Scenarios of combustion of plane hydrogen microjets at sub- and supersonic velocities

Mikhail Katasonov, *Victor* Kozlov, *Yury* Litvinenko, and *Andrey* Shmakov

Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences, 4/1 Institutskaya Street, Novosibirsk, 630090, Russia

Abstract. Experimental data on diffusion combustion of plane hydrogen microjets emanating from a slotted micronozzle at subsonic and supersonic velocities are reported. Four scenarios of diffusion combustion of the hydrogen microjets are presented. As is found, the stabilization of subsonic combustion of the hydrogen microjet is related to the origination of a "bottle-neck" configuration of flame while in supersonic conditions the flow pattern is dominated by supersonic cells. Hysteresis of the diffusion combustion of plane hydrogen microjet is found depending on its ignition far from or close to the nozzle exit and velocity variation.

1 Introduction

Hydrogen energy is not only an overdue transition to the development of a new environmentally acceptable source of energy, but also an incentive to achieve more efficient use of traditional fuels, increase the efficiency of the engines used and ensure a higher degree of environmental safety of fuel and energy enterprises and transport. One of the main ideas in the modern race for environmentally acceptable energy technologies has been the desire for further decarbonization of atmospheric air (reducing the share of greenhouse gas emissions). For these purposes, the consumption of fuel oil, oil and coal is being reduced. Their replacement with environmentally friendly natural gas continues. The position of nuclear energy is strengthening and the use of renewable energy sources is actively increasing. In the future, the struggle for efficient energy sources and progressive decarbonization of the atmosphere will inevitably continue in the process of active development of hydrogen energy. The results obtained will make it possible to propose new technological solutions for burning fuel (hydrogen gas) at subsonic velocities of microjets (up to transonic velocities) during their diffusion combustion, for stable and safe combustion of hydrogen gas in the surrounding inert environment, for example at the inlet of a steam turbine, for increasing the pressure and raising the temperature of the working steam. Therefore, the study of the combustion of hydrogen jet flows arising when using various types of injectors, burners and nozzles is of interest.

This paper examines the results of studies of the combustion of hydrogen microjets. Microjets are understood as flows behind the exit of a nozzle having a flat or round cross-section and a transverse size of less than 3 mm. Experimental data on diffusion combustion of circular microjets reported in refs. [1–5] testified to different behavior of the microjets emanating from round micronozzles at their diameter ranging from 0.25 to 1.00 mm. As a result, four scenarios of the microjet combustion were observed. 1. Combustion of a laminar microjet with an extended laminar flame at $U_0 \leq 150$ m/s. 2. Generation of a spherical "bottle-neck" flame region of laminar flow close to the nozzle exit, the microjet turning into turbulent one when overcoming a narrow layer of high density gradient at $U_0 > 150$ m/s. 3. Further, at $U_0 > 200$ m/s turbulent flame separates from the "bottle-neck" flame region. 4. Termination of combustion in the turbulent section of microjet, the latter still burning in the "bottle-neck" region. In this case, combustion proceeds in the "bottle-neck" configuration up to transonic velocities of the microjet, however nozzle blocking becomes pronounced at $U_0 >$ 331 m/s [5, 6]. Combustion of the microjet stops at about $U_0 = 331$ m/s. Similar behavior of plane microjets at their diffusion combustion was found in Refs. [2, 7]. Notice that nozzle blocking in conditions of hydrogen microjet occurred at flow velocity close to the sound speed in air $U_0 \approx 331$ m/s.

Combustion of both round and plane microjets was stabilized by the burning "bottle-neck" flame region. However, in our experiments we could not observe supersonic diffusion combustion of hydrogen microjet because of nozzle blocking by the "bottle-flame" region, the latter heating the nuzzle, thus, preventing separation of flame form its exit. Also, we point to supersonic cells generated at high velocities of the microjet in the case of flame separation from the nozzle exit. This was clearly demonstrated in Refs. [6, 8] at ignition of circular hydrogen microjet far from the nozzle exit. In this case, the supersonic cells were found both in the microjet and in the flame separating from the nozzle.

In the present paper we focus on experimental study of diffusion combustion of a plane hydrogen microjet, see Fig. 1 and Fig. 2. Most of all, we are interested in evolution of the microjet at high-speed conditions making $U_0 > 331$ m/s for air and $U_0 > 1284$ m/s for hydrogen in the presence of supersonic cells.

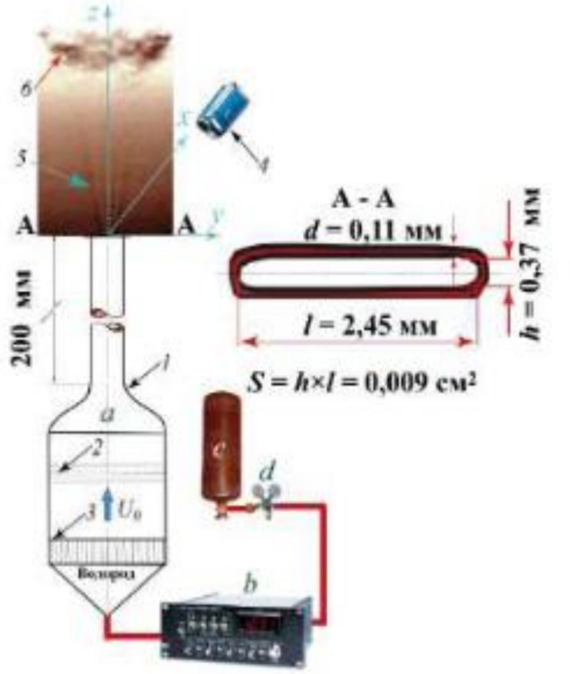


Fig. 1. Experimental scheme. a – nozzle section, b – flow meter, c – section of compressed hydrogen at 100 atm., d - reducer. The nozzle section includes a prechamber (1), a set of smoothing grids (2), a honeycomb and a microtube 200-mm long with a slotted micronozzle (3). Using a digital camera and thermal imager (4), shadow patterns of supersonic cells (5) and flame configuration were recorded (6).

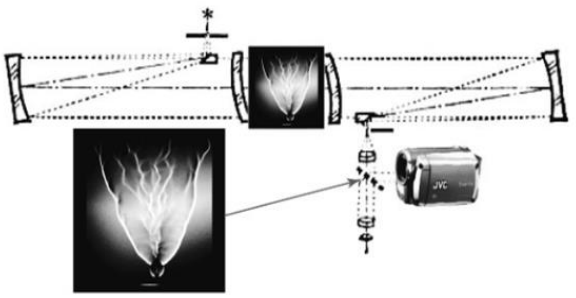


Fig. 2. Schematic representation of the Tepler IAB-451 shadow device and shadow picture of hydrogen combustion in a flat microjet.

2 Experimenatal data

As a result, four options of diffusion combustion of a plane hydrogen microjet were found, including combustion in the presence of supersonic cells typical of air and hydrogen high-speed flows, see Fig. 3.

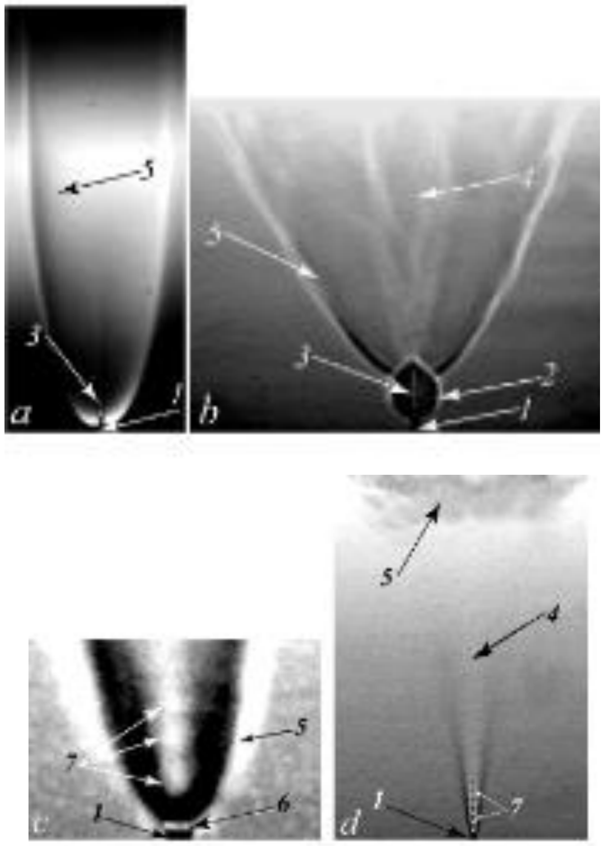


Fig. 3. Four scenarios of diffusion combustion of a plane hydrogen microjet at $U_0 \leq 150$ m/s (a), $U_0 = 150$ m/s (b), $U_0 = 330$ m/s (c), and $U_0 = 1280$ m/s (d). 1- initiation, 2 – narrow flame, 3 – laminar microjet, 4 – turbulent microjet, 5 – flame, 6 – separated flame, 7 – supersonic cells.

As is found, the stabilization of subsonic combustion is due to the presence of “bottle-neck” flame region in the upstream section of microjet. At high velocities, the stabilization of combustion is associated with the generation of supersonic cells. Hysteresis of the diffusion combustion was observed at ignition of the microjet either close to the nuzzle exit or far from it. Also, the behavior of burning microjet depends on variation of flow velocity going up or down, see Fig. 3.

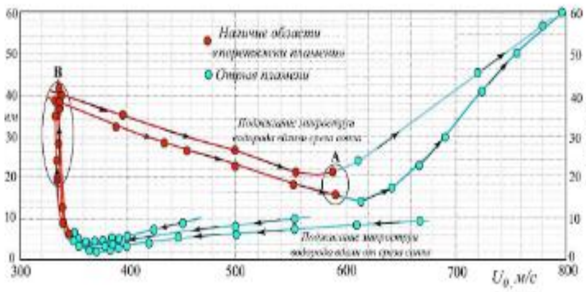
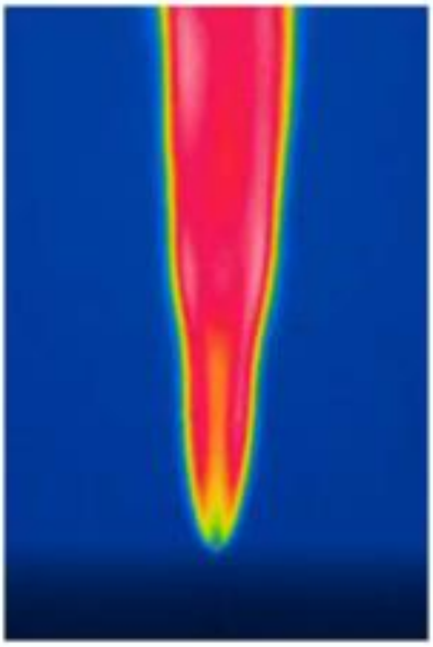
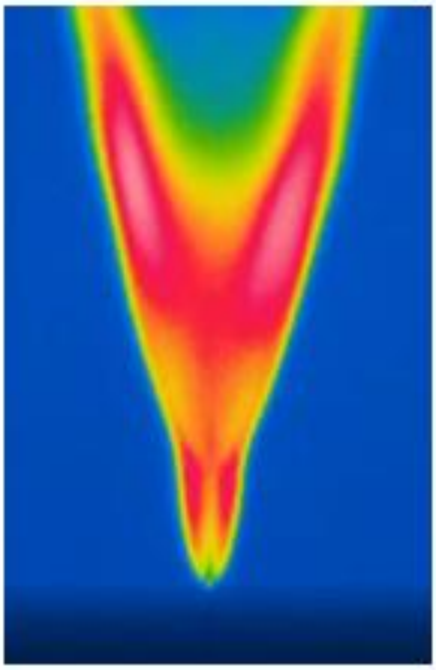


Fig.4. Graph (hysteresis) of the dependence of flame development of the hydrogen microjet depending on its outflow rate and ignition method (near/far from nozzle exit), speed range of (A) disappearance of the flame constriction region and beginning of flame detachment and (B) appearance of the flame constriction region. Arrows indicate the direction of change in the microjet.

In the present experimental configuration (see Fig. 1), an effect of external acoustic forcing on the spatial structure of plane hydrogen microjet emanating from the nozzle at velocities less than 150 m/s was clarified. In this case, the data were acquired using a thermal imager, see Fig. 5.



a)



b)

Fig. 5. Acoustic effect on the flame configuration at $U_0 < 150$ m/s., side view: without forcing (a) and under harmonic sonic excitation at 5500-Hz frequency, the sound pressure level being 95 dB (b).

For comparison, we examined a plane hydrogen microjet generated by much smaller micronozzle than that shown in Fig. 1 with the cross section of its exit measured as 0.40×0.07 mm^2. Thermal-imager patterns of combustion obtained in this case at different flow velocities as a side view of the microjet are presented in Fig. 6. The hysteresis which was already noticed was found at flow velocity varying from 320 to 370 m/s. The other scenarios of diffusion combustion were much similar to those observed in the case of round micronuzzle 30 microns in diameter, see Ref. 4. Also, we emphasize that transition to turbulence in the microjet did not occur in all of the experimental regimes and the flow did not respond to acoustic excitation in the range of 10 Hz to 20 kHz.

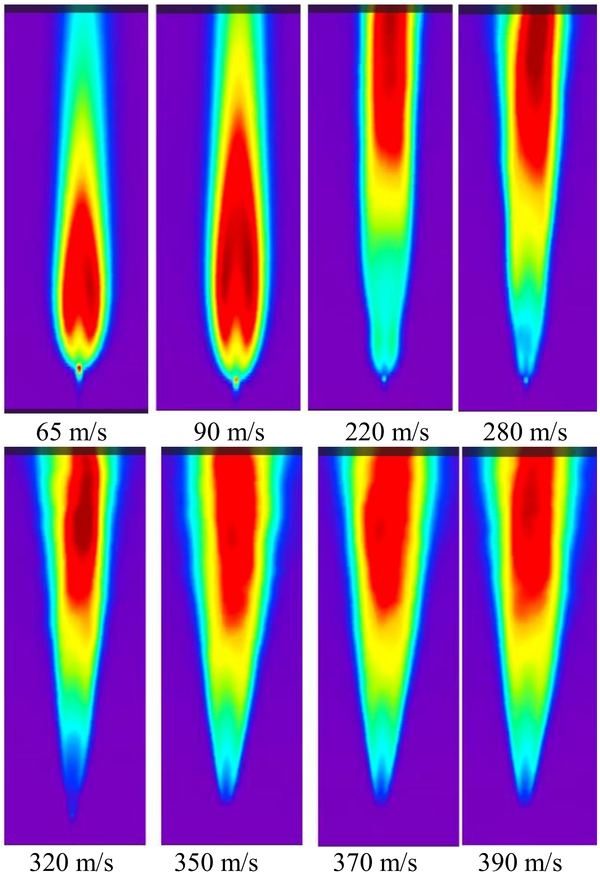


Fig. 6. Visualization of hydrogen combustion using a thermal imager CEM DT-9897H for different flow rates of the hydrogen stream.

To conclude, in the present work we found application of thermal imager to investigation of the microjets combustion as a much useful method to be used in further experimental studies on similar problems.

3 Conclusions

Summarizing the results of the research, it is necessary to state the fact that a new physical phenomenon of microjet diffusion combustion of Great Britain with nozzle heating has been experimentally established, ensuring stabilization of liquid combustion to transonic outflow velocities of Great Britain. External mode can be used for various technological purposes, such as organizing effective regulation of various flows and their heating. In this mode, only a small proportion of the UK population is burned, and the remaining mixture is produced with combustion products and air, with the result that the temperature of such mixtures can be generated (by choice of flow rate and nozzle diameter) close to the initial auto-ignition temperature of the UK. In addition, such a system can serve as a kind of reactor for carrying out, for example, under mild and controlled conditions, various thermolytic effects, such as the synthesis of metal nanoparticles and metal oxides from volatile metal-containing precursors, processing of hydrocarbon raw materials, etc. Such systems can also be used for effective mixing fuel with air and heating such mixtures for organizing aircraft, etc. burning devices.

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