Combustion of Round Hydrogen Microjet in Concurrent Flow

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Abstract—Experimental data on the diffusion combustion of a round hydrogen microjet in a concurrent coaxial flow are presented. The effects on the combustion of a concurrent air flow and an air flow premixed with nanopowder of TiO$_2$ are of interest. The hydrogen microjet emanates from a round micronozzle, which is surrounded by a coaxial slit to produce the concurrent flow. Combustion events found in these conditions are similar to those observed in the previous studies on the 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 concurrent 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.

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INTRODUCTION

Experimental data on the diffusion combustion of round hydrogen microjets [1–5] testified to a variety of combustion events at an increasing velocity of microjet emanating from nozzles with an exit diameter ranging from 0.25 to 1.00 mm. The following main stages of the combustion were suggested.

1. Combustion of the microjet with an extended laminar flame at $U_0 \leq 150$ m/s.
2. Generation of the laminar “bottleneck-flame region” close to the nozzle exit with subsequent turbulization of the microjet, overcoming the narrow layer of density gradient at $U_0 > 150$ m/s.
3. Separation of turbulent flame from the “bottleneck-flame region” at $U_0 > 200$ m/s.
4. Termination of the combustion in the turbulent section of the microjet, the laminar portion of microjet still burning. The last option applies to flow velocities of up to transonic values. In our previous experiments [5, 6], we failed to examine the supersonic combustion because of the nozzle choking at $U_0 > 331$ m/s.
5. The combustion of the microjet completely terminates at $U_0 \approx 331$ m/s. Similar scenarios were found at the diffusion combustion of plane hydrogen microjets [2, 7]. Note that the nozzle choking takes place at a velocity of hydrogen close to the speed of sound in air, that is, $U_0 \approx 331$ m/s. Combustion of both round and plane microjets is stabilized by the generation of “bottleneck-flame region.”

As already noted, in our previous experiments we failed to achieve supersonic velocities of the hydrogen microjet at preservation of its diffusion combustion. The nozzle choking might be due to the generation of “bottleneck-flame region,” resulting in the nozzle heating and preventing the flame lift-off from its exit. The supersonic jet flow has a feature of the generation of supersonic cells in the conditions of the flame lift-off from the nozzle, which was demonstrated in [6, 8] at ignition of hydrogen microjet

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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].

There is another issue of the effect of 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 shown, the diffusion combustion of gas mixtures features the origination of the “bottleneck-flame region” similar to that in the diffusion combustion of pure hydrogen microjet. The “bottleneck-flame region” appears as a spherically-shaped laminar area of 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” 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, the 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 hydrogen/methane mixture were found at microjet velocities varying from 200 to 500 m/s, which is much lower than the velocity range of 600 to 800 m/s of the same phenomena observed at combustion of pure hydrogen. The microjet combustion of hydrogen/methane mixture appears more stable than that of pure methane and thus a hydrogen additive enables stabilization of the combustion of hydrocarbon in a wide range of flow velocity. It was also shown that for more stable diffusion combustion of microjets of hydrogen premixed with methane, helium, or nitrogen at increasing flow velocity, the portion of hydrogen should be increased. So, 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 with 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 experimental investigation of the diffusion combustion of round hydrogen microjet interacting with concurrent flows of air and that of air premixed with nanopowder. The combustion is examined at subsonic and supersonic flow velocities. The present results are compared with our previous experimental data on combustion of hydrogen microjets.

**EXPERIMENTAL ARRANGEMENT**

The experimental set-up is shown in Fig. 1. To generate a burning microjet, the nozzle section of the test facility was supplied with hydrogen from a vessel at a pressure of 100 atm; a concurrent air flow emanated from a coaxial slit due to injection of compressed air, as shown in Fig. 1. In the conditions of concurrent air flow seeded with nanoparticles, 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 concurrent air flow. In the case of micronozzle 2, the coaxial slit was replaced by a set of openings equally spaced around the central port.

The diffusion combustion of the hydrogen microjet occurring with and without a concurrent air flow was recorded by a digital camera and examined via acquisition of its shadow images using the schlieren method and a camera Nikon D7500 with a resolution of 24 Mpix. The volume flow rate \( Q \) (cm\(^3\)/s) was controlled by precision flow meters from MKS Instruments (USA) with an accuracy of 0.7%. The 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 concurrent flow. Note that the above formula is not appropriate in supersonic conditions because it does not take into account some parameters, particularly, the 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 is \( U = \sqrt{2 \cdot \frac{\Delta P}{\rho}} \), where \( \rho \) is the density of hydrogen.

In what follows, the cross section of round micronozzle generating the hydrogen microjet interacting with the concurrent air flow is calculated as
Fig. 1. Experimental sketch: 1—hydrogen, 2—air flow, 3, 4—flow meter valve, 5—flow meter controller, 6—nozzle section, 7—schlieren device; the cross section of the nozzle is shown in the bottom.

\[ S_1 = \frac{\pi \cdot d^2}{4} = \frac{3.14 \cdot 0.1^2}{4} = 0.0078 \text{ cm}^2 \]

and that of the coaxial slit for air injection is given by the formula

\[ S_2 = \pi \cdot r_1^2 - \pi \cdot r_2^2 = 0.0772 \text{ cm}^2. \]

In the conditions of concurrent flow of air with nanopowder, the cross section \( S_1 \) of the central port of micronozzle 1 generating the hydrogen microjet is

\[ S_1 = \frac{\pi \cdot d^2}{4} = \frac{3.14 \cdot 0.11^2}{4} = 0.0095 \text{ cm}^2 \]

and the cross section of the coaxial slit \( S_2 \) for injection of concurrent flow is

\[ S_2 = \pi \cdot r_1^2 - \pi \cdot r_2^2 = 3.14 \cdot 0.17^2 - 3.14 \cdot 0.14^2 = 0.0292 \text{ cm}^2. \]

Similarly, in the case of micronozzle 2, the cross section \( S_1 \) is the same,

\[ S_1 = \frac{\pi \cdot d^2}{4} = \frac{3.14 \cdot 0.11^2}{4} = 0.0095 \text{ cm}^2, \]

while the size of coaxial openings \( S_2 \) is calculated as

\[ S_2 = \pi \cdot r_1^2 - \pi \cdot r_2^2 = 3.14 \cdot 0.248^2 - 3.14 \cdot 0.175^2 = 0.097 \text{ cm}^2. \]
EXPERIMENTAL RESULTS

Combustion of Round Hydrogen Microjet in Concurrent Air Flow in Subsonic Conditions

Shadow images of the microjet combustion at variation of the velocity of hydrogen \( U_1 \), m/s, and of the coaxial air microjet \( U_2 \), m/s, are presented in Figs. 2 and 3. In the absence of concurrent air flow (Fig. 2a), one can observe the origination of “bottleneck-flame region,” the phenomenon already discussed in our previous studies [1–5]. The “bottleneck-flame region” is still found in the conditions of the hydrogen microjet interacting with the air microjet (Figs. 2b, 2c, and 3); however, the above spherically-shaped flow region turns into a cylindrical one. With increase in the velocity of the concurrent air flow, the “bottleneck-flame region” shrinks, as at acceleration of the hydrogen microjet, which was observed in [1–5]. One can also see in Fig. 4 that the turbulent combustion is intensified downstream of the “bottleneck-flame region” as the speed of axial air jet is getting higher.

Thus, we conclude that the main features of subsonic diffusion combustion of a hydrogen microjet surrounded by a concurrent air jet are similar to those we observed earlier in hydrogen microjets [1–5], except for some details, e.g., the deformation of “bottleneck-flame region” and the intensification of turbulent combustion at increase in the velocity of the coaxial air jet.

![Fig. 2](image)

**Fig. 2.** Shadow images of hydrogen combustion modulated by concurrent air jet at constant \( U_1 = 130 \) m/s and \( U_2 \) equal to (a) 0, (b) 2.33, and (c) 4.53 m/s.

![Fig. 3](image)

**Fig. 3.** Shadow images of hydrogen combustion modulated by concurrent air jet at constant \( U_1 = 130 \) m/s and \( U_2 \) equal to (a) 17.5, (b) 35, and (c) 50 m/s.
Fig. 4. Shadow images of hydrogen combustion modulated by concurrent air jet at constant $U_1 = 204$ m/s and $U_2$ equal to (a) 0, (b) 9, (c) 18, and (d) 26 m/s.

Fig. 5. Supersonic round microjets of (a) air and (b) hydrogen at $U_1 = 340$ m/s and 1300 m/s, respectively.

Supersonic Microjets of Air and Hydrogen in the Absence of Combustion

Two supersonic microjets emanating from identical micronozzles are compared in Fig. 5. In both cases, one can observe supersonic cells, whose spatial configuration is somewhat different. Moreover, the transverse spread of the air microjet is obviously smaller than that of the hydrogen flow.

Supersonic Air Microjets with and without Concurrent Air Flow in the Absence of Combustion

Figure 6 shows the flow patterns of round air microjet, which were obtained with and without a concurrent air microjet. In both cases, the supersonic cells are clearly seen as an indication of high-speed conditions.

Figure 7 illustrates a supersonic air microjet emanating from the plane slit, which simulates the coaxial slit of the concurrent microjet with the same dimensions, $h = 0.8$ mm and $l = 13$ mm. Once again, supersonic cells similar to those shown in Fig. 6 are observed.

Figure 8 presents the shadow images of air microjet generated at the exit of coaxial slit, demonstrating supersonic cells (compare with Fig. 6.).
Figure 6. (a) Isolated round air microjet and (b) round air microjet interacting with concurrent air flow, $U_1 \approx 340$ m/s.

Figure 7. Shadow images of plane air microjet taken from narrow (0.8 mm) (a) and wide (13 mm) (b) sides of nozzle.

Figure 8. Shadow images of concurrent air microjet recorded at (a) $U_2 = 280$ m/s, (b) 340 m/s, and (c) 370 m/s.

Figure 9 gives the flow patterns of the interacting air microjets. As in the previous sections, $U_1$ and $U_2$ stand for the velocity of microjets emanating from the round nozzle and the coaxial slit, respectively. In cases $a\text{--}d$, the value of $U_1$ stays equal to 340 m/s with $U_2$ varying from 0 to 400 m/s. Oppositely, in cases $e\text{--}h$, the velocity $U_2$ stays equal to 340 m/s, while $U_1$ ranges from 0 to 400 m/s. In this way, the interaction of two microjets is made clear at supersonic velocities of round ($a\text{--}d$) and concurrent ($e\text{--}h$) jet flows.

Finally, the combustion of round hydrogen microjet at $U_1 \approx 340$ m/s in the absence of concurrent microjet is illustrated in Fig. 10a; compare with the combustion of round hydrogen microjet at $U_1 =$
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Fig. 9. Shadow images of round and concurrent microjets at (a–d) $U_1 = 340$ m/s and $U_2 = 0, 260, 340, \text{ and } 400$ m/s and (e–h) $U_2 = 340$ m/s and $U_1 = 0, 280, 340, \text{ and } 400$ m/s.

Fig. 10. Shadow images of hydrogen combustion at $U_1 = 340$ m/s (a) without concurrent microjet and (b) with it at $U_1 = 340$ m/s and $U_2 = 25$ m/s. 340 m/s in the presence of concurrent flow at $U_2 = 25$ m/s (Fig. 10b). In both cases, one can observe the flame lift-off from the nozzle exit and turbulent combustion of the microjet. Note that the flame becomes more detached from the nozzle exit in the conditions of concurrent flow (Fig. 10b).

To sum up the presented findings, we conclude that the main features of the supersonic diffusion combustion of round hydrogen microjet in a concurrent air flow are similar to those we observed in our previous experiments on the combustion of hydrogen microjets [1–5].

Combustion of Round Hydrogen Microjet in Concurrent Flow of Air with Nanopowder in Subsonic Conditions

Shadow images of the diffusion combustion of round hydrogen microjet emanating from micronozzle 1 are presented in Fig. 11. One can compare the flow patterns taken in the absence (Fig. 11a) and in the presence (Fig. 11b) of concurrent flow of air with nanopowder. In particular, Fig. 11b 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 concurrent flow, respectively.
Fig. 11. Shadow images of burning hydrogen microjet (a) in the absence of concurrent flow \((Q_1 = 150 \text{ cm}^3/\text{s}, U_1 = 158 \text{ m/s})\) and (b) at their interaction \((Q_1 = 150 \text{ cm}^3/\text{s}, U_1 = 158 \text{ m/s}, Q_2 = 110 \text{ cm}^3/\text{s}, U_2 = 37.5 \text{ m/s})\); micronozzle 1.

In a similar way, the combustion of hydrogen microjet in the case of micronozzle 2 is shown in Fig. 12. At the diffusion combustion of pure hydrogen without additive, the flame pattern is almost transparent (Fig. 12a), while the flame turns orange in the presence of concurrent air flow with nanopowder (Fig. 12b).

Note that at the diffusion combustion of the hydrogen microjet emanating from micronozzle 1, a laminar flame is observed both with and without a concurrent flow (Fig. 11). The flow patterns generated by micronozzle 2 are somewhat different (Fig. 12). Though the velocities of the hydrogen microjet and concurrent flow become lower, one can see the origination of “bottleneck-flame region” at the micronozzle exit and the turbulent flame further downstream. The interaction of the hydrogen microjet with the concurrent flow results in the intense burning of the air-nanopowder mixture, as visualized in Fig. 12b.

Diffusion Combustion of Round Hydrogen Microjet in Concurrent Flow of Air with Nanopowder in High-Speed Conditions

As in Fig. 11, the diffusion combustion of round hydrogen microjet emanating from micronozzle 1 is illustrated in Fig. 13 at increase in the 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.

Further, the combustion of round hydrogen microjet at variation of the flow velocity is demonstrated in Figs. 14–16, the main features being as follows. As seen in Fig. 14, the flame separates from the nozzle exit and thus the laminar combustion is not sustained. At reduction of the flow velocity, one can observe the laminar flame (Fig. 15). Then, the flame gets a neck at the border of the concurrent flow with distinct radiation by the heated nanoparticles (Fig. 16).

Thus, the presented data on the diffusion combustion of high-speed round hydrogen microjet affected by a concurrent coaxial air flow with nanopowder support the combustion scenarios 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 the laminar section of the microjet (Fig. 14). If so, the nozzle is not heated and the stability of the flame declines at increase in the flow velocity. At diminution of the velocity of the hydrogen microjet, the flame stays at the nozzle (Fig. 15). In such conditions, the temperature of nanoparticles injected through the coaxial slit grows up to 1500°C and even higher so that the burning mixture radiates in yellow. At further reduction of the flow velocity down
Fig. 12. Shadow images of burning hydrogen microjet (a) in the absence of concurrent flow ($Q_1 = 102$ cm$^3$/s, $U_1 = 107$ m/s) and (b) at their interaction ($Q_1 = 102$ cm$^3$/s, $U_1 = 107$ m/s, $Q_2 = 18$ cm$^3$/s, $U_2 = 6$ m/s); micronozzle 2.  
1—turbulent flame of combustion of hydrogen; 2—flame of combustion of air/nanopowder mixture.

CONCLUSION

In the present paper, we reported our recent experimental results on the combustion of round hydrogen microjet interfering with a concurrent coaxial flow. Two options were considered: a concurrent flow of air and that of air seeded with nanoparticles. In the first case, the flame configuration features the origination of “bottleneck-flame region” close to the nozzle exit, which is in agreement with our previous observations on the subsonic diffusion combustion of hydrogen microjets. At variation of the flow velocity, the spherically-shaped “bottleneck-flame region” turns into a cylindrical one. In the conditions of supersonic combustion, supersonic cells are generated both in the hydrogen microjet and in the concurrent air flow. The diffusion combustion of round hydrogen microjet affected by a supersonic concurrent air jet occurs with the flame detached from the nozzle.

In the case of concurrent air flow premixed with nanoparticle, the experimental data are also obtained at subsonic and transonic flow velocities. The scenarios of the diffusion combustion in the conditions of concurrent flow turned out to be similar to those of an 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. As the flow velocity increases, the diffusion combustion becomes more intense. With the appearance of “bottleneck-flame region,” the flame becomes deformed both in the centre of the microjet and in the concurrent flow. The heating of nanoparticles is not uniform over the microjet cross section. As seen in Fig. 16b, the nanoparticles emanating from the coaxial slit are heated to the highest temperature in the central area of the hydrogen flow. The effect is so strong that they start radiating visible light. At the same time, the temperature of the burning concurrent 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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Fig. 13. Shadow images of burning hydrogen microjet (a) interacting with concurrent flow ($Q_1 = 200 \text{ cm}^3/\text{s}$, $U_1 = 210 \text{ m/s}$, $Q_2 = 200 \text{ cm}^3/\text{s}$, $U_2 = 20.5 \text{ m/s}$) and (b) in the absence of air-nanopowder coaxial jet ($Q_1 = 200 \text{ cm}^3/\text{s}$, $U_1 = 210 \text{ m/s}$); micronozzle 1. 1—turbulent flame of combustion of hydrogen; 2—flame of combustion of air/nanopowder mixture; 3—flame separation.

Fig. 14. Shadow images of burning hydrogen microjet (a) in the absence of concurrent flow ($U_1 = 210 \text{ m/s}$) and (b) at their interaction ($U_1 = 210 \text{ m/s}$, $U_2 = 6 \text{ m/s}$) and (c) $U_1 = 107 \text{ m/s}$, $U_2 = 6 \text{ m/s}$); micronozzle 1. 1—turbulent flame of combustion of hydrogen; 2—flame of combustion of air/nanopowder mixture; 3—flame separation.

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Fig. 15. Shadow images of burning hydrogen microjet (a) in the absence of concurrent flow ($U_1 = 150\ m/s$) and (b) at their interaction ($U_1 = 175\ m/s$, $U_2 = 6\ m/s$) and (c) $U_1 = 175\ m/s$, $U_2 = 9\ m/s$); micronozzle 1. 1—turbulent flame of combustion of hydrogen; 2—flame of combustion of air/nanopowder mixture.

Fig. 16. Shadow images of burning hydrogen microjet (a) in the absence of concurrent flow ($U_1 = 50\ m/s$) and at their interaction, (b) $U_1 = 60\ m/s$, $U_2 = 4.5\ m/s$ and (c) ($U_1 = 70\ m/s$, $U_2 = 9\ m/s$); micronozzle 1. 1—bottleneck-flame region; 2—turbulent flame of combustion of hydrogen; 3—nozzle; 4—“bottleneck-flame” region of hydrogen combustion; 5—flame of combustion of air/nanopowder mixture; 6—“bottleneck-flame” region of combustion of concurrent flow.

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