A study and comparison of the modes of diffusion combustion of hydrogen and methane at their outflow from the annular nozzle together with the flow of supplied air from the coaxially located circular nozzle

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Abstract. The article presents qualitative data on the study of the process of diffusion combustion during the outflow of a gas jet from a nozzle apparatus with a certain arrangement of nozzles. The nozzle apparatus is a round nozzle with a straight channel and a coaxially located annular slot. In the experiments, hydrogen or methane was supplied through an annular slot, and the air was supplied through a central circular micro nozzle. The main features of the diffusion combustion of hydrogen and methane during the outflow from the nozzle apparatus are revealed and a qualitative comparison of the processes is carried out. In both cases, at the initial stage, laminar combustion is observed near the nozzle exit and a breakthrough of the flame front occurs with the release of an incombustible mixture of combustible gas and air. At a high flow rate, the flame separates from the nozzle exit. The fundamental difference is that hydrogen exhibits significantly better combustion stabilization characteristics at the nozzle exit.

1. Introduction
In recent decades, alternative and clean fuels have attracted increased attention from researchers due to global concerns about the energy crisis and emissions of pollutants. Numerous candidates such as biofuels, natural gas (where methane (CH$_4$) is the main component), ammonia, and hydrogen (H$_2$) are considered as alternative energy sources. Methane is widely used in industry, as a fuel for transportation, heating, and energy production. Hydrogen, on the other hand, is not so widespread due to some unresolved issues related to its production and transportation, but hydrogen has a number of advantages. H$_2$ exhibits unique features during combustion such as the absence of emissions of CO$_2$, soot and other pollutants (except NO$_x$). In addition, there are many ways to produce H$_2$ from various energy sources, including fossil fuels and renewable sources, such as hydropower and solar energy [1-3]. H$_2$ has great potential to become one of the main sources of alternative energy in the near future. In this regard, there is interest in the study of the jet outflow of hydrogen, methane and other gases from various types of nozzles.

A lot of theoretical and experimental works are devoted to the study of micro and macrojet flows. When outflowing from nozzles with micro diameters, some peculiarities are observed in the flow, for
example, in [4,5] it is shown that the jet remains laminar at a much greater distance from the nozzle exit than in the case of macro diameters. Also, quite a lot of works are devoted to the study of diffusion combustion processes. Detailed data on the influence of the initial conditions on the development of instability in the combustion process were obtained, and it was also experimentally revealed that hydrogen has the best flame stabilization characteristics at the nozzle exit in comparison with such fuels as methane and propane.

The main scenarios of diffusion combustion of hydrogen associated with the presence of a two-zone flame structure in a wide range of flow rates or velocities of the microjet outflow are revealed. According to the results of [4] on hydrogen flowing out of circular nozzles with diameter \( d = 250-500 \) μm, depending on the flow velocity of the jet \( U_0 \), the following combustion scenarios are observed:

1) The combustion of a long-range laminar flame \((U_0 \leq 150 \text{ m/s})\);
2) The separation of the flame into two zones by a “bottleneck” of the flame \((U_0 \approx 150 \text{ m/s})\);
3) The detachment turbulent flame from the laminar zone \((U_0 \approx 200 \text{ m/s})\);
4) Maintaining combustion in the laminar flame region and the turbulent flow of hydrogen upstream without combustion \((U_0 \approx 331 \text{ m/s})\);
5) Turbulent flow without combustion \((U_0 > 331 \text{ m/s})\).

This study continues the cycle of works, where the study of diffusion combustion of various gases from the outflow from various types of nozzles was carried out.

The aim of this study is to consider the processes of flow and combustion of gases when they flow out of the annular slot together with the airflow supplied through a coaxially located nozzle. Hydrogen and methane are used as combustible gases.

2. Experimental Arrangement

In the experiments, a nozzle apparatus is used, which provides an independent supply of gases through a circular micro-nozzle and through a coaxially located annular slot.

In the experiments, two regimes of gas supply were used: 1) hydrogen supply through an annular slot, air supply through a central circular micronozzle, 2) methane supply through an annular slot, air supply through a central circular micronozzle. The regimes of free outflow of both hydrogen and methane through an annular slot without coaxial air supply were also considered preliminary.

Parameters of the nozzle apparatus used for experiments with hydrogen are as follows: \( d_0 = 0.8 \text{ mm} \) is the diameter of the central micronozzle; \( S_0 = 0.5 \text{ mm}^2 \) is the exit area of the circular micronozzle, and \( S_1 = 0.4 \text{ mm}^2 \) is the area of the annular slot. A diagram of the nozzle apparatus used in experiments with hydrogen is shown in Figure 1. Parameters of the nozzle apparatus used in experiments with methane: \( d_0 = 0.7 \text{ mm} \), \( S_0 = 0.384 \text{ mm}^2 \), and \( S_1 = 0.8 \text{ mm}^2 \).

The schematic of the experiment is shown in Figure 2.

![Figure 1. Cross section of the nozzle tool](image1)

![Figure 2. Experimental setup: 1- Hydrogen tank, 2 – Air tank, 3, 4 – Digital Mass Flow Controllers, 5 – Power supply unit, 6 – Nozzle tool, 7 – Schlieren optical system](image2)
From the tank, gas (hydrogen (1) or methane, air (2)) entered the valve of the volumetric flow regulator of type 1179B from MKS Instruments (3), (4), which provided an accuracy of flow measurement within 0.7%. With the help of a 2-channel flow meter PR4000B-F (MKS Instrument), the gases flowing out of the nozzle apparatus were regulated. In the experiments, ignition was performed near the nozzle exit. The shadow picture of the diffusion combustion process was obtained using the IAB-451 (7), and the image of the shadow picture was recorded on a digital video camera.

3. Experimental results

3.1. Diffusion combustion of $H_2$ during its outflow from the annular slot, together with the air flow outflowing from the central circular nozzle

Diffusion combustion of $H_2$ during its outflow from the annular slot, without air flow is shown in Figure 3. At low flow rates, an extended laminar flame section can be observed (Figure 3 (a)). As the flow rate increases, a bottleneck is formed and the flame is divided into two zones: laminar and turbulent (Figure 3(b)). Near the nozzle exit, the laminar section acquires a spherical shape, the combustion scenarios are similar to those previously described in [4]. With a further increase in the outflow velocity, the turbulent flame descends closer to the nozzle exit (Figure 3(c)), and the laminar section of the flame decreases until it finally disappears, after which the separation of the turbulent flame from the nozzle exit is observed (Figure 3(d)).

The development of a laminar flame region, its specific shape, and transformation with an increase in the flow rate of a coaxial jet in the presence of a supersonic air jet are shown in Figure 4.

![Figure 3](image3.png)

**Figure 3.** Diffusion combustion of hydrogen flowing out of an annular slot. From (a) to (d), the flow rate of hydrogen increases

The microjet of air flows out at a constant supersonic speed. The pictures clearly show the small-scale supersonic cells created by the airflow. Supersonic cells are also observed in the resulting flow in the presence of a burning jet of hydrogen flowing out of the annular slot.

The following combustion scenarios are identified:

1) At a low flow rate of hydrogen, combustion occurs only near the nozzle exit, the flame front has a conical shape. A supersonic air jet breaks through the top of the cone and an unignited mixture of air with hydrogen is released (Figure 4(a));

![Figure 4](image4.png)

**Figure 4.** Diffusion combustion of hydrogen flowing out of an annular slot when air is supplied from a coaxially located circular nozzle at supersonic speed. From (a) to (f), the flow rate of hydrogen increases
2) As the ejection of the mixture from the cone-shaped shape near the nozzle exit increases, local combustion regions are formed further downstream, acoustic noise appears, and the flame front first stretches out and then takes a hemispherical shape (Figure 4(b));

3) Stable turbulent combustion is established and develops far from the nozzle exit, accompanied by a sharp generation of acoustic noise, and near the nozzle exit, the flame front acquires a spherical shape.

4) The turbulent zone of the flame descends closer to the nozzle exit, the laminar section of the flame is blurred and disappears (Figure 4(e, f)).

3.2. Diffusion combustion of CH4 during its outflow from the annular slot, together with the air flow outflowing from the central circular nozzle

Photographs of the process of diffusion combustion of methane during its outflow from the annular slot are shown in Figure 5. With an increase in the outflow rate of methane, combustion from the laminar regime goes to the turbulent one with a flame separated from the nozzle exit. In contrast to hydrogen, combustion exists in much narrower flow ranges.

In the absence of air flowing out of the central micronozzle, both in the case of hydrogen and in the case of methane, laminar combustion proceeds to turbulent combustion with a flame detached from the nozzle exit; however, in the case of methane combustion, no flame constrictions are formed.

Combustion of methane together with the supplied air is shown in Figure 6. With an increase in air flow rate, the laminar section of the flame is shortened and becomes spherical, and the air flow breaks through the flame front.

The scenarios of combustion of hydrogen and methane together with the air supplied from the central micronozzle are similar in the sense that both there and there the formation of a laminar flame zone near the nozzle exit, its breakthrough by an air stream and release of an unignited fuel/oxidizer mixture further upstream are observed. However, in the case of methane, the spatial dimensions of the
laminar section of the flame are much larger. In addition, in the case of methane, the laminar portion of the flame decreased with increasing airflow. In the case of hydrogen, the laminar section of the flame did not decrease, but its shape transformed, at first, it was conical, then hemispherical, spherical, and finally, its boundaries blurred and it disappeared.

4. Conclusion
As a result, typical scenarios of the diffusion combustion of methane and hydrogen, both freely flowing and with coaxially supplied airflow, were found.

1) Typical scenarios of the combustion of a jet of hydrogen flowing from an annular nozzle, as in the cases of a jet flowing out of a circular or flat micronozzle described in previous works, are associated with the formation of a two-zone flame structure at a low flow rate and with combustion with a flame detached from the nozzle exit at high flow rates.

2) Maintaining the combustion of methane in all regimes occurs in a much narrower range of flow rates.

3) The laminar flame zone during the combustion of methane, together with the supplied airflow, acquires a kind of spherical shape and its spatial size decreases with an increase in the airflow.

4) The scenarios of combustion of hydrogen and methane together with the air supplied from the central micronozzle are similar in the sense that in both cases the formation of a laminar flame zone near the nozzle exit and its breakthrough by an air stream and the release of an unignited fuel/oxidizer mixture further upstream are observed.

5) The air supplied from the central micronozzle significantly changes the hydrogen combustion process. The evolution of the laminar zone of a hydrogen flame with an increase in the outflow rate is as follows: the laminar section of the flame transforms from a conical shape to a hemispherical, and then to a spherical one, after which its boundaries blur and it disappears, leaving a turbulent flame separated from the nozzle.

6) The air supplied during methane combustion leads to the formation of a laminar flame section, which then takes on an elongated spherical shape and decreases with an increasing airflow.

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