Diffusion combustion of hydrocarbon under the conditions of jet source instability

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Abstract This paper presents experimental results on the instability of diffusion combustion of a hydrocarbon jet in still air both in the jet flame and inside the source of jet formation. The experiments in the subsonic jet are carried out for propane-butane mixture, flowing out of a long (l/d = 172) quartz tube with diameter d= 3.2 mm at Reynolds numbers Re=200–13500. Measurements of average velocity and velocity pulsations are performed in the near field of the jet without combustion. To analyze the flame structure the visualization is made with the help of Hilbert optics method. The temperature profiles are measured in the near field of the jet by Pt/Pt/Rh thermocouple.

Key words: diffusion combustion, combustion control, subsonic gas jets, laminar-turbulent transition in channels and jets, vortex structures, turbulence, visualization, experiment.

Introduction

Control over mixing and combustion processes in jet flows is an important and topical problem. The devices based on diffusion combustion in hydrocarbon jets are widely used in energy and chemical technologies. This problem has been investigated in detail and presented in the literature [1]. Technologies mainly assume the use of such jet sources as holes or profiled nozzles; whereas tubes (cylindrical channels) are applied less often because of their largeness. Most gas jets are characterized by Reynolds numbers over 4000 and turbulent flow regimes [2]. Various methods are used to control over the processes of combustion and mixing: co-axial jets, adding of inert gases, vibration, acoustic and plasma effects, etc. One of the perspective directions is the usage of jet diffusion combustion with the instability evolution both in the jet flame and inside the source of the jet formation.

The instability of gas jets (without combustion) is observed at low Reynolds numbers (Re = 10-30) and has been thoroughly investigated [3-5]. However, the process of transition to turbulence occurs at much higher Reynolds numbers (Re=500-2000); and it still requires further experimental study [5-11]. It is explained by the fact that high Reynolds numbers are of interest for practice, first of all, for aviation and space rocket technologies, as well as, in the case of jets flowing from the profiled nozzles [2, 5]. Here, the initial profile is “uniform” and has thin boundary layers. There, the laminar-turbulent transition occurs rather quickly in the mixing layer of the initial part of the jet [3-4]. The gas outflow from the hole occurs in a similar way. A fundamentally different is the jet flowing from a long cylindrical channel. Here, one can expect the appearance of large velocity fluctuations and the existence of vortex structures inside the tube in the regimes of laminar-turbulent transition [12].

The origin and development of instability in the flame jet flow is the subject of a number of studies [13]. This topic remains relevant by now both for premixed and diffusion flames: Yule et al. [14], Takahashi et al. [15], Savas and Gollahalli [16], Mungal et al. [17], Gollub et al. [18]. Low-velocity diffusion flares exhibit low-frequency oscillations (F=10-20 Hz). Pulsations are associated with large-scale eddies formed on the outer flame boundary. The eddies can “float" under the action of buoyancy forces. Such pulsations are often referred to as “flame flickering”. Low-frequency pulsations of the flow are observed both in the combustion of homogeneous mixtures and in the diffusion combustion. According to Qadri [19] the dynamics of development of flow oscillations in attached and detached flame jets is different. Sirignano and Krieg [20] numerically investigated the effect of acoustics on diffusion combustion when a jet of air flows into a stationary atmosphere of fuel. They noted that the heat release could be a kind of amplification of acoustic oscillations in the jet stream. In the research of V.V. Kozlov [21] the stability of jets combustion to acoustic effects was analyzed. The external effect of pressure pulsations on the premixed swirling flames was described in the works of Alekseenko et al. [22] and etc. The features of the flow in the flame jet may be significantly influenced by the fuel composition. Thus, Li and Zhang [23] have shown that low-frequency oscillations of the jet flame during diffusion combustion of a mixture of methane and propane in air depend on the relationship between the components of the fuel mixture. Kolhe and Agrawal [24] investigated various types of instability leading to the development of turbulence in a diffusion jet flame. They used the high-speed imaging based on the Schlieren method which allowed the authors to detect the secondary instability of the flow that arises in the flame front. Matsumoto et al. [25]

believes that for the diffusion flames, the hydrodynamic instabilities may become the important source of perturbations. Thus, the study of diffusion combustion of hydrocarbon flames remains an urgent problem, in particular in the field of critical Reynolds numbers.

However, the method to control combustion using the laminar-turbulent transition in the jet source (a cylindrical channel) is studied insufficiently. The principal advantage of mixing and combustion control in the unstable regime is the use of jets with low Reynolds numbers (Re<4000), which correlates with the objectives of energy saving and energy efficiency.

1. Experimental methods and technique

In this work, we consistently study the jet without burning ("cold jet") and then the jet at combustion ("hot jet"). The working gas is the propane-butane mixture (50% propane, 50% butane). The experimental conditions are the room temperature and atmospheric pressure. The experimental setup consists of the gas vessel, gas reducer, regulating valve, flowmeter, flexible connecting hoses and jet test section. The jet source is a quartz cylindrical channel with diameter d= 3.2 mm, length l = 550 mm and a wall thickness of 1.2 mm. The propane-butane mixture jet flows out into the air. For the "cold jet" the axial velocities range within U_0=0.2-17 m/s, and Reynolds numbers vary within $Re=U_m d/\nu$=200–13500; here, U_m is the mass flow velocity and ν is the kinematic viscosity of gas.

For the "cold jet", average velocity, root mean square pulsations and turbulence degree are measured with hot-wire anemometer of constant temperature

DISA 55M and DISA measuring equipment. The used probe is DISA 55P11 mini sensor (gilded tungsten wire with a diameter of 5 μm and a length of 0.6 mm). The method of [26] is applied for hot-wire anemometer data analysis on the assumption that the wire sensitivity to velocity pulsations is much higher than to density pulsations. Hot-wire anemometer probe is shifted with 2D coordinate device with a shifting step of 50 μm. The gas temperature is measured with the digital thermometer Ebro TFX392L. The gas flow rate is controlled by the Bronkhorst flowmeters. The measurement inaccuracy of base parameters in the range of Reynolds numbers 500-13500 is 4-6% for average velocity, 7-9% for root mean square value of velocity pulsations, 0.5% for gas temperature, 0.5% for gas mass flow rate, and 0.7-1% for Reynolds numbers.

One of the problems in experimental investigations of the reacting flow medium perturbed by vortex structures is the need for high-sensitivity imaging of the optical density fields. An optical diagnostic technique suitable for solving the problem is the Hilbert optics [27], used in the present study. To measure the flame temperature in the range from 300 to 1800 ° C a Pt / Pt-Rh thermocouple TPR-0392-01 with a wire diameter of 100 μm is used. It is well known that the catalytic effect and the radiation of thermocouple wires distort the readings of the platinum thermocouple in the reacting gas stream. Nevertheless, no correction for temperature measurements is made in this work.

2. Investigating the "cold jet"

The free jets expansion is known to depend on initial conditions significantly [2-4]. Therefore, at the first stage of experimental work the hot-wire measurements in the channel outlet are carried out.

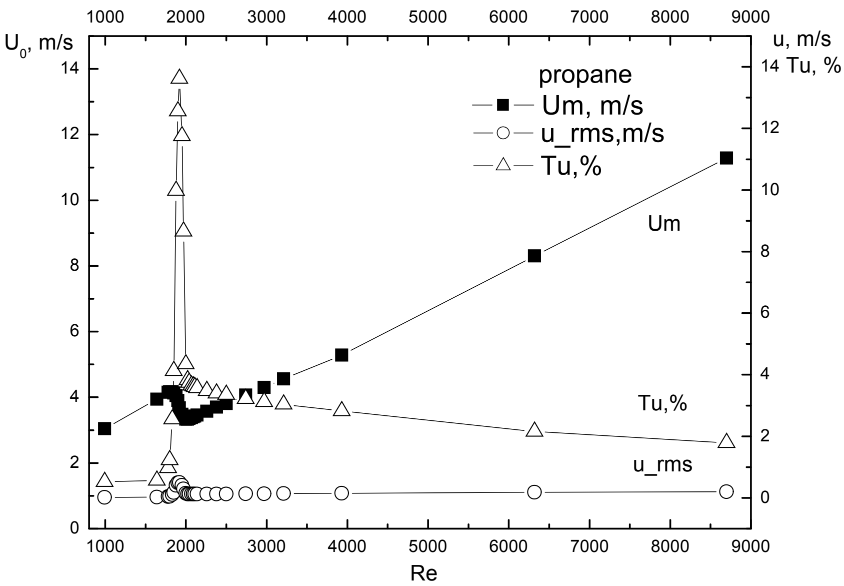

Fig. 1. The dependence of average velocity, root mean square value of velocity pulsations and turbulence degree (on the channel axis) on Reynolds number at the jet source outlet cross-section.

Fig. 1 shows the dependence of average velocity, root mean square value of velocity pulsations and turbulence degree (on the channel axis) on Reynolds number. As can be seen from the figure, for the dependence of the average velocity on the Reynolds number, there is a local decrease in the region Re = 1800-2000. It indicates a velocity profile transformation associated with the laminar-turbulent transition of the gas flow inside the channel. The experiments have shown that the velocity distribution in the channel outlet cross-section changes from laminar parabolic

Poiseuille profile to smooth one typical for a turbulent flow. The local extremum at Re = 1920 for root mean square value of velocity pulsations and turbulence degree is observed in the transition region with the maximal value of the turbulence level Tu=13.6 %. At Reynolds numbers Re>2000 the oscillograms character becomes fully turbulent. Thus, the three parameters and an intermittent character of the flow evidence that the laminar-turbulent transition in the channel outlet exists in the region with Re = 1800-2000.

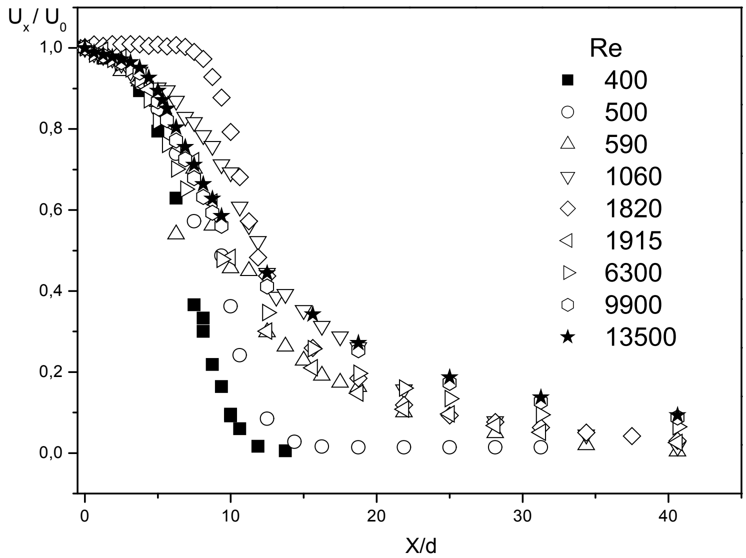

Fig. 2. The average velocity U_x normalized to the initial velocity at the jet axis U_0 depending on undimensional distance x/d from the jet inlet with the Reynolds number variation.

At the second stage of the work, the hot-wire measurements are carried out along the gas jet axis. Fig. 2 shows the dependence of average velocity U_x normalized to the initial velocity at the jet axis U_0 on undimensional distance x/d from the jet inlet with the Reynolds number variation (x – longitudinal coordinate with the beginning at the jet inlet). The common character of velocity changing along the axis is the monotonous decrease of the relative velocity U_x/U_0. As seen, the major transformation of the velocity distribution along the axis occurs in the region of Re = 1800-1915, which is typical for the laminar-turbulent transition. At Re = 1820 the longest laminar flowing zone is observed.

The change in root mean square value of velocity pulsations (u) and turbulence degree (Tu=u/Uo*100%) depending on Reynolds number at the jet axis are presented in fig. 3-4. Several special regimes of jet expansion may be selected. The initial jet impulse at Re<400 slowly decreases downstream because of viscous dissipation and velocity pulsations that monotonically damp. This regime seems complicated for the standard hot-wire method because of a significant uncertainty of measurements. The jets with low Reynolds numbers (Re=500) are characterized by an extended zone of the laminar flow (up to x/d=20) with low level of velocity pulsations, followed by the laminar-turbulent transition region with the growth of pulsations, and the zone of turbulent flow with the decreasing pulsations, both located downstream. With the Reynolds number growth, the length of the laminar region decreases and the maximum of velocity pulsations increases. At Re=1820, the laminar zone length is x/d = 10, and the level of pulsations reaches Tu=21%. At Re =1915, the velocity pulsations drastically increase at the initial cross-section of the jet.

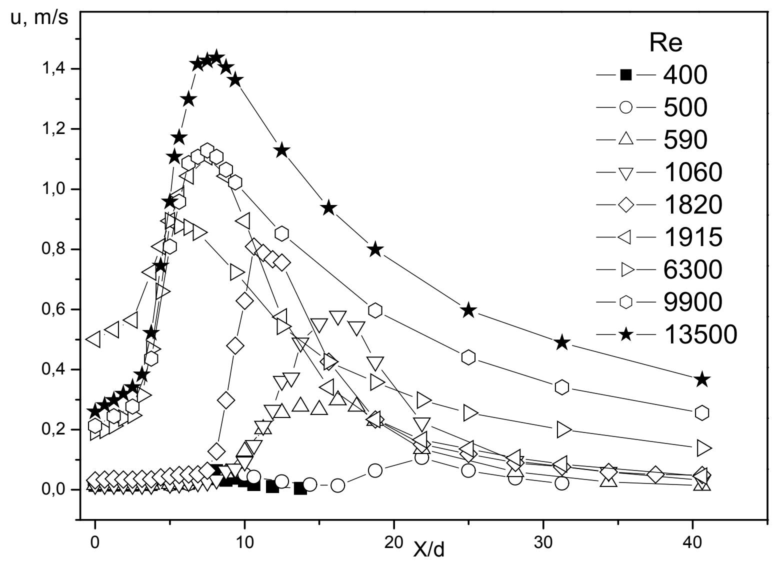

Fig. 3. The change in root mean square value of velocity pulsations at the jet axis depending on undimensional distance x/d from the jet inlet.

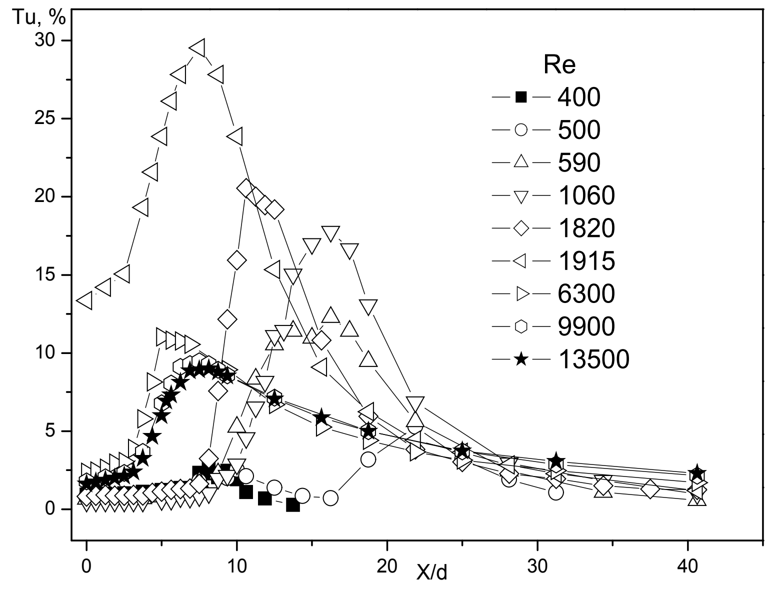

Fig. 4. The turbulence degree at the jet axis depending on undimensional distance x/d from the jet inlet.

The intermittent character of instantaneous velocity behavior and the presence of turbulent spots are recorded in an oscillogram of the hot-wire anemometer signal. They serve as indicators of the laminar-turbulent transition inside the jet source (cylindrical channel). As a result, the fluctuations grow sharply in the near field of the jet (at x/d = 7 up to Tu = 30%). With further increase in the Reynolds number (Re> 1915) the initial level of pulsations decreases to Tu = 4%, and the maximum at x/d = 7 decreases to Tu = 12%. Downstream (x/d > 7), a significant decrease in pulsations is observed, which indicates a strong dissipation of turbulent energy.

From the analysis of the data presented on fig. 1-4 the following conclusions may be drawn. There are four characteristic regimes of jet expansion: dissipative, laminar, transitional and turbulent [28]. It is known, that free jets are unstable at low Reynolds numbers about 10-30 [3-5]. However, the beginning impulse decreases, and the velocity pulsations attenuate because of the presence of viscous dissipation. Thus, the *dissipative* regime (Re <10-30) is characterized by the absence of local instability and the growth of velocity pulsations in the downstream direction.

In the *laminar* regime (30 <Re <1800), the flow inside the tube is laminar; in the initial section of the jet the velocity profile is parabolic, and the level of turbulence is low (Tu <1%). The main reason of the fluctuations growth is the instability of the jet flow. Three zones are located along the jet in sequence: a long part of the laminar flow, the field of laminar-turbulent transition with quite high level of velocity fluctuations (Tu >3-5%), and the zone of turbulent flow with attenuating velocity fluctuations.

The *transition* regime (1800<Re<2000) is characterized by the forming of two cascades of hydrodynamic amplifier. The first cascade is instability inside the jet source (round channel), and the second one is unstable behavior of the jet itself. This mode is characterized by a significant change in parameters and by the appearance of intermittency. In the initial section of the jet, the profile of the average velocity changes from laminar to turbulent, and there is also a sharp increase in the velocity pulsations (on the axis, to the value Tu = 13.6%). The distribution of average velocity along the axis changes, and the velocity pulsations increase sharply. The level of fluctuations at the axis reaches Tu = 30%. The intermittent behavior of the instantaneous velocity in time is observed. Such behavior is caused by the existence of turbulent spots in the near field of the jet.

The *turbulent* regime (Re>2000) is characterized by the turbulent flow inside the jet source. Two sections are located successively along the jet length: a zone of substantial growth of velocity pulsations and an extended section with attenuating velocity fluctuations. The extremum of velocity pulsations distribution in the initial part of the jet is caused by internal processes of the turbulent flow, turbulent energy generation and turbulent diffusion.

In terms of controlling the processes of mixing and combustion in jet flows the base regimes which are the mainly optimal are the laminar and transitional ones. Both regimes (laminar and transitional) imply mixing and combustion regulation in the jet instability field at low Reynolds numbers (Re<4000). It allows using low velocities and flowing rates of the working gas in practice that is close to the objectives of energy conservation and efficiency.

3. Investigating the “hot jet”

Figure 5 shows photographs of Hilbert visualization of optical density in the combustion of propane-butane jet in still air. The video sequence illustrates the flame perturbation by the vortex. The fuel consumption during this experiment is kept constant. It is apparent that the instant picture is quite complicated. At random moments of time, turbulent plums occur on the flow axis in the fuel region.

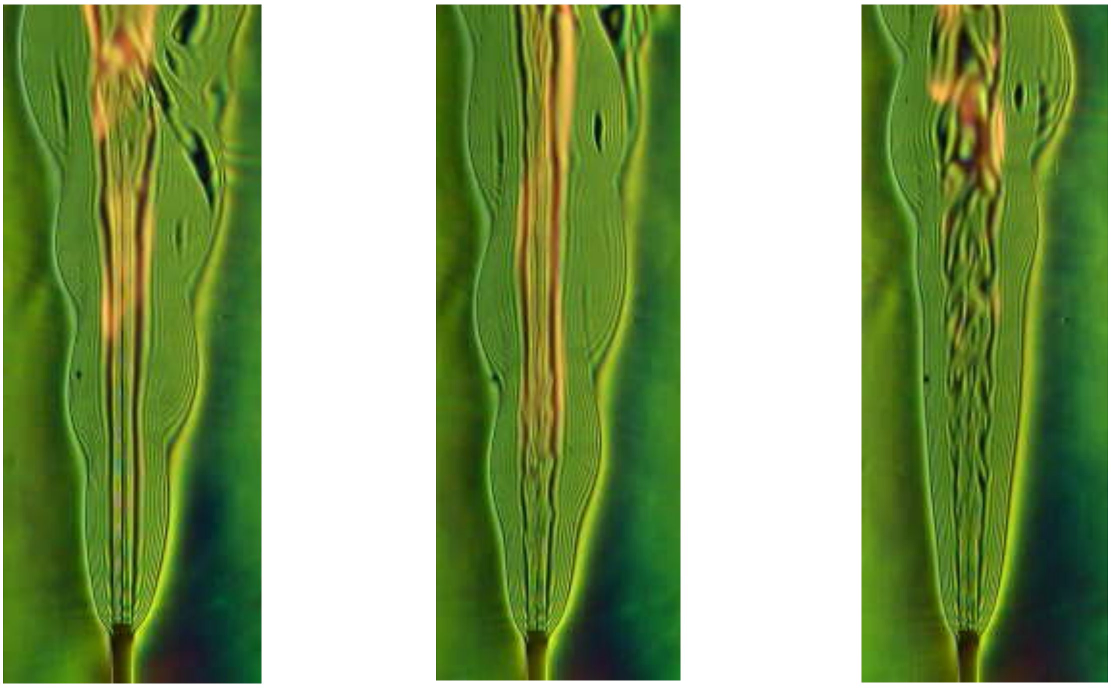

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Fig. 5. Time sequence of Hilbert images of the jet flame

Furthermore for a given Reynolds number, a turbulent flow regime can be established in the jet core from time to time. In the case under consideration, the oscillations of the outer boundary of the flame occur at a frequency of 10-20 Hz. The measured temperature distributions in the flame are shown in Fig. 6. Comparing the Hilbert-visualization and temperature profiles, we can distinguish three areas: the paraxial fuel flow, surrounding air, and the curved bands corresponding to a luminous flame.

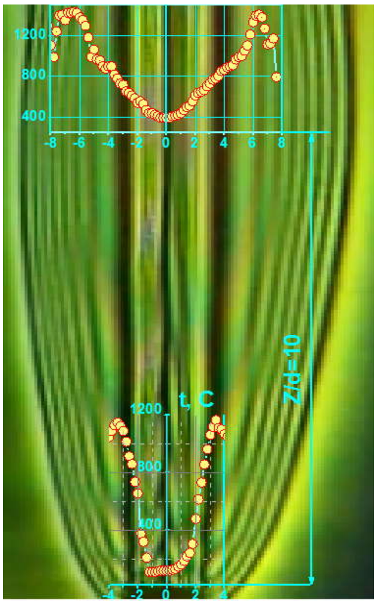

Fig. 6. Distribution of flame temperature.

The time scales of dynamical structures arising in the flame flow and a fuel jet are essentially different (Fig. 7). For one conditional wave period at the outer boundary of the torch, it was possible to observe several turbulent plums passing through the frame. Despite the scales differ a lot, the plums have a noticeable effect on the dynamics of the external shape of the torch. The diffusion combustion of a propane-butane jet flame submerged in the air is accompanied by periodic changes in the outer boundaries of the torch. As Darabkhani [29] showed, in the cocurrent airflow,

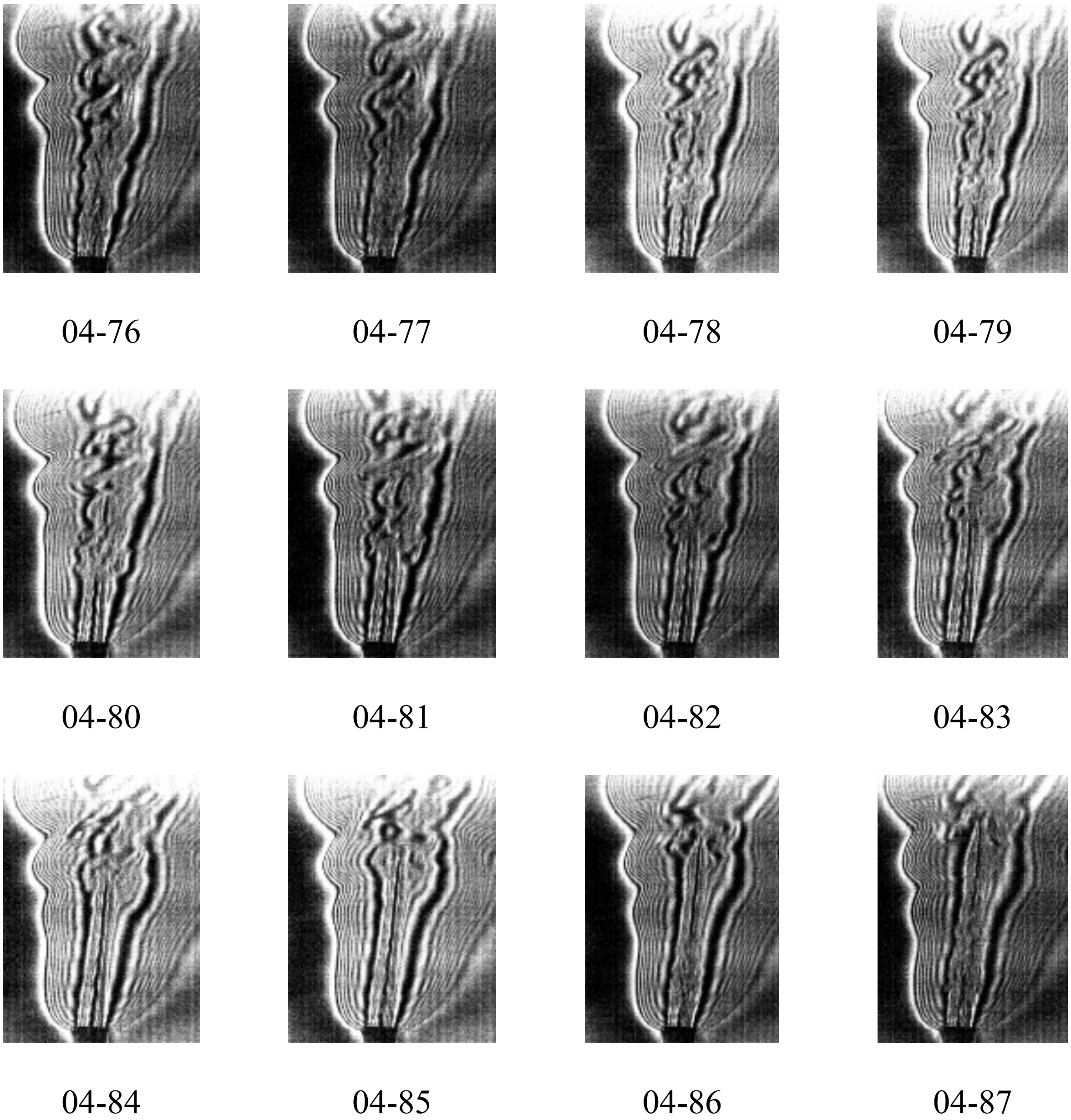

Fig. 7. Time sequence of high speed Hilbert images

the air velocity increases, the amplitude of such pulsations decreases, and the wavelength, on the contrary, increases. Under these conditions, the effects of processes associated with the development of instabilities in the fuel jet flowing out of the round tube will become more noticeable.

4. Conclusion

Along with the traditional methods for controlling mixing and combustion processes, the use of diffusion combustion with instability evolution both in the jet flame and inside the jet source is a perspective approach. Within the approach, the hydrodynamics and combustion of propane-butane mixture in the subsonic jet flowing out from the long cylindrical channel ($l/d = 172$) with a diameter $d = 3.2$ mm was experimentally investigated in the range of Reynolds numbers 200-13500. The average velocity and velocity pulsations were performed in the near field of the jet without burning. For the case with combustion, the density field was visualized, and the temperature profiles were measured in the near field of the jet. On the basis of experiments with the “cold jet,” two regimes, i.e. the “laminar” ($30<Re<1800$) and the “transitional” ($1800<Re<2000$) with possible regulation of mixing and combustion were defined at low Reynolds numbers ($Re<4000$) in the range of the jet instability.

The flame jet instability (the flame front oscillations) may have features associated with the dynamics of the laminar-turbulent transition of a fuel jet, flowing out of a round tube. The effect of turbulent plums on the distribution of average flame temperatures under the experimental conditions turned out to be weak.

The visualization allowed qualitatively tracing the temporal and spatial scales of temperature field perturbations, occurring in the flame.

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