Combustion of round hydrogen microjet in a cocurrent air flow

V V Kozlov¹,²,*, G R Grek¹, M M Katasonov¹, M V Litvinenko¹, Yu A Litvinenko¹, A S Tambovtsev¹,² and A G Shmakov³

¹Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences
²Novosibirsk State University, Novosibirsk
³V.V. Voevodsky Institute of Chemical Kinetics and Combustion of the Siberian Branch of the Russian Academy of Sciences

*E-mail: kozlov@itam.nsc.ru

Abstract. Experimental data on combustion of a round hydrogen microjet in a cocurrent coaxial air jet are presented. As is found, the combustion of microjet is dominated by the generation of “bottleneck-flame region” that is in agreement with our previous observations on the diffusion combustion of subsonic hydrogen microjets. Transformation of the spherical “bottleneck-flame region” to a cylindrical one is observed. At supersonic combustion of the round hydrogen microjet, supersonic cells are generated both in the microjet and in the cocurrent coaxial air flow. A feature of the combustion process is the flame lift-off from the nozzle exit.

1. Introduction

Experimental data on the diffusion combustion of round hydrogen microjets [1–5] testified to a variety of combustion events at increasing velocity of the microjet emanating from the nozzles with the exit diameter ranging from 0.25 to 1.00 mm. The following stages of the combustion were distinguished. Combustion of the microjet with an extended laminar flame was observed at $U_0 \leq 150$ m/s. Then, generation of the laminar “bottleneck-flame region” close to the nozzle exit with the following turbulization of the microjet overcoming the narrow layer of density gradient occurred at $U_0 > 150$ m/s. Turbulent flame separated from the “bottleneck-flame region” at $U_0 > 200$ m/s. Turbulent combustion was terminated, however, the microjet was still burning in the “bottleneck-flame region” at $U_0 > 331$ m/s. In the last case, the combustion was observed in the “bottleneck-flame region” up to transonic velocities of the microjet in conditions of nozzle choking [5, 6]. Combustion of the microjet was completely terminated at $U_0 \approx 331$ 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 microjet close to the velocity of sound in air ($U_0 \approx 331$ m/s). Combustion of both round and plane microjets is stabilized by the generation of “bottleneck-flame region”.

In our previous experiments we failed to examine the supersonic diffusion combustion of hydrogen microjet because of the nozzle choking by the “bottleneck-flame region” which resulted in the nozzle heating and prevented the flame lift-off from its exit. A feature of the supersonic combustion is the generation of supersonic cells in conditions of flame separation from the nozzle exit. For detail on the round hydrogen microjet at its ignition far from the nozzle exit see [6, 8] where the supersonic cells
were observed both in the microjet and in the flame detached from the nozzle. Experimental and numerical results on combustion of subsonic and supersonic round hydrogen jets are reported in Refs. [9–11].

An issue is the effect of gas additives to the hydrogen microjet on its combustion. Experimental data on the diffusion combustion of hydrogen premixed with methane, helium, or nitrogen in round microjets are presented in [12]. As it 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 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 gas mixture were found at the microjet velocities 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. Also, the microjet combustion of the hydrogen/methane mixture is found 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. To make the combustion of round microjets of hydrogen premixed with methane, helium, or nitrogen more stable at flow velocity getting higher, the portion of hydrogen should be increased.

On the other hand, the microjet combustion in conditions of hydrogen premixed with an oxidizer was the focus of [13]. It was found that the oxygen additive makes the velocity range of burning microjet smaller as compared to the combustion of pure hydrogen. At increasing velocity of the microjet, the combustion was terminated at reduction of the portion of oxygen in the gas mixture. Simultaneously, the spherically-shaped “bottleneck-flame region” of laminar microjet turned into a cylindrical-flow configuration becoming more narrow with the growth of microjet velocity. Note that in the above experimental studies [12, 13] the gas mixtures were generated upstream of the nozzle section.

The objective of the present work is investigation of the combustion of round hydrogen microjet in a cocurrent coaxial air microjet. Most of all we are interested in the interaction of both jets 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 illustrated in figure 1. To generate a burning microjet, the nozzle section of the test facility was supplied with hydrogen from a vessel at 100–atm pressure; a cocurrent air jet emanated from a coaxial slit as is shown in figure 1. The volume flow rate $Q$ (sm$^3$/s) of both microjets was controlled by electromagnetic valves 179B from MKS Instruments with an accuracy of 0.7 %. Diffusion combustion of the hydrogen microjet, occurring with and without the cocurrent air flow, 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. Microjet velocity was calculated as $U(m/s) = Q$ (sm$^3$/s) / $S$ (sm$^2$) where $S$ stands for the cross section of the round nozzle of hydrogen microjet or that of the coaxial slit generating the cocurrent air flow. Note that the above formula is not appropriate in supersonic conditions ($M > 1$) 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 $\Delta P = P_{inlet} - P_{atm}$ at the inlet of micronozzle ($P_{inlet}$) and its exit ($P_{atm}$). If so, the microjet velocity makes $U_0$ (m/s) = $\sqrt{2 \Delta P / \rho}$ where $\rho$ (kg/m$^3$) 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-section of the nozzle is shown in the bottom.

Here, the crossection of round micronozzle generating the hydrogen flow is calculated as

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

(1)

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

\[
S_2 = \pi \times r - \pi \times r = 0.0772 \text{ sm}
\]  

(2)

3. Experimental Results

Shadow images of the microjet combustion at variation of the hydrogen velocity \(U_1, \text{m/s}\) and coaxial air microjet \(U_2, \text{m/s}\) are presented in figures 2 and 3. In the absence of cocurrent air flow (see figure 2a) one can observe the origination of “bottleneck-flame region”, the phenomenon which we discussed in our previous studies [1–5]. The “bottleneck-flame region” is still found in conditions of the hydrogen microjet interacting with the air microjet (see figures 2b,c and 3); however, the above spherically-shaped flow region turns into a cylindrical one. At increasing velocity of the cocurrent air flow, the “bottleneck-flame region” shrinks similarly to that at acceleration of the hydrogen microjet which was observed in [1–5]. Also, one can see in figure 4 that the turbulent combustion is intensified downstream of the “bottleneck-flame region” at the speed of axial air jet getting higher.
Figure 2. Shadow images of the hydrogen combustion modulated by the cocurrent air jet at a constant $U_1 = 130$ m/s and at variation of $U_2$ as 0 (a), 2.33 (b), and 4.53 (c) m/s.

Figure 3. Shadow images of the hydrogen combustion modulated by the cocurrent air jet at a constant $U_1 = 130$ m/s and at variation of $U_2$ as 17.5 (a), 35 (b), and 50 (c) m/s.

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

3.1. Supersonic microjets of air and hydrogen in the absence of combustion
Two supersonic microjets emanating from identical micronozzles are compared in figure 5. In both cases one can observe supersonic cells whose spatial configuration is somewhat different. Also, the transverse spreading of air microjet is obviously smaller than that of the hydrogen flow.
Figure 4. Shadow images of the hydrogen combustion modulated by the cocurrent air jet at a constant $U_1 = 204$ m/s and at variation of $U_2$ as 0 (a), 9 (b), 18 (c) and 26 (d) m/s.

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

3.2. Supersonic air microjets with and without the cocurrent air flow in the absence of combustion

Figure 6 shows flow patterns of the round air microjet which were taken with and without the cocurrent air microjet. In both cases, the supersonic cells are clearly seen as an indication of high-speed conditions.
Figure 6. Isolated round air microjet (a) and that interacting with the cocurrent air flow (b), $U_1 = 340$ m/s. Arrows are supersonic cells.

Supersonic air microjet emanating from a plane slit, the latter simulating the coaxial one of the cocurrent microjet with the same dimensions of $h = 0.8$ mm and $l = 13$ mm, is illustrated in figure 7. Once again, the supersonic cells are observed similarly to that shown in figure 6.

Figure 7. Shadow images of the plane air microjet taken from the narrow (0.8 mm) (a) and wide (13 mm) (b) sides of the nozzle.
Figure 8. Shadow images of the cocurrent air microjet recorded at $U_2 = 280$ m/s (a), 340 m/s (b), and 370 m/s (c).

Then, in figure 8 the shadow images of air microjet generated at the exit of coaxial slit are presented demonstrating the supersonic cells, compare to figure 6.

Flow patterns of the interacting air microjets are given in the figure. 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–d, the value of $U_1$ keeps constant as 340 m/s at $U_2$ varying from 0 to 400 m/s. Oppositely, in conditions of e–h, the velocity $U_2 = 340$ m/s is the same while $U_1$ is ranging from 0 to 400 m/s. In this way, the interaction of two microjets is made clear at supersonic velocities of the round (а–d) and the cocurrent (e–h) jet flows.

Finally, the combustion of round hydrogen microjet at $U_1 \approx 340$ m/s in the absence of cocurrent microjet is illustrated in figure 10a, compare to the combustion of round hydrogen microjet at $U_1 = 340$ m/s in the presence of cocurrent flow at $U_2 = 25$ m/s (see figure 7b). 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 conditions of the cocurrent flow (see figure 7b).

Figure 9. Shadow images of the round and cocurrent microjets at $U_1 = 340$ m/s, $U_2 = 0$, 260, 340 and 400 m/s (a–d), and $U_2 = 340$ m/s, $U_1 = 0$, 280, 340, and 400 m/s (e–h).
Figure 10. Shadow images of the hydrogen combustion at \( U_1 = 340 \) m/s in the absence of cocurrent microjet (a) and in its presence at \( U_1 = 340 \) m/s and \( U_2 = 25 \) m/s (b).

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

Conclusions
In the present paper we reported our recent experimental results on the combustion of round hydrogen microjets interfering with a cocurrent coaxial air flow. As it is found, the flame configuration is distinguished by the origination of “bottleneck-flame region” close to the nozzle exit that is in agreement with our previous observations on the subsonic diffusion combustion of hydrogen microjets. At variation of flow velocity, the spherically-shaped “bottleneck-flame region” turns into a cylindrical one. In conditions of supersonic combustion, the supersonic cells are generated both in the hydrogen microjet and in the cocurrent air flow. The diffusion combustion of round hydrogen microjet affected by the supersonic cocurrent air jet occurs when flame detached from the nozzle.

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