QUALITATIVE FEATURES OF FLAME DEVELOPMENT IN CASE OF FUEL INJECTION INTO MEDIUM WITH COUNTERPRESSURE UP TO 10 atm

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The use of photomicrography with laser illumination and pulsed x-ray photography for investigation of the processes associated with flame development in the case of high-pressure fuel injection into a working volume [1, 2] have shown that a substantial role in flame formation is played by the unsteady hydro- and gasdynamic phenomena accompanying this process. This unsteadiness is expressed in the fact that in the first 300-500 μsec after the start of injection the jet is formed and the cumulative mechanism of its interaction with the medium is stabilized; during the rest of the time inhomogeneities of different scale continually arise within the body of the flame. Small-scale inhomogeneities will obviously have little effect on the general nature of the advance of the jet of fuel–air mixture, whereas large-scale inhomogeneities, prescribed both by the nature of the pressure variation in the fuel system and by disturbances of flow stability [2], will certainly determine the dynamics of development of the fuel flame. On the other hand, the flow of the fuel–air jet is affected by the state of the medium into which the fuel is injected and, in particular, by the pressure in the working volume.

Investigation of the internal structure of a fuel flame by optical techniques is difficult, since the flame is a structure filled with a large number of small liquid droplets and is optically opaque. Hence, in the present experiments we used the pulsed x-ray technique as in [2]. This paper gives the results of a qualitative investigation of the special features of development of the fuel flame when liquid is injected into a medium with an excess pressure up to 10 atm.

The experiments were conducted on the apparatus described in [2]. Injection of a mixture of diesel fuel and x-ray contrast additives (ethyl iodide and butyl iodide in proportion 1:1:1) was effected by a standard diesel injector of the closed type, fitted with a single-hole nozzle with nozzle diameter 0.35 mm (Fig. 1). In this case the curve of pressure in the fuel system was of the standard type – increase in pressure up to 800-900 atm in the course of 4 msec and a decline for 2 msec.

The working volume was a thick-walled cylinder with internal diameter 150 mm, with its ends closed by caps, the distance between which was ~50 mm. Since the adjustment of caps of any kind for sealing of the working volume leads to such x-ray absorption that conduction of experiments is impossible we selected the following methodological solution. Photographic film in the cassette 2, made from opaque paper and protected

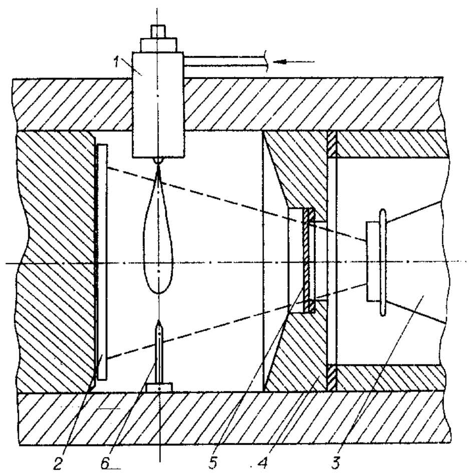

Fig. 1

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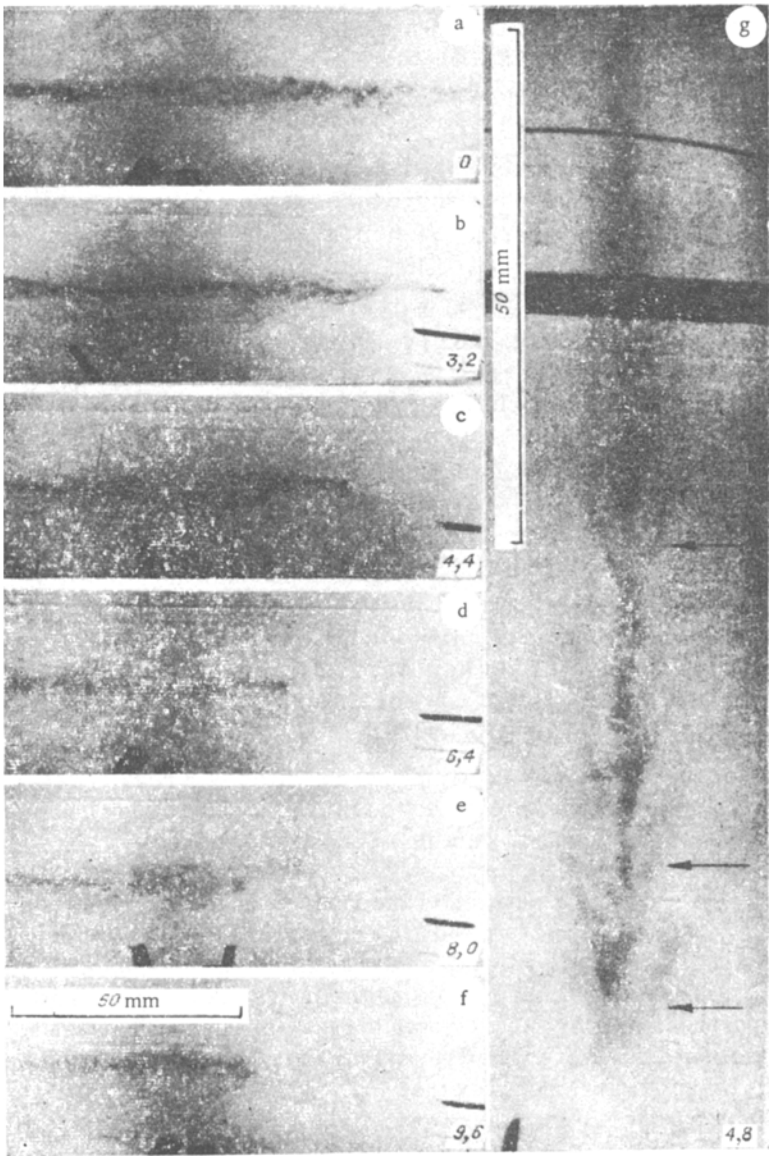

Fig. 2

from spray and vapor by a Lavsan film 5 μm thick, was placed directly inside the working volume and the volume in each experiment was unsealed for change of the film. Mounted in front of the x-ray tube 3 was a plug 4 with a 1.5-mm-thick beryllium membrane 5 which could withstand a load corresponding to a pressure difference of up to 40 atm. These components were positioned in the working volume so that the distance between the plane of the photographic film and the injector axis was 20 mm, and the distance between the injector axis and the focal spot of the x-ray tube was 110 mm. The presence of the protective beryllium membrane reduced the aperture, and the maximum angle at which the image of the flame could be observed was ~35°. Hence, only the central region of the working volume of diameter 80 mm, where the parallax at the edges is insignificant, was projected onto the photographic film. The distance from the injector nozzle tip to the center of the frame was 55 mm.

Figure 2 shows a series of reproductions from x-ray diagrams obtained 1.75 msec after the start of the increase in pressure in the fuel system for different pressures in the working volume. The excess pressure in the working volume is indicated by the figures in the photographs. The reproductions of the x-ray diagrams show the reference needle 6 (Fig. 1), the tip of which was 24 mm from the frame center. Figure 2a (the head of the jet is several mm beyond the edge of the frame) clearly shows the usual structure for injection into a volume filled with air at atmospheric pressure. On the right-hand side of the frame a clot of fuel–air mixture is beginning to form in the jet, and the entire middle part of the jet consists of a stream of uniformly dispersed small (~1 mm) inhomogeneities.

A relatively small increase in pressure (Fig. 2b, c) destroys the uniform structure of the flow in the jet and even in those regions where no large-scale inhomogeneities are formed there appear thickenings, which are situated close together and acquire a specific shape. These thickenings are conical, with the apex pointing in the direction of propagation of the flame, and the fuel component is more dense in the head region. The concentration of liquid decreases towards the base of these conical clots.

The interaction of these structures with one another is of interest. Since each successive clot moves in the relatively dense medium left by the previous one due to deposition of liquid droplets, we frequently observed cases of "gliding" of the next clot and its deflection to the side. This leads to the appearance of a multiheaded flame (Fig. 2c, e).

Another feature of particular interest that was sometimes observed was the formation of a detached precursor wave that prepared the way for the clot. For instance, the arrows in Fig. 2g clearly show how the signal preceding the clot cleared the fuel–air mixture from the trail left by the passage of the preceding part of the jet. This wave cannot be regarded as the classical shock wave accompanying the propagation of a body in a medium at supersonic velocity, although in [3, 4] the possibility of formation of low-velocity shock waves in the body of a flame, as in a polydisperse medium, was indicated. It is known [5-7] that gasdynamic discontinuities in polyphase systems have large dispersion and the shock wave, formed in some way in them, is converted to a compression wave.

It is understandable that the formation of such waves also accompanies the pulsation of the mixture clots which results from the collapse of individual parts of the jet, which have definite inertia (presence of a dispersed liquid phase) and elasticity (saturation of mixture with air and vapor). The formation of such waves in the body of the flame at a rate sufficient for alteration of the structure of the fuel–air flow appears to be an important factor affecting the whole process of charge formation.

Numerous observations show that in the case of injection into a medium with excess pressure >3 atm the formation of frequent conical clots and, hence, of compression waves is a regular feature. An increase in overall density of the medium, however, leads to reduction of the velocity of advance both of the flame as a whole, and of individual structures in its body. This is clearly seen in Fig. 2, for instance, where all the x-ray diagrams were obtained at the same time and, hence, with increase in pressure in the volume the flame becomes shorter and shorter. The result of reduction of the velocity of motion of parts of the jet is that the clots occur more frequently and the cone angle in their tail part increases. Hence, with increase in pressure in the medium the flame becomes broader and broader and on the sides has structures which anticipate the development of the "fir-tree" [4]. In addition, in these conditions there is a greater tendency for individual thickenings to "glide away" from the flame axis and for even greater broadening of the flame head. At excess presures up to 10 atm in the medium the flame still traverses the working volume fairly rapidly and does not hover in it, but the internal structure of the flame is more complex than in the case of injection without counterpressure, and the fuel component is distributed extremely inhomogeneously in it not only longitudinally, but also transversely.

The above-cited results of observations raise the question of the causes of the different nature of the development of the inhomogeneities when fuel is injected into a medium with a different excess pressure. In the case of injection into air at atmospheric pressure clots of fuel–air mixture begin to form at a distance 40-60 mm from the injector nozzle tip and their appearance is not correlated with pressure fluctuations in the fuel system, where the formation of the conical thickenings, closely following one another, in the body of a flame developing in a medium with increased pressure is of a different nature. As the results of investigation [2] indicate, the formation of inhomogeneities in a jet advancing in a medium without counterpressure and having a positive longitudinal velocity gradient is a consequence of the development of hydrodynamic instability in such a flow, which leads to the appearance of a distinctive longitudinal segmentation of the jet. In this case the perturbations developing near the injector nozzle do not develop into larger disturbances, since the velocity of propagation of the compression waves in the jet, which carry information about the possibility of concentration of the component in a particular cross section of the jet, is less than the velocity of relative motion of its parts. In addition, in these conditions the jet is narrow and considerable scattering of the signal to the side of the jet axis will occur. When the excess pressure in the volume is increased to 3-5 atm the velocity of advance of the jet head is reduced by a factor of 2-3, which is probably sufficient to produce the possibility of signal propagation along the jet and the interaction of its individual parts with one another. Hence, the entire fuel flame in this case becomes a single system, along which the interaction of the parts is established, and acquires the property of longitudinal elasticity. In the case of injection into a medium with counterpressure up to 2 atm, however, individual sections of the jet, scattered by inhomogeneities, hardly interact at all with one another and each successive portion of the jet has no effect on the advance of the previous one. Hence, the dynamics of the motion of the jet head is independent of the behavior of the remainder and, hence, of the nature of the change in pressure in the fuel system, except for the earliest stage of the process.

At higher pressures in the medium (7-10 atm or more) the transmission of information along the jet becomes reliable and the rear parts of the jet begin to affect the advance of the head. In this sense we use the term "property of longitudinal elasticity." It should also be noted that at pressures in the medium >5-7 atm the development of large-scale inhomogeneities dividing the jet into sections is not observed.

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LOCALIZED THERMAL STRUCTURE IN MEDIUM WITH BULK HEAT ABSORPTION

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Investigations of nonlinear processes of the diffusion type [1-6] have revealed several qualitatively new features of the course of such processes in comparison with linear processes.

In particular, in heat-conduction processes nonlinearity can be responsible for such an unusual property as thermal inertia. In the wide sense the property of thermal inertia means a finite velocity of propagation of thermal perturbations, when the perturbations propagate in a nonlinear medium in the form of heat waves with a finite velocity of motion of the front.

The property of thermal inertia is manifested in a qualitatively new form when the thermal perturbations are spatially localized. In this case the front of the thermal perturbation, propagating from the source with finite velocity, penetrates only a finite depth into the medium even in an infinite period of time. As was shown in [7-10] the nonlinear spatial localization of thermal perturbations can be due to the effect of bulk absorption of thermal energy, the rate of which depends on the temperature.

One of the most interesting regimes of spatial localization of thermal perturbations is the stable localization regime [11]. The heat wave front in this localization regime remains stationary, and the size of the perturbation region does not vary with time. In this case the localized heat pulse is self-insulated from the surrounding space and evolves into a space region of constant size. As an example of realization of this type of nonlinear heat conduction regime we consider the evolution of a heat pulse in a medium of constant density ρ, heat capacity c, and thermal conductivity k in the presence of bulk absorption of thermal energy in it, the rate of which is related to the temperature by a power law and depends explicitly on the time – it decreases exponentially with time with a characteristic relaxation time τ. In the one-dimensional case this process is represented by the following parabolic quasilinear equation with a nonlinear lowest term:

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