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# DEVELOPMENT OF A LIQUID-FUEL JET AT HIGH-SPEED PULSE INJECTION INTO A GASEOUS MEDIUM. I. PHYSICAL MODEL

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*A three-stage scheme for calculation of the main parameters of a high-speed pulse jet of a fuel-air mixture in a gaseous medium is proposed. First, the development of a comparatively dense axial flow of the mixture, which is formed during quasistationary high-speed injection of a liquid fuel from the nozzle, is considered. Then the character of motion of the head part of this flow is examined taking into account the cumulative character of interaction between the flow and the medium. Finally, the dependences typical of an autonomous vortex ring, which allow one to determine the diameter and the root angle of the jet, are presented.*

**Introduction.** The most promising direction toward increasing the economical efficiency and ecological safety of diesel engines is the improvement of the process of fuel combustion [1]. The character of this process is determined to a large extent by the quality of mixing and pre-burning treatment of the fuel–air mixture. Incomplete combustion manifested in the presence of soot and coke particles, underoxidized hydrocarbons, etc., is caused first of all by the formation of inhomogeneities in the jet [2], which contain different-scale time and space fluctuations of the fuel distribution density, and also by the violation of homogeneity of the mixture [3]. Therefore, many papers are devoted to the study of one of the key processes in the diesel combustor: the development of a high-speed pulse jet of a fuel–air mixture. Nevertheless, although the main results were obtained many years ago [4–6], numerical, theoretical, and experimental studies are continuing [3, 7–9], since the requirements on economical efficiency and ecological characteristics of existing and newly created engines are becoming more and more stringent, and the solution of these problems is intimately connected with more profound knowledge of the mechanisms of heat and mass transfer in the engine combustor.

Based on the results of complex experimental investigations, a new physical model of the development of a high-speed pulse jet of a fuel–air mixture in a gaseous medium is proposed in the paper. The interaction of the head part of this jet with a gas is considered as cumulative [10]. The jet is represented as a comparatively dense high-speed axial flux of the mixture surrounded by the gas–liquid mass with a small content of the fuel component, which hangs in space. The specific feature of the flow in the head part of the jet is its similarity to the flow observed in a vortex ring [11].

**1. State-of-the-Art of the Problem.** A jet formed by high-speed pulse injection of fuel into a gaseous medium is usually characterized by the dependence of the jet length $L$ and root angle $\alpha$ on the time $t$ (Fig. 1a). The third important quantity, the jet diameter $D$, is referred to much more seldom, since it is believed to be possible to express this parameter in terms of $L$ and $\alpha$. But if we assume this parameter to be the jet diameter in the maximum cross section, it turns out that the position of the cross section $l_m$ relative to the nozzle has a different dependence on the time and test conditions than the total length of the jet $L$. Therefore, the shapes of jet structures at different stages of their evolution are not, strictly speaking, geometrically similar. At the same time, only the information on the dependence of $D$ and $l_m$ on the character of injection and test conditions allows one to determine the most important parameter of the jet, its volume, and, in terms of the volume, the distribution density of the fuel component in the mixture [3]. Hence, it follows

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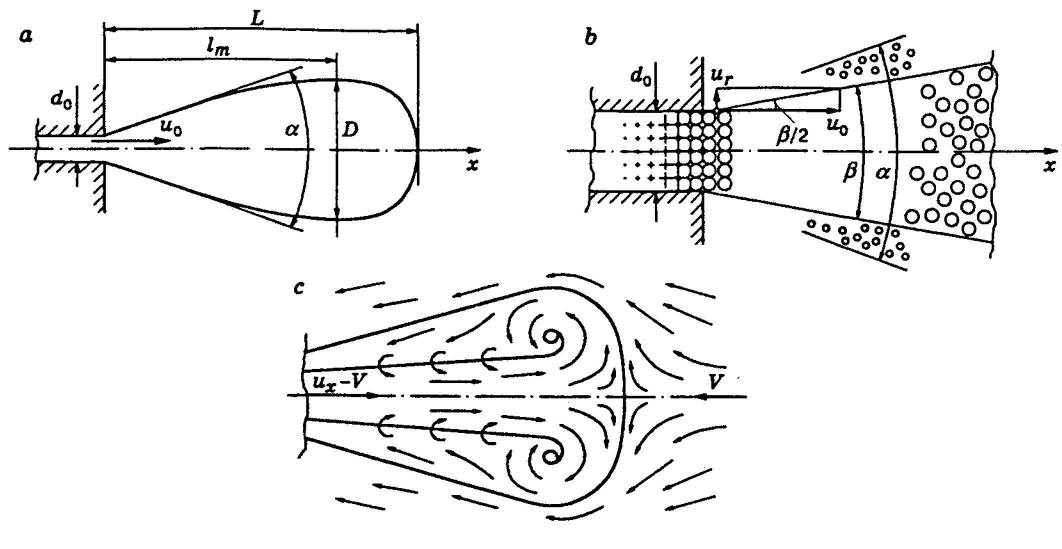


Fig. 1

that an adequate prediction of the specific features of the mixing process in a diesel engine requires knowledge of single-valued functional and physically grounded dependences of the above-mentioned four characteristics of the jet of a fuel–air mixture on the governing parameters.

It was found experimentally that $L$ increases with increasing nozzle diameter $d_0$ and injection intensity, which is characterized either by the pressure $p_l$ in the fuel-injection system or by the velocity $u_0$ of fuel injection from the nozzle. However, as the pressure $p_g$ in the gaseous medium increases, the jet length decreases and the jet angle $\alpha$, vice versa, increases. The angle also increases with increasing $u_0$ and $d_0$. To a smaller extent, these two geometric parameters depend on such properties of the fuel as its dynamic viscosity $\eta$ and surface tension $\sigma$. Some features of the behavior of $D$ and $l_m$ depending on the test conditions have been established considerably recently [3].

Numerous more or less successful attempts have been made to calculate the form of the parameters $D$ and $\alpha$ as functions of $d_0$, $p_l$, $p_g$, $u_0$, $\eta$, $\sigma$, etc. [4–6, 12–19]. Most of these papers deal with the problem of inertial flight of a compact or distributed (a group of droplets) body of constant or variable mass through a gas medium. Under the action of aerodynamic drag and friction forces, this body is decelerated and describes the trajectory $x$–$t$ in space, which is qualitatively similar in most cases to that observed experimentally. For quantitative agreement, however, strong empirical coefficients are generally added to formulas or physically unjustified assumptions are used. Therefore, the evolution of high-speed jets of a fuel–air mixture cannot be reduced to the simplest form of one-dimensional motion, whereas no suggestions on the calculation of $D$ are given in the literature.

One of the alternative approaches to solving the problem of the motion of the head part of the gas–liquid mixture in a gas medium was proposed by Trusov and Ivanov [20], and this approach was finally developed by Buzukov [21]. In this case, we mean the cumulative mechanism of the flow considered [10], which allows us to estimate the jet diameter $D$ among other parameters. Nevertheless, despite the fact that this mechanism was experimentally verified [22, 23], the corresponding numerical model was not developed.

Several approaches to calculation of $L$ and $\alpha$ have been described and purely empirical formulas, which relate the test conditions to these parameters, have been proposed, but their use is hindered by the fact that the coefficients in them were obtained for specific cases and in a narrow range of the governing parameters. Therefore, the known formulas suggested by Lyshevskii [24] are often used in practical calculations. These formulas were obtained as a result of generalization of a great body of experimental data:

$$L = \sqrt{\frac{d_0 u_0 t}{\sqrt{2}a}}, \qquad \alpha = 1.26\,\frac{\mathrm{We}^{0.32}\rho^{0.5}}{M^{0.07}}. \tag{1}$$

Here $a = 2.72\rho/(\mathrm{We}^{0.21}M^{0.16})$, $\rho = \rho_g/\rho_l$ ($\rho_g$ and $\rho_l$ are the gas and liquid densities), $\mathrm{We} = (u_0^2 d_0 \rho_l)/\sigma$, and $M = \eta^2/(\rho_l d_0 \sigma)$.

**2. Justification of the Physical Model.** The physical model was developed on the basis of the results of a complex experimental study of the evolution of pulse jets of a liquid fuel injected at a high pressure into a gaseous medium [25]. Some important specific features of the phenomenon considered were observed using the methods of high-speed photography [3, 8, 22], microphotography with pulse laser lighting [26], and pulse x-ray photography [23, 27].

First of all, the assumption is confirmed [28, 29] that the so-called "head part" [24], where the integrity of the liquid flow exhausted from the nozzle is preserved, is not formed in pulse high-speed jets ($p_l$ = 20–100 MPa and $d_0$ = 0.15–0.75 mm). Because of cavitational destruction induced by unloading at the end of the nozzle duct [8, 26, 28, 29], the liquid is already dispersed to a fine state when it enters the gaseous medium, but near the sprayer the liquid is packed almost to a "monolith" density (see the microphotograph of the initial stage of evolution of the jet in Fig. 2a [26]). It is important that the particles in this flow regime acquire the radial velocity $u_r$ along with the initial longitudinal velocity $u_0$ (see Fig. 1b). The intensity of the radial spreading of the jet material is determined not only by the injection pressure but also by a noticeable rupture strength of the liquid at sudden unloading [8, 29, 30]. In most cases which are interesting from the viewpoint of practical applications, the velocity of spreading of the outer layers of the jet $u_r$ is comparatively small and equal to 10–30 m/sec [24] (the longitudinal velocity of the flow is $u_0$ = 150–350 m/sec). Considering this component of the flow as the motion of a cylindrical piston, we can easily show that the velocity $u_r$ decreases only by 5–10% during the characteristic time of injection (2–10 msec) because of the opposing action of the medium. This allows us to represent the jet rarefaction induced by radial spreading of the layers of liquid droplets as a quasistationary process.

The specific feature of the longitudinal motion of a gas–liquid mixture is the small losses on friction in the cocurrent gas flow. Part of the gas is not only set into motion by the jet, but actively penetrates into it [31]. It is due to this process of ejection that the flow of the mixture is gradually decelerated, which generally has a weak effect on the radial flow. Therefore, under the condition of a constant exhaustion regime of the fuel, the portion of the jet from the nozzle to the head part can be characterized by an angle of divergence $\beta$, which varies little in time and over the jet length (see Fig. 1b). Thus, the introduction of the parameter $\beta$ means that the process of evolution of the jet of a fuel–air mixture exhausted from the nozzle is considered as stationary and not affected by phenomena that occur in the head part of the jet because of its active interaction with the ambient medium.

Note that the parameter $\beta$ cannot be associated with the root angle $\alpha$ described by formula (1). The principal difference in these parameters is that they characterize phenomena of different hydrodynamic nature. The angle $\beta$ depends directly on the injection conditions and the properties of the liquid as a physicochemical body, whereas the angle $\alpha$, which is usually determined from the results of high-speed photography [4–6, 24], describes the shape of an optically opaque layer of the gas–liquid medium surrounding the axial flow, which hangs in the medium after the head part of the jet is sprayed there. Figure 2b [23] shows an x-ray photograph of the jet, which illustrates such a structure. In this case, the axial flow is divided into several sections, each of them moving in the wake of the previous section [23]. This regime of jet evolution is typical of fuel injection into a gas with pressure up to 1 MPa and has a specific dependence $L(t)$ [22].

We consider the character of the flow developed near the contact region between the jet and medium materials. In the initial stage of injection, where the total length of the jet does not exceed $(30–50)d_0$ and the density of its material is close to the density of nondispersed liquid, the head part moves according to the classical cumulative mechanism with the formation of the "turned-out stocking" typical of this mechanism (Fig. 2a [26]). As the axial flow of the mixture becomes more rarefied, the frontal surface of the jet is perforated, becomes porous, and, beginning from the distance of $(70–100)d_0$, a quasicumulative regime of interaction of

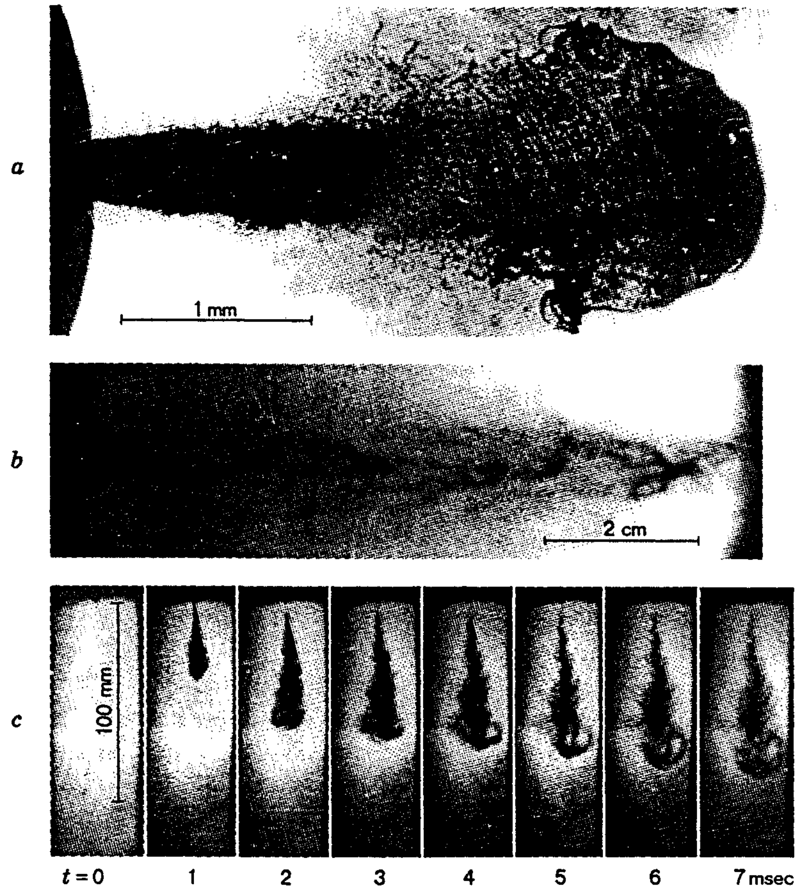


Fig. 2

the jet and the medium is established [22]. This means that the high-speed flow of the gas–liquid mixture entering the interaction region with the velocity $u_0$ is decelerated by the action of the aerodynamic drag of the medium, spreads to the sides, and the vacant space is occupied by the next portion of the mixture. Part of the jet material cast to the periphery, which is enriched by the gas contacting the jet due to turbulent diffusion, loses velocity, hangs on the sides of the axial flow, and forms an external shell of the jet with a lower content of the fuel component as compared with its core. It is this shell portion of the jet that determines its root angle $\alpha$ (see Fig. 1b). This structure of the flow is confirmed by the results of pulse x-ray photography [23, 27] and laser holography [32, 33]. In contrast to the classical cumulative scheme, which describes only the divergence of the jet material, part of the mixture cast to the periphery performs a circular motion and again enters the axial flow in the interaction region. Thus, the flow in the head part of the jet is similar to a certain extent to that observed in a turbulent vortex ring at the stage of its formation [34, 35]. Nevertheless, there is a significant difference between an autonomous vortex ring and the hydrodynamic structure considered here: in the latter case, the quasivortex is continuously fed up by the pulse of the fuel–air mixture that enters the flow. It is shown [3] that this representation allows one to obtain calculation results that agree with experimental data. Figure 1c shows the flow pattern in the head part of the jet being observed from the coordinate system moving with velocity $V$ of the contact point between the jet and medium materials. In some cases, this flow can be clearly visualized by high-speed photography (see Fig. 2c [22], the numerals in the photographs show the time from the injection beginning in milliseconds).

**3. Principles of the Numerical Scheme.** As a result of experimental studies, a hydrodynamic model of the evolution of a pulse high-speed jet of a fuel–air mixture is proposed. It can be considered as a basis for the development of the corresponding numerical scheme [see *Prikl. Mekh. Tekh. Fiz.*, **40**, No. 1, 166–173 (1999)]. In this model, the process of jet evolution is conventionally divided into three stages. At first, a quasi-stationary axial flow of the mixture is described. This flow does not depend of the phenomena that take place in the head part of the jet and is formed by high-speed injection of a liquid fuel into a gaseous medium. The flow saturation by the gas and the attendant gradual decrease in flow velocity are taken into account. The key moment in this consideration is the constancy of the angle $\beta$ of the axial jet in time and over the length. The parameter $\beta$ itself can be determined from the results of some study independent of diesel-engine building, because under the conditions considered the processes of liquid dispersion and jet formation are determined by the character of injection and the properties of the liquid as a physicochemical body, which affects the process of mixture formation only indirectly.

The second stage of solving the problem is the determination of the trajectory of the head part of the jet $L(t)$. Knowing the main characteristics of the axial jet (local density, velocity, etc.), we can use the known dependence for the process of cumulative interaction of the jet with the medium [10]: the length of the jet section $\Delta l_s$ "spent on making a hole in a target" of length $\Delta l_t$ is found from the relation $\Delta l_s = \Delta l_t\sqrt{\rho_g/\rho_x}$, where $\rho_x$ is the local density of the jet material in the interaction region.

In both cases, we consider the process of evolution of the axial jet in the one-dimensional approximation. The introduction of the angle $\beta$ only indirectly affects the current density and velocity of the flow of the mixture, but this is by no means connected with the determination of the jet diameter $D$ and the position of its maximum cross section $l_m$. Thus, assuming the flow in the head part of the jet to be identical to the flow observed in a vortex ring, we can use the known functions [34, 35], which establish a unique correspondence between the longitudinal and transverse diameters of the vortex core (the development of a classical autonomous vortex ring obeys the principle of self-similarity [36]). In this case, the transverse diameter of the vortex should be used as the maximum diameter of the jet $D$ and the position of the maximum cross section of the vortex (geometrical center) should be taken as the parameter $l_m$. The relationship between the geometric characteristics of the vortex and the conditions of its formation is established by Buzukov [34] and Pullin [35]: the diameter of the vortex core is larger by 10–12% than the size of the orifice from which the vortex-forming fluid is injected (in our case, it is the axial jet in this or that cross section).

Finally, we note that there is no contradiction in representation of the head part of the jet as interacting with the medium in accordance with the cumulative law on the one hand and as a vortex ring on the other hand. In both cases, the flow structure in the interaction region is identical with the only difference that the diverging material of the medium remains in this state during the entire process in the first case and this material comes back and the flow is closed on the back side of the vortex in the second case.

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