Turbulent spots in the flame of a diffusion torch

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Abstract. Jet flame in modes of manageable instability development inside the source of jet formation is one of the methods for controlling the space-time and thermodynamic parameters of the torch. When a system of vortices flows into a free atmosphere, their interaction with the mixing layer and the flame front is accompanied by the appearance of a number of effects. The introduction of artificial perturbations into the flow allowed initiating the onset of a laminar-turbulent transition in the tube, which led to the formation of vortex structures in the jet stream. Hot-wire anemometric measurements of the velocity pulsations in the isothermal flow has shown that the disturbance introduced by the controlled valve is an acoustic precursor and a large-scale vortex formation. In this work, we investigated the effect of a system of turbulent spots on a laminar diffusion plume. Based on the two-point space-time temperature correlation dependences, data characterizing the rate of propagation of thermal perturbations during burning of H₂/CO₂ and C₃H₈/CO₂ fuel mixtures were obtained.

1. Introduction
Jet burning in modes of controlled development of instability inside a source of jet formation is one of the methods for torch space-time and thermodynamic parameters operation [1, 2]. When the fuel mixture flows in a long tube in the region of transition Reynolds numbers (Re=1800–2200), localized vortex structures of the “puff” type with a smooth forward and steep trailing front are realized. The characteristic length of such turbulent spots is 10-20 diameters. At the expiration of the “puff” into the free atmosphere a system of vortices is formed, penetrating into the mixing layer. The interaction of vortex formations and the flame front may be accompanied by the appearance of a number of effects. Changes in the flame front area in time under the influence of vortex structures lead to variations in the volume heat release. This may cause the generation of intense acoustic pulsations. Pressure fluctuations in turn cause an instability of the mixing layer in the jet streams. The dynamics of the propagation of disturbances in a reacting jet is qualitatively different from the isothermal flow. For hydrocarbon fuels (C₃H₈ binary mixtures with inert gas), turbulent spots do not develop beyond the front of the attached flame. At the time of passage of the turbulent spot, an increase in the wavelength of low-frequency flicker oscillations of the flame is observed almost twofold. In the disconnected flame mode, flow regimes are observed at which a “low velocity” flame-off can occur. When burning hydrogen-containing fuel mixtures, due to the small mass ratio of hydrogen to air required for stoichiometric combustion, the flame front, unlike burning propane, tends to move far to the “air” side of the mixing layer. An important feature of the torch dynamics is the violation of the integrity of the outer boundary of the H₂/CO₂ flame after the passage of turbulent spots [2]. In this case, the vortex
structure can cause local extinction in places with severe deformation of the flame, creating "holes" on the flame surface, limited by the flame edge, which acts as a front of extinction or re-ignition.

An important characteristic of the diffusion plume is the spatial-temporal correlations of temperature fluctuations. To measure the space-time correlations of the temperature fluctuations of the plume in [3], two iridium temperature sensors similar to hot-wire anemometer sensors were used. This allowed determining the integral scale of the turbulent torch. On the basis of data on the thermal characteristics of the flame, the applicability of the Taylor hypothesis on frozen turbulence in a torch was investigated.

In the present work two chemical systems are considered. In both cases, the conditions of the experiments were selected in such a way as to provide an attached flame and suppression of low-frequency flicker oscillations of the flame front. In this paper, a mixture of hydrogen with CO₂ and propane-air mixtures are used as fuel. H₂/CO₂ mixtures can be considered as a compromise application of CO₂ in hydrogen energy: "re-use" of the product of using natural gas to reduce the combustion temperature of hydrogen and, accordingly, the level of NOx emissions. In this work, we investigated the effect of a system of turbulent spots on a laminar diffusion plume. Measurements of the distributions of spatial-temporal correlations of temperature fluctuations were aimed at obtaining data characterizing the development of thermal flame perturbations when turbulent spots appear in the reagent flow.

2. Experimental setup
In the present work, a diffusion torch that forms when a round jet of fuel flows vertically upward into still air is investigated. The Reynolds number in the central tube was maintained in the range Re = 1800–7500. In this case, a laminar – turbulent transition began in the tube. The transition is a random process, which is not always convenient for registering such events. In experimental studies, various means of external impact on the flow are used to diagnose a flow with turbulent spots, which allow one to control the appearance of “puff” structures. Being at the lower boundary of the laminar-turbulent transition mode in a pipe, an external impact on the flow allows one to initiate the appearance of large-scale vortex formations. In [4], a pulsed jet was applied into the tube in the transverse direction. In the study [5], as in this work, a controlled mechanical action on the flow was used.

Figure 1. Installation for measuring the “cold flow”. 1 – computer; 2 – DAC / ADC; 3 – hot-wire anemometer; 4 – air tank; 5 – digital flow regulator; 6 – controlled valve; 7 – tube with a diameter of 5 mm; 8 – hot-wire anemometer probe.

To study the response of the jet flame to the occurrence of turbulent spots in the jet stream, a system of controlled generation "puff" was developed; the experimental setup scheme is shown in figure 1. In figure 1, the highlighted arrows indicate the gas line. To establish the Poiseuille profile at the outlet of the straight tube with a diameter \( d = 5 \) mm and a length of 1 m, a 30 m length air duct is
used. The E14-140 2 module operated in two modes, as an ADC for collecting an array of voltages from a thermal anemometer, and as a DAC for supplying a control rectangular signal to valve 6, which in turn was used as a source of artificial disturbances. The probe of the hot-wire anemometer was located on the geometric axis of the tube, at a distance of 1 mm from the tube outlet. The control of the valve (6) by reducing for a predetermined time (~ 20–40 ms) the air flow in the tube at fixed intervals, allowed introducing the controlled disturbances into the flow. An example of such measurements is presented in figure 2.

![Diagram](image_url)

**Figure 2.** Oscillogram of voltage pulsations of the hot-wire anemometer sensor.

After the acoustic precursor (1st second in figure 2a), a vortex structure of the "puff" type (5th second in figure 2a) is diagnosed and propagates at a speed close to the average flow rate in the tube. In the course of testing the method of generating artificial disturbances, the flow regime and the operating conditions of the valve were revealed, under which the suppression of natural disturbances is observed (figure 2b, only acoustic precursors).

Thus, the presented data show that two types of disturbances are recorded in the near field of the jet. Along with the formation of moving in the puff stream, acoustic “precursors” are recorded, propagating in the pipe at the speed of sound. The extension of the gas line allows distinguishing in time the movement of the turbulent spot and the pressure wave generated from the operating valve. In this work, we used a pipe with an internal diameter of 5.6 mm and a length of 30 meters, which was laid in a bay with a diameter of 1 m. The flow in a curved pipe may be accompanied by the formation of Dean vortices. In [6] the Dean number is determined: $D_n = \text{Re}(d/R)^{0.5}$, where $d$ is the characteristic size of the pipe (diameter), $R$ is the radius of curvature of the channel. In our experiments, $D_n > 11.6$, which means that secondary vortices appear in the laminar flow. It was experimentally confirmed [6] that under such conditions the laminar – turbulent transition in the tube can be significantly delayed.

Under the conditions of this work, the minimum Reynolds number at which natural turbulent spots began to be recorded was $\text{Re} = 3420$. Note that the tightening of the laminar – turbulent transition can increase several times the range of average flow rates of the fuel mixture.

To obtain the spatial-temporal correlation pulsations of temperature in the flame, an automated experimental test bench was made, the scheme of which is shown in figure 3.
Figure 3. Automated experimental setup. 1 – computer; 2 – ADC; 3 – DAC; 4 – digital flow meter; 5 – controlled valve; 6 – expense regulator; 7,8 – thermocouples; 9 – gas cylinders; 10 – burner.

The work of the setup is based on software-controlled analog-digital 2 (ADC LTR114) and digital-analog 3 (D/A E14-140) converters, for which the program code in C ++ was written. The ADC 3 is used to measure two-point temperature correlations using platinum – platinum – rhodium thermocouples (100 µm and 20 µm), one of which 8 was rigidly fixed on the burner 10, and located in the mixing layer, and the other 7 could move freely. With the help of two thermocouples, changes in the spatial-temporal scales of the flame temperature at the moments of generation of vortex structures were recorded. Measurement of point-to-point temperature correlations requires a sufficiently high resolution and minimum sampling time between channels, which is why the LTR114 24-bit ADC was chosen, which has a maximum sampling frequency of 4 kHz. The source of artificial disturbances is the valve 5 (K000-303-K12) with a minimum shutter response time of 10 milliseconds. With the help of a DAC 3, a pulse 12V electrical signal was applied to the valve, with adjustable duration. In figure 3, lines with arrows indicate a pipeline, without arrows, electrical connections. The flow rates and the ratio of fuel/oxidizer and diluent from cylinders 9 were regulated using digital flow meters 4.6. A coaxial jet was used in the experiments.

3. Results

Figure 4. Spatial-temporal correlation dependence. Fuel flow in the annular channel at Re = 1640.
Air flow along the axis at Re = 3600.

To determine the spatial characteristics of the vortex structures in the flame, we used the technique of two-point measurements by thermocouples. Figure 4a shows the correlation dependence at different (in distance from tube outlet) positions of the movable thermocouple, which was located on the axis of
the burner. The fuel was fed through the central tube, Re = 1640. As can be seen, the process is correlated, and as the moving thermocouple moves away from the rigidly fixed one, the determinism of events decreases. The rigidly fixed thermocouple was in the mixing layer, and therefore, negative correlation dependences are observed, which is consistent with the results of [3]. Figures 5 demonstrate the spatial-temporal correlations r(t) of temperature fluctuations at different distances between thermocouples. Mobile type R thermocouple was 100 μm in diameter and fixed reference type S thermocouple was 20 μm. Response times for probes [7] are about 10 for 20 μm and about 120 ms for 100μm.

![Figure 5](image1)

**Figure 5.** Spatial-temporal correlation dependence. Movable thermocouple on the burner axis(a), movable thermocouple on 1mm radius from the axis of the burner(b).

Mode with the number Re = 5670, fuel H₂(25%)/CO₂, pulse duration 100ms. The rigidly fixed thermocouple is located on the outer edge of the burner. Figure 5 (a) characterizes weakly correlated events, this is especially clearly seen at a distance of 10 mm, since the velocity on the axis is rather high, the disturbance does not have time to develop in order to introduce temperature pulsations. In figure 5 (b), perturbations that came after 3 seconds are clearly visible, and their amplitude increases with distance from the burner outlet. It should be noted that the correlation function, when the mobile thermocouple is in the flame front figure 5 (b), changes sign. Consequently, temperature fluctuations caused by large-scale disturbances from the valve are in opposite phase.

![Figure 6](image2)

**Figure 6.** The rate of propagation of thermal perturbations. The H₂ / CO₂ fuel has a volume content of hydrogen, on the right, 35%, on the left, 25%.

The fixed thermocouple was in the mixing layer, and therefore, negative correlation dependences are observed, which is consistent with the results of [3]. Using the correlation dependences, we
determined the propagation velocity of a thermal perturbation in a flame under the influence of a large-scale vortex structure obtained by an artificial method (figure 6). The flame front was at a point of 5 mm (in figure 5 it is highlighted by a rectangular area), 0 mm corresponds to the center of the burner. Velocities obtained for different distances between thermocouples, depending on the radius.

4. Conclusion
The introduction of artificial perturbations into the flow allowed initiating the onset of a laminar-turbulent transition in the tube, which led to the formation of vortex structures in the jet stream. Hot-wire anemometric measurements of the velocity pulsations in the isothermal flow has shown that the disturbance introduced by the controlled valve is an acoustic precursor and a large-scale vortex formation. Similar structures (precursor and puff) are registered in the case of the formation of a hydrogen flame.

Two-point spatio-temporal correlations were obtained during combustion of H$_2$/CO$_2$ and C$_3$H$_8$/CO$_2$ fuels. It is shown that the nature of the correlation distribution in the vicinity of the flame front for these fuels is qualitatively different. These dependences allow us to estimate the integral scale of disturbances and the rate of propagation of thermal disturbances.

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