion originates close to the nozzle exit; in this case, the radiation of nanoparticles is not so pronounced, as compared to figure 6.

Conclusions
In the present study we examined the combustion of round hydrogen microjet interacting with cocurrent coaxial flow, the latter representing a mixture of air with nanopowder. The experimental data are obtained at subsonic and transonic flow velocities. As is found, the scenarios of diffusion combustion in conditions of the cocurrent flow are similar to those of the isolated hydrogen microjet. The origination of “bottleneck-flame region” at the nozzle exit is observed as well as the flame lift-off at increasing velocity of hydrogen. At flow velocity getting higher the diffusion combustion is intensified. At the generation of “bottleneck-flame region”, the flame becomes deformed both in the centre of microjet and in the cocurrent flow. One more observation is that heating of nanoparticles is not uniform over the microjet cross section. As it is seen in Fig. 7b, the nanoparticles emanating from the coaxial slit are heated most of all in the central area of hydrogen flow. The effect is so strong that they become radiating visible light. At the same time, flow temperature of the burning cocurrent flow is lower so that the radiation goes down. Finally, when the hydrogen velocity approaches the transonic range of air, the laminar combustion is terminated and the flame becomes completely turbulent.
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