DISPERSION OF A HIGH-PRESSURE WATER-FUEL EMULSION JET

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A way of radically increasing fuel efficiency in diesel engines and improving the ecological characteristics of their operation is the use of water−fuel emulsion [1]. However, in spike of the large number of computational an experimental studies, the physical−chemical mechanism of the effect of the water emulsified in the fuel on the processes of carburetion, ignition, and combustion under typical conditions for diesel engines remains unclear, for the most part. In particular, it is assumed that the leading mechanism of water liberation in the fuel and the cause of the additional dispersion of hot water−fuel emulsion droplets is thermal micro-explosions of minute water droplets [2, 3]. In the opinion of many researchers, this effect also explains the mechanical dispersion of the centers of fuel−air jets [1, 4]. Hence emulsification of the fuel leads not only to changes in the kinetics of the ignition and combustion of the mixture, but also affects the pre-ignition stage, i.e., the process of carburetion. But estimates show that the micro-explosion mechanism is possible only at sufficiently low static pressures in the medium [3], and that micro-explosions occur with large induction times for heating of the water−fuel emulsion droplets such that a large fraction of the fuel has been vaporized [5]. Therefore the assumption that thermal explosions of water droplets are responsible for the evolution of the jet of emulsified fuel is questionable, at least in the initial stages of the process.

An alternative model of the evolution of a jet of water−fuel emulsion in air was given in [6]. Emulsification is considered as one of the physical factors that leads to an increase in the dispersion angle of the jet immediately after discharge from the sprayer nozzle. It is known that for high-pressure injection of a liquid into a gas the liquid is stretched over the nozzle cross section and the liquid cavitates. In the initial stages the flow resembles the motion of closely packed particles [7]. Because of the cavitation breakdown of the jet, the particles acquire a radial velocity component u_r together with the longitudinal velocity u_x. The radial velocity determines the dispersion angle of the gas−liquid jet (Fig. 1a).

The cavitation breakdown of a liquid under high tension is well known in the physics of shock waves [8]. Here the velocity of the surface layers (the phenomenon of "peeling") is determined by the difference between the amplitude of the relieved pressure p_f and the dynamical tensile strength of the liquid σ_f. It is important to note that for the condition considered here σ_f is comparable to the tension and strongly depends on the presence of cavitation centers in the liquid. For example, σ_f can be as large as 30 MPa for purified and degassified water [9], but it decreases to 0.8 MPa for ordinary water [8]. Therefore the emulsification of the fuel, i.e., the artificial introduction of interfacial boundaries in the fuel in the form of water droplets, leads to enhanced breakdown of the jet and an increase in the radial velocity of the material and hence to an increase in the dispersion angle of the jet. Also the sprayed water−fuel emulsion always contains finer droplets than water-free fuel. The dispersion of jets of water−fuel emulsion and pure fuel is shown schematically in Fig. 1a, b.

To see the effect of the cavitation breakdown of the jet on the shape of the jet, we consider the following numerical estimates based on energy arguments. It is now difficult to show that the specific kinetic energy of the longitudinal motion imparted to the fuel discharged from the nozzle under a pressure of $p_f = 40$ MPa is $\varepsilon_x = u_x^2/2 \sim 25$ kJ/kg. In cases of practical interest the dispersion angle of the jet is equal to 10-12° [10], hence $u_r \sim 0.1u_x$. Then, assuming that u_r varies linearly with the radius of the jet, we find that the specific kinetic energy of the radial motion of the liquid is $\varepsilon_r = u_r^2/4 \sim 0.15$ kJ/kg. But the specific elastic energy $\varepsilon f = \text{æ}p_f^2/2\rho_f$, released in the discharge of the liquid, and which goes into the breakdown of the liquid and its motion, is ~ 0.8 kJ/kg (the coefficient of isothermal compressibility of kerosene $\text{æ} = -(dv/dp)/v$ is 0.8 GPa^{-1} [11]). Hence even a small change in the work required to break down the liquid can affect the evolution of the jet shape through a change in u_r, but not through a change in u_x. Therefore a criterion of the effect of emulsification of the fuel on the nature of the cavitation breakdown in the jet is the change in the dispersion angle of the jet.
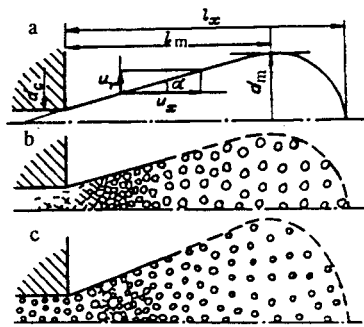
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Fig. 1

In the present paper we discuss the results of experiments using motion pictures to study the geometrical characteristics of jets of pure fuel and water−fuel emulsions ejected impulsively at high pressure into a gas. We consider the initial stage of this process up to the point where the micro-explosion mechanism of water liberation can begin to act.

The experimental equipment has been discussed in detail in [7]. A gas cylinder of constant volume is filled with nitrogen at temperatures ranging from 400 to 900°K and with initial static pressures from 2 to 6 MPa. A single impulsive injection of DL diesel fuel of water−fuel emulsion is injected into the chamber by means of a standard closed diesel sprayer with nozzle aperture diameter d_c = 0.25 mm. Because there is a needle valve in the sprayer which opens only when the pressure in the fuel system reaches 25 MPa, the injection begins at this level and lasts for 0.5 msec. The pressure reaches 45 MPa only near the center of the injection (at 2.5 msec). The pressure then begins to drop and fuel injection stops.

The mass of a cyclic injection of pure fuel was 40 mg, regardless of the conditions in the operating volume. For the water−fuel emulsions with mass content of water of C_m (%) the injected mass was the same in some of the experiments and in others was increased so that the energy content in the injected dose would be constant. This was achieved by adjusting the injection duration, but the variation of the pressure in the fuel-injection system was the same in all cases and the experiments showed that it was independent of the presence of absence of water in the fuel.

A drum-type SK-2 movie camera was used with a prism compensator with an exposure rate of 5000 frames per second. The images of the evolving jets were projected onto a screen and the following parameters were read off (Fig. 1a): the total length l_x of the jet, the diameter d_m of the jet at its maximum cross section, and the distance l_m between the maximum cross section and the opening of the sprayer nozzle. Obviously the dispersion angle α of the jet, which depends on the ratio between the radial u_r and longitudinal u_x velocities of the liquid, can be approximated as the ratio of $d_m/2$ to l_m. Taking into account the operating characteristics of the movie camera, it was estimated that the accuracy of the measured dispersion angle of the jet was not less than 10%.

For our studies the measurements were taken on the fourth frame after the start of the injection, i.e., at the time t = 0.6 msec. This time was chosen mainly for reasons of accuracy (the relative error in the geometrical parameters of the jet decreases from frame to frame). Also at this time the length of the jet is 30-40 mm and the initial and transitional stages of the evolution of its leading edge have already occurred [7]. On the other hand, the jet has not yet separated from the nozzle by such a distance that its conical shape has been lost. (Then our approximation for the angle α would become incorrect.) It is also important to note that at this time the micro-explosion mechanism of water liberation has not yet appeared, since, according to the estimates of [12], at t = 0.5 msec less than 2% of the mass of injected fuel has been vaporized for the conditions of our experiments. An additional argument in favor of the time of measurement chosen here is the fact that the pressure in the fuel system is practically constant at 25 MPa over this period of time and the nature of the discharge has not yet changed in response to its later increase.

As an example, the evolution of the jet is shown in Fig. 2a, b for the case of pure fuel injected into nitrogen with pressure 4 MPa and temperature 900°K (the time in milliseconds since the start of the injection is noted on the frames). It follows from visual observation of these and similar pictures that vaporization, which is most susceptible to thermal disturbances of the leading edge of the jet, becomes important only 0.8 to 1 msec after the start of the injection. This fact supports the validity of the methodology described above. Figure 2c shows a series of frames which can be used for quantitative analysis of the evolution of water−fuel emulsion jets with water contents C_m = 0, 5, 10, 20, 30%. This set of photographs shows that water−fuel emulsion jets appear bulkier than pure fuel jets because of the widening.
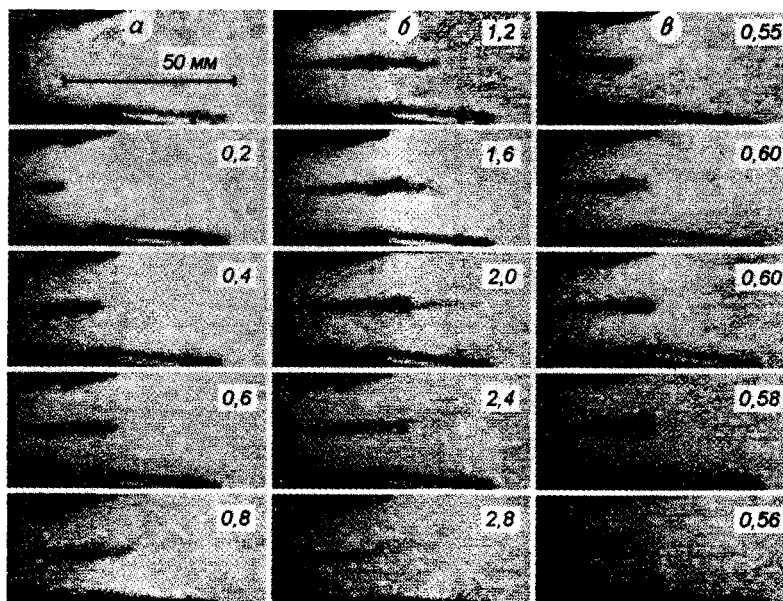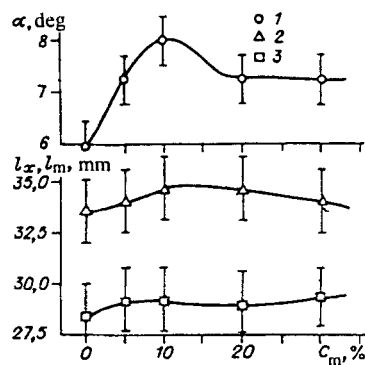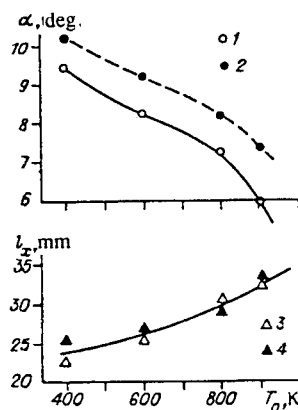
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Fig. 2

Fig. 3

Fig. 4

The dependence of the quantities α, l_x, and l_m (sets of points 1-3) on the water content of the fuel is shown in Fig. 3 for $p_0 = 4$ MPa and $T_0 = 900°$K. As for the dispersion angle of the jet, we note that emulsification of the fuel leads to a 35% increase in α when C_m varies from 0 to 10%. With further increase in C_m the angle α begins to decrease somewhat and it then stabilizes at a level of 25% above the value of α for water-free fuel. The observed increase in the dispersion angle of the jet is directly related to its expansion immediately after discharge from the nozzle. This is supported by the dependence of l_x and l_m on C_m shown in this figure. It is evident from the graphs that at a fixed instant of time l_x and l_m are practically independent of the water content in the fuel.

Figures 4 and 5 show the dependence of α and l_x on the temperature of the medium for the fixed pressure $p_0 = 4$ MPa and on the pressure in the cylinder for the fixed temperature $T_0 = 900°$K for pure fuel (sets of points 1 and 3) and for a 20% water–fuel emulsion (sets of points 2 and 4). The experimental results show the typical [10] increase in the dispersion angle of the jet and its decrease in length with increasing density of the medium. While some of the variation in the $l_x(T_0)$ or $l_x(p_0)$ curves with the parameters of the medium and C_m are within the experimental error, in all cases the parameter α for $C_m = 20\%$ (dashed curve) is systematically above the curve for pure fuel (solid curve). Note especially the case of injection into cold nitrogen, when the vaporization mechanism is known not to operate (Fig. 4).
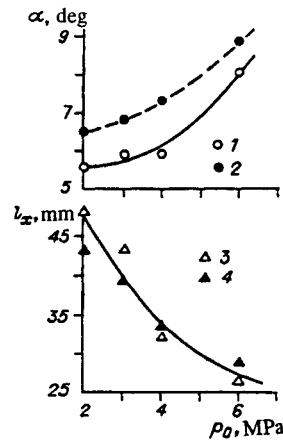
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Fig. 5

In summary, our experimental results show that a high-pressure jet of emulsified fuel leaves the sprayer nozzle at a larger dispersion angle than pure fuel. The change in the tensile strength of a water−fuel emulsion sudden discharge is the only factor (including thermal disturbances) which can explain this phenomenon. As for the nonlinearity of the dependence of the dispersion angle on the water content of the fuel, we note that the increase in α as C_m increases from 0 to 10% is associated with the increasing number of interfacial surfaces, which leads to more favorable conditions for dispersion of the liquid. The decreasing effect of the widening of the jet as the water content increases to 20-30% is possibly due to a significant change in the rheological properties of the liquid: a sharp increase (by a factor of 5 to 7) in the coefficient of internal friction [2], which leads to an increase in functional losses and to a rearrangement of the structure of the flow inside the nozzle.

A detailed explanation of this quantitative result is difficult because there is insufficient information to construct phenomenological physical models. Therefore the result should be considered as qualitative, though it is important in analyzing the processes of carburetion, ignition, and combustion of water−fuel emulsions in diesels. The importance of this factor, which is associated with the widening of a water−fuel emulsion jet in air, is obvious from the following estimate. When the dispersion angle increases by 20% (we take $\alpha \sim 6\%$) the volume of the jet increases by 40% for the same length. Hence at the corresponding instant of time the mean density of the fuel component in the jet decreases by more than 40% because some of the fuel was replaced by water. This undoubtedly leads to a significant change in the nature of the ignition and the initial stage of the combustion of the fuel [6].

The main conclusions of the present paper are as follows. Emulsification of the fuel leads first to a change in the dynamics of the shape of the jet beginning immediately after injection of the water−fuel emulsion from the sprayer nozzle. The change in the nature of the carburetion due to emulsification of the fuel is associated with the increase in the dispersion angle of the jet, which reaches a maximum of 35% for a water content of 10%. In the second phase the shape of the jet can change as the result of thermal processes such as the micro-explosion mechanism of liberation of water, which acts both as an inert coolant and a chemical reagent. The dispersion of a high-pressure injection of a water−fuel emulsion is stronger because of a decrease in its dynamical tensile strength due to the large number of interfacial surfaces in the form of minute water droplets introduced in the fuel.

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