X-RAY PULSE METHOD FOR INVESTIGATION OF THE INTERNAL STRUCTURE OF A FUEL JET

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In order to construct analytic models [1-3] of the development of a fuel jet formed upon the high-pressure pulsed injection of fuel into a working chamber, e.g., under the operating conditions of diesel motors, empirical data on the motion of its outer boundaries are used which are obtained mainly by high-speed cinematography. In the majority of cases a uniform fuel distribution is assumed through out the jet, and an average outflow velocity of fuel from the nozzle opening is used. Moreover, it has been shown by the investigations of [4, 5] that time-dependent phenomena caused by pressure pulsations in the fuel system play a significant role in development of the jet, which results in nonuniformity of the jet structure and the formation in it of regions with enhanced or reduced density of the liquid component. Accurate knowledge of the distribution of the fuel component throughout the jet is necessary for the development of the correct ideas about the processes of fuel ignition and combustion. Investigation of the internal structure of the jet by optical methods is hindered, since it is a feature filled by a large amount of fine fuel droplets and is optically opaque. Attempts to investigate a jet by taking different kinds of profiles of it with separators [5, 6] also fail to provide objective information, since the introduction of cutoff elements into the jet distorts the true distribution of the fuel component. The use of laser holographic methods to investigate the process of development of a fuel jet [7] permits in principle obtaining information about its internal structure; however, complications of a methodological nature as well as basic restrictions imposed by the Doppler effect [8] have not up to now allowed this method to gain wide acceptance in measurement practice. It is possible to obtain the direct distribution of the fuel component in a jet by means of x-raying it. The first tests in which a qualitative observation of the development of a fuel jet ejected from a model of a diesel injector was made were carried out in 1958 and described in [9]. However, the procedure employed then did not permit conducting a rigorous quantitative analysis of the phenomenon. Here the difficulties consist of the necessity of producing a pulse of a sufficiently large dose of soft x-ray radiation with a duration no longer than several tens of nanoseconds and with an effective radiation source size of a fraction of a millimeter. The deciphering of the rapidly moving elements of the fuel jet possessing relatively small x-ray-absorbing ability is possible only when these conditions are fulfilled. If the solution of this problem for pulsed radiography with respect to large jets entails no special effort [10], then the development of a special operating mode of the x-ray radiation source and the introduction of additives with x-ray contrast into the fuel are necessary in order to obtain x-ray photographs of a fuel jet having characteristic dimensions of several centimeters and an average density similar to the density of the surroundings [11]. The results of experiments which show the possibility of applying the pulsed x-ray method to the qualitative and quantitative investigation of the internal structure of a fuel jet during its development process are presented in this paper.

Organization of the Experiment. The layout for pulsed x-ray photography of a fuel jet is given in Fig. 1. A mixture of diesel fuel and a material with x-ray contrast (ethyl iodide) in a 1:1 proportion was supplied from the small tank 1 with the help of a booster pump 2 and a piston pump 3 through a pressure valve 4 into a standard diesel injector 5 equipped with a single-hole atomizer having a nozzle diameter of 0.25 mm. A needle valve adjusted so that the flow of fuel from the atomizer nozzle began only when a pressure greater

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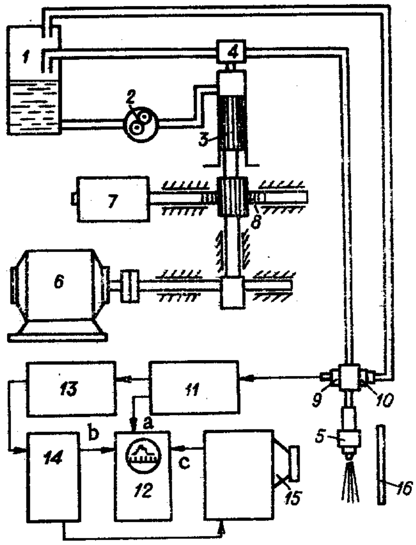

Fig. 1

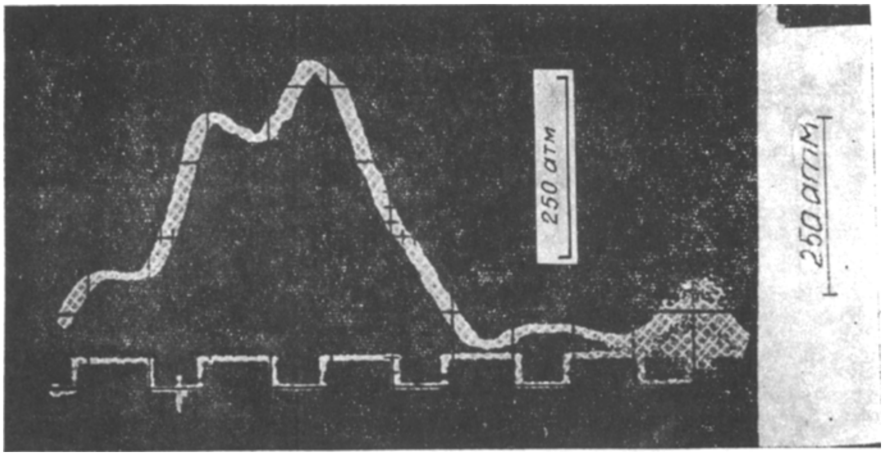

Fig. 2

than 250 atm is achieved in the fuel system is located in the injector housing directly preceding the atomizer tip. The control system of the fuel apparatus provided for its operation under conditions of a single injection. After a signal on the readiness of the entire rig and the achievement of the specified revolutions of the shaft of the main motor 6, which operates the piston pump (900 ± 10 rpm), repositioning of the rod 8 of the fuel pump was accomplished by command of the operator with the help of the electromagnet 7 in the time of a single piston stroke from zero capacity to a maximum of 0.135 cm^3/cycle. A measuring-regulating unit is mounted preceding the injector in which a Type LKh-600 quartz crystal detector 9 is placed to measure the pressure in the fuel system and in which a discharge nozzle 10 is located for the discharge of fuel excesses directly back into the small tank and for bringing the operating conditions of the fuel system into agreement with those characteristic of a real motor.

In order to provide synchronization and control of the operation of all systems of the installation, a signal from the pressure detector entered a BBT-1 high-impedance preamplifier 11 which had an input resistance no less than 10^{10} Ω and shunted with a capacitance of 0.05 μF to avoid an overload, and from there the signal was routed to one of the beams of an S8-11 oscillograph (channel a) 12. The large time constant of the detector—preamplifier system allowed performing its static calibration on a special hydraulic press.

The signal was fed in parallel to a U2-6 selective amplifier 13, which shaped the front of a synchronizing pulse at the start of the pressure rise in the fuel system, and was then routed to a G5-15 pulse generator 14. The pulses from the generator acted to trigger the oscillograph scans (channel b) and then reached the triggering device of the x-ray pulse equipment 15 with the required time delay. The second beam of the oscillograph performed control functions, and a meander with a frequency of 1 kHz and a pulse fixing the time of the x-ray radiation (channel c) was fed to it.

The x-ray pulse equipment is a variant of the Series PIR equipment developed at the Institute of Hydromechanics of the Siberian Branch of the Academy of Sciences of the USSR [12], and it is fabricated starting from the PIR-600 unit [13]. The operating voltage of the pulse transformer was about 100 kV, and the shock capacitance (200 pF) is formed by a length of coaxial cable combined with a pulse transformer. The voltage in the primary circuit was 10 kV. One of the versions of a Type IMA-5 sharply focused sealed x-ray tube was used in the equipment [14]. The application of a relatively large shock capacitance and a small-size sealed x-ray tube, as well as the careful preparation of the discharge circuit with minimum inductances, permitted producing a short (up to 20 nsec) pulse of relatively soft x-ray radiation and providing a dose of it sufficient for radiography with shieldless film 16. The layout selected permitted resolving drops up to 30 μm in size on the x-ray photographs. The use of amplifying screens appreciably reduces the size of the radiation dose required but greatly "smears out" the image and worsens the spatial resolution of details of the jet.

Experimental Results. A typical oscillogram of the pressure in the fuel system is given in Fig. 2. The three-step pressure rise here with a pulsation frequency of 0.7 msec and the relatively smooth decline in 1.3 msec is characteristic. The presence of pressure pulsations during the stage of its increase is associated with the arrival of relief waves in connection with the advance of the injector needle and with the onset of fuel outflow from the nozzle as well as with the development of self-oscillatory processes in the pipes and storage reserves of the injector. The true pressure in the fluid directly preceding the atomizer nozzle differs somewhat from that which is recorded by the pressure detector located in the measuring-regulating unit at a distance of 10-12 cm from the injector. This situation is related to the complex nature of the flow of fuel from the main line into the space above the needle valve, the presence of fine purifying filters in the injector, and so on [2]. Therefore the mode of the pressure increase preceding the atomizer nozzle is less steep, and the high-frequency components of the pressure oscillations are smoothed out.

The instant of the emission of the x-ray pulse is noted on the second beam in Fig. 2 1 msec after the start of the pressure rise in the fuel system.

A series of photoreproductions from the x-ray photographs of the development of the fuel jet taken is given in Fig. 3. These frames are not consecutive and are not made with one and the same injection. But since the pattern of development of the jet is repeated stably from test to test, a set is presented in Fig. 3 which illustrates the nature of this process in time. In all the frames the jet is propagating from left to right, and the edge of the side border of the injector is visible in the left part of the frame.

An investigation of the material presented shows that in the initial development stage of the jet its leading part interacts with the medium out to a distance of 40-50 mm according to the classical pile-up mechanism [15] with the formation of a separation sheet of fluid with a frontal surface characteristic of this case (Figs. 3a, b). Such complex structure of a jet cannot be observed with the usual optical photography, since the sheet of atomized fuel which surrounds in a concentric way the central relatively compact jet of fluid completely blocks it from view. For comparison, photographs of a fuel jet taken at the same scale but in transmitted light with the help of a brief spark exposure (exposure time ∿ 1 μsec) are given in Fig. 4. Frames a–c in Fig. 4 correspond to frames c, e, and g in Fig. 3 insofar as when they were taken is concerned. The sheet of atomized fluid surrounding the central jet shows up faintly on the x-ray photographs since the concentration of material with x-ray contrast was chosen in such a way that the sheet did not obscure the jet. With the appropriate choice of the concentration of ethyl iodide it is possible to observe both the central jet and the layers of atomized fluid surrounding it. As an example, a reproduction is given in Fig. 5 from an x-ray photograph which captured the process of atomization of the fuel jet connected with the operation of an AR-21 injector nozzle. The formation in this x-ray photograph of a compact core right by the injector nozzle produced upon the break-up by the high-speed jet ejected from the nozzle of a fuel droplet prior to the emergence of the jet is noteworthy. This operating mode of an injector nozzle is characteristic.

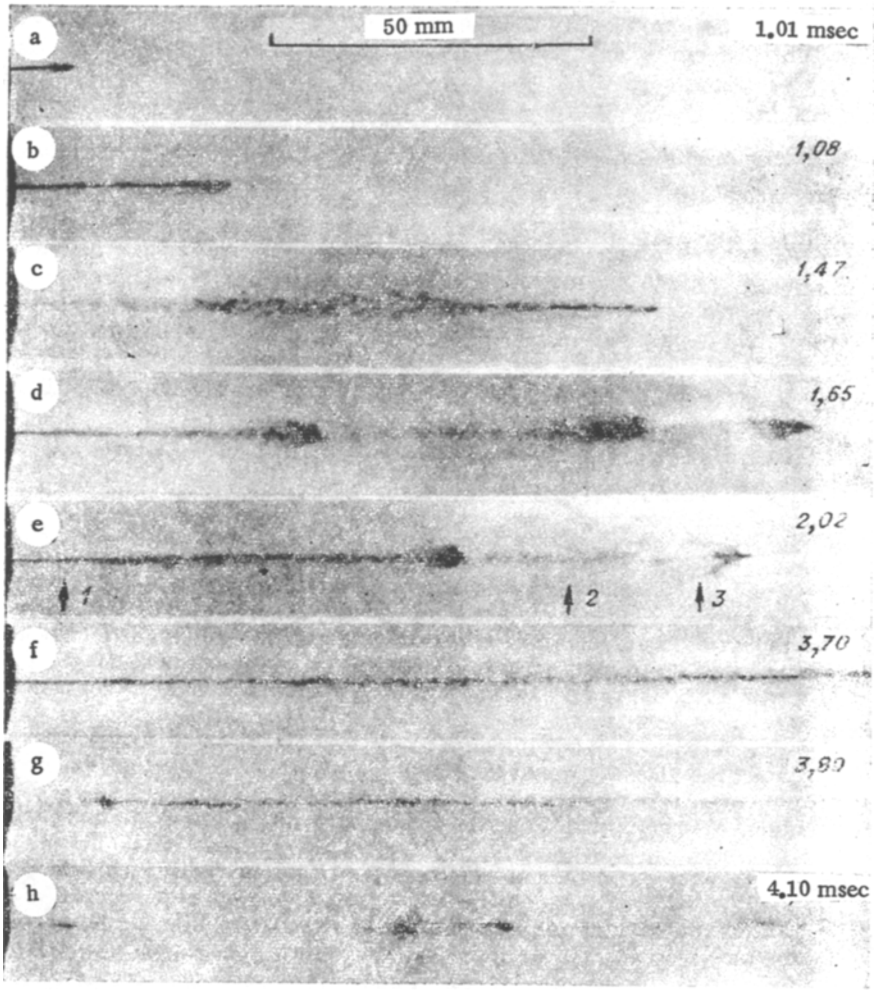

Fig. 3

Upon reaching a distance of 60-70 mm the jet loses its continuity and starts to break up; zones of compaction and rarefaction of the fuel component appear. We note that at this stage of the phenomenon the pressure in the fuel system is still continuing to increase and the velocity of fluid outflow from the injector nozzle increases. Therefore, the following sections of the jet separate from the slower preceding sections, and zones of increased fluid concentration are periodically formed within the jet which are not observed on the usual optical photographs (Figs. 3c-e). It is noteworthy that the formation of these successive compaction zones in the jet is not correlated with the pressure pulsations in the fuel system, but possibly it is associated with the appearance of some kind of hydrodynamical instability. Up until when the velocity of fluid outflow from the atomizer nozzle increases, each subsequent section of the jet forms a perturbation in its own main part with a definite periodicity, the density of the jet at this point increases, a slowing down of the flow occurs, and the rest of the jet section flows into the "trap" formed. The process of atomization of the main part of such a jet segment also proceeds according to the pile-up mechanism (Figs. 3d, e); each subsequent fluid blob advances into a continuously denser fuel—air medium.

When the pressure in the fuel system starts to fall off, the outflow velocity of the jet decreases, and a negative longitudinal velocity gradient is established along it. In this case the formation of inhomogeneities within the jet is curtailed (Figs. 3f, g).

Reproductions from x-ray photographs taken during the concluding stage of the phenomenon are presented in Figs. 3g and h. The tail end of the jet which concludes the ejection of the final blob of fuel upon closure of the needle valve is visible in these pictures. The so-called subinjection is captured in Fig. 3h, i.e., a short-duration ejection of a

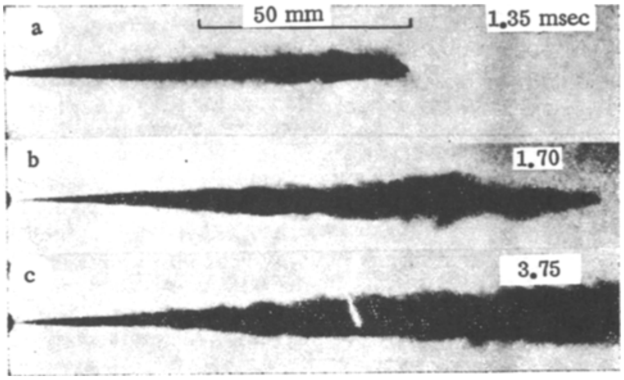

Fig. 4

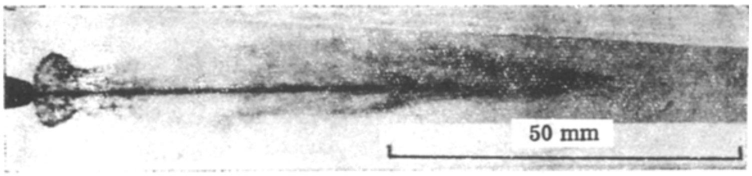

Fig. 5

small amount of fuel characteristic of the operation of injectors with a needle valve when the tail end of the main jet has already left the injector nozzle. This ejection is produced in connection with a hydraulic shock in the fuel system and a short-duration pressure increase upon the sudden closing of the valve which is associated with it.

In order to obtain quantitative dependences, a polygon made out of polychlorvinyl film was glued to each cassette upon completion of the x-ray photographs. By means of photometric measurement of the sections of the negative having the projections of the polygon with a different total film thickness for each x-ray photograph, calibration curves were constructed from which the degree of attenuation of the negative upon absorption of x-ray photons was determined as a function of the local thickness of the film. These curves were used in processing the results of microdensitometer scanning of the fuel jet with the goal of a quantitative analysis of the distribution of the fuel component within the jet.

As an example, the galvanometer readings of the microdensitometer as a function of the jet radius which were obtained in connection with the analysis of the x-ray photograph, of which a reproduction is presented in Fig. 3e, are given in Fig. 6 at the three cross sections indicated by the arrows 1, 2, and 3. The size of the section photometrically scanned in these measurements was 100 × 250 μm (the long side of the section is positioned along the jet), and the measurement step was 100 μm. Analysis of a negative was carried out from the axis of the jet to the point at which the signal imposed on the background illumination disappeared. The graphs presented illustrate the total amount of fuel in the jet and the nonuniformities in its distribution in the cross sections scanned. Integration of the area under the curves 1-3 in Fig. 6 shows that up to 7-10 times more fuel accumulates in the blobs than at the rarefaction zones or near the end of the injector nozzle.

Conclusions. 1. A portable pulsed x-ray instrument for the investigation of the internal structure of gas hydrodynamical flows of low density which permits resolving details up to 30 μm on shieldless x-ray film has been developed and is being applied in practical scientific investigation.

2. A procedure has been developed for investigation of the internal structure of a fuel jet under the operating conditions of natural diesel injectors.

3. Comparison with an optical photograph shows that the shape of the jet recorded in visible light is determined by a fluid sheet separated from the jet and does not correspond to the true distribution of fuel in the jet.

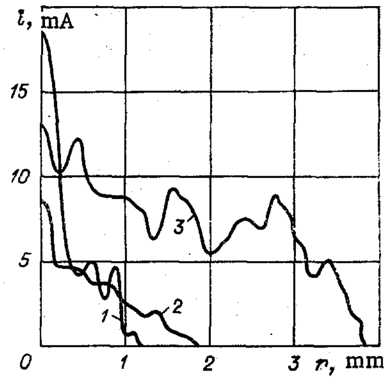

Fig. 6

4. It has been shown experimentally that a jet of a fuel–air mixture has an appreciably nonuniform structure, and the concentration and overall distribution of the fluid component along it differ by an order of magnitude in different cross sections.

5. The formation of blobs of fuel within the jet is not directly related to the pressure pulsations in the fuel system but is possibly the result of a hydrodynamical instability, since such a flow occurs only during the time interval in which the pressure in the fuel system is increasing and a positive longitudinal velocity gradient has been established along the jet.

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AN INVESTIGATION OF A LONG SLIDING SPARK

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The breakdown characteristics of sliding sparks up to 2.5 m in length of different gases are investigated at various pressures. Investigations of sliding sparks in air at atmospheric pressure have been described in [1, 2]. The investigations in this paper were conducted in argon, neon, helium, and air at pressures from 10 to 1600 mm Hg. Creepage arose on the surface of the dielectric film with which the metal tube attached to one of the electrodes (the so-called "initiator") was wrapped. The diameter of the initiator was equal to 40 mm. The film thickness was 0.4-4 mm. The length of the discharge gap was varied from 0.25 to 2.5 m. The discharge occurred in a dielectric chamber 450 mm in diameter which was evacuated and then filled with the different gases. A cable transformer [1, 2] served as the voltage source. The voltage in the secondary winding had the shape of a decaying cosine with a frequency from 30 to 120 kHz. The logarithmic damping constant was equal to 10^{-2}.

Experimental Results. The value of the breakdown voltage U_{br} was investigated in all the experiments. This value was defined as the smallest amplitude at which the sliding spark spans the discharge gap.

The effect of the thickness of the dielectric film Δ(mm) can be expressed in terms of the effect of the specific capacitance of the film $C_{sp} = 0.88\, \varepsilon/\Delta$, upon which the breakdown voltage depends uniquely.

The $U_{br}(C_{sp})$ relation for argon, neon, helium, and air plotted for a gap length of $l = 1$ m at atmospheric pressure is given in Fig. 1 (curves 1-4, respectively). It is evident that as C_{sp} increases U_{br} falls off sharply at first. But starting from C_{sp} of 2-5 pF/cm², the variation of U_{br} becomes mild. It is possible to explain this physically by the fact that initially the increase of C_{sp} results in an increase of the capacitive current, and consequently of the total current through the incomplete discharge channel. The current increase leads to a decrease in the resistance of the channel and an effective transfer of the potential of the high-voltage electrode (from which the creepage develops) to the tip of the incomplete leading channel. This potential provides for the occurrence of ionization processes at the tip and the development of a leader. At a sufficiently large value of C_{sp} the increase in the potential at the tip undergoes saturation.

It is also evident from the data of Fig. 1 that the relation of the breakdown voltages for different gases depends weakly on the quantity C_{sp} for sufficiently large values of C_{sp}. One can explain this situation also by the decisive effect of ionization processes at the tip of the incomplete channel of the leader. The processes are determined mainly by the area in front of the tip in which multiplication of cascades and streamers occurs. The dependence of U_{br} on the length of the discharge gap l is given in Fig. 2 for argon (1 and 1'), neon (2 and 2'), and helium (3 and 3') with C_{sp} equal to 1.6 (curves 1-3) and 3.0 pF/cm² (curves 1'-3').

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