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DEVELOPMENT OF A LIQUID-FUEL JET AT HIGH-SPEED PULSE INJECTION INTO A GASEOUS MEDIUM. II. CALCULATION AND EXPERIMENT

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A three-stage calculation scheme developed previously on the basis of a complex experimental study is used to calculate the parameters of a gas–liquid jet formed at pulse high-speed injection of a liquid fuel into a gaseous medium. The results obtained using this model are in good qualitative and quantitative agreement with experimental data, and a physically grounded explanation is offered for the discrepancies observed in some ranges of parameters.

Formulation of the Problem. An analysis of the results of a complex experimental study of evolution of a pulse high-speed jet of a dispersed liquid fuel in a gaseous medium [1] allowed us to propose a simplified hydrodynamic model of this process. Based on this model, it is possible to calculate the main characteristics of the resultant gas–liquid flow in all stages of its development. In accordance with this model, it is reasonable to consider this process in three stages. First, the parameters (distributions of density and velocity over the jet length) are determined for a comparatively dense axial part of the jet of a gas–liquid mixture, which is formed directly by high-speed injection of a liquid from the nozzle. This high-speed flow is characterized by the fact that it has a low tangential friction drag in the developed cocurrent gas flow. However, because of its intense ejection, the flow gradually loses its velocity. It is shown [1] that the angle β of the axial jet varies weakly over the jet length and in time and the flow described can be considered as quasistationary and independent of the phenomena that occur in the head part of the jet. Under the conditions of high-speed injection, the angle β is mainly determined by the physicochemical properties of the liquid and by the intensity of its injection.

The second stage of solving the problem is the analysis of the flow in the head part of the jet. The main mechanism of interaction of the jet with the ambient medium is a quasicumulative mechanism. The use of dependences that exactly describe this mechanism allows us to obtain the main characteristic of the jet: the dependence of its length L on the time t. It is important that the formation of such a hydrodynamic structure in the head part of the jet is responsible for the appearance of one more parameter: the "root" angle of the jet $\alpha(t)$. This parameter is used to describe the conical shape of the outer shell of the gas–liquid jet surrounding the high-speed axial flow. The shell is formed by radial spreading of the mixture in the region of its interaction with the medium (the effect of cumulative penetration through a target) and hanging of the mixture in the space surrounding the jet.

In the first two stages of calculation, the flow is considered in the one-dimensional approximation, and it is impossible to obtain here any quantitative information about its radial components and, hence, to determine the jet diameter $D(t)$ and the external angle $\alpha(t)$. However, in the third stage, identifying the complex spatial flow in the head part of the jet with that observed in a vortex ring [1], we can use the one-to-one relationship between the longitudinal and transverse diameters and the core diameter (the latter is found by the area of the nozzle of the vortex generator from which the vortex-forming liquid is exhausted). In our case, we can use the axial jet of the gas–liquid mixture as this liquid, and the jet diameter in the interaction region with the medium can be used as the nozzle diameter.

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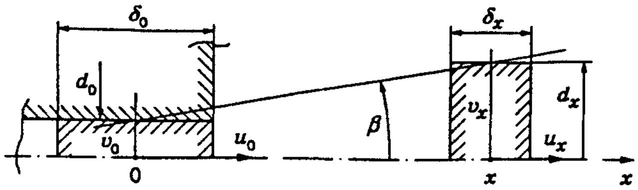

Fig. 1

Thus, the proposed three-stage calculation system yields all the main characteristics of the jet of a gas–liquid mixture: the jet length $L(t)$, the root angle of the jet $\alpha(t)$, the jet diameter in the maximum cross section $D(t)$, and the position of this cross section $l_m(t)$. In the present paper, the calculation procedure is described and the results are compared with experimental data.

Numerical Scheme. We consider the evolution of the axial jet of a dispersed liquid and ignore the problem of interaction of the head part of the jet with the medium (Fig. 1). Let a liquid of density ρ_l be injected from a nozzle of diameter d_0 with a constant velocity u_0. The elementary volume of this liquid $v_0 = \pi\delta_0 d_0^2/4$ is already dispersed because of cavitation destruction [2, 3], and the particles are not connected with each other. When this elementary volume moves along x, it does not experience drag forces and does not have to overcome tangential friction forces, but it is still deformed for two reasons. First, its diameter gradually increases from d_0 to d_x because of the initially prescribed divergence of the flow:

$$d_x = d_0 + 2x\tan(\beta/2), \tag{1}$$

where β is the angle of the axial jet, which does not change over its length or in time [1]. Second, the longitudinal size of the volume decreases from δ_0 to δ_x because of the decrease in its velocity caused by setting into motion the gas captured by the flow in the ambient medium [4]. Therefore, the current velocity u_x of the changed volume $v_x = \pi\delta_x d_x^2/4$ can be found from the conservation law of momentum

$$u_0\rho_l v_0 = u_x\rho_x v_x, \tag{2}$$

where ρ_x is the mean density of the jet material at a distance x from the nozzle.

Obviously, ρ_x is primarily determined by the presence of the initial amount of liquid in the form of distributed droplets in the elementary volume v_0. The remaining part of the volume $v_x - v_0$ contains a gas of density ρ_g. Hence, we have

$$\rho_x = \frac{v_0}{v_x}\rho_l + \Big(1 - \frac{v_0}{v_x}\Big)\rho_g. \tag{3}$$

System (1)–(3) is closed by the following relation, which indicates the continuity of the flow and the independence of the longitudinal and radial motion of the mixture in the axial jet [1]:

$$u_x/\delta_x = u_0/\delta_0. \tag{4}$$

We have to determine the angle β. At the moment, no satisfactory physicomathematical model has been developed that would allow a quantitative description of liquid dispersion in the process of the high-speed injection of the liquid from the nozzle. Thus, to estimate the angle β, we use the most reliable experimental results [5, 6] where the following generalized semi-empirical dependence was obtained:

$$\tan(\beta/2) = \frac{4\pi}{A}(\rho)^{0.5}\frac{\sqrt{3}}{6}. \tag{5}$$

Here $\rho = \rho_g/\rho_l$ and the coefficient A is determined by the shape of the nozzle orifice: in the case considered (a cylindrical nozzle with the aspect ratio of 4–6), we have $A = 4.2$ [6].

The solution of system (1)–(4) with account of Eq. (5) allows us to describe all the characteristics of the axial flow of a gas–liquid mixture. We present two final relationships for determining the main parameters, which will be used in what follows to consider nonstationary hydrodynamic flows in the region of interaction

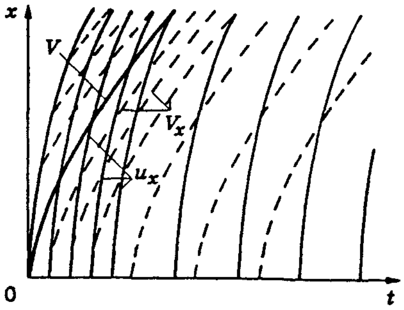

Fig. 2

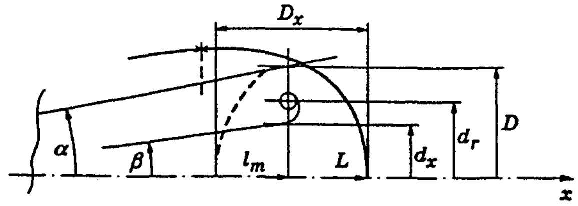

Fig. 3

between the head part of the jet and the ambient medium:

$$[1 + 2\bar{x}\tan(\beta/2)]^2\,\bar{u}_x^2 + (\bar{\rho} - 1)\,\bar{u}_x - \bar{\rho} = 0; \tag{6}$$

$$[1 + 2\bar{x}\tan(\beta/2)]^2\,(\bar{\rho}_x - 1)\,\bar{u}_x = \bar{\rho} - 1. \tag{7}$$

The main parameters in Eqs. (6) and (7) are the relative velocity of the mixture $\bar{u}_x = u_x/u_0$ and its mean relative density $\bar{\rho}_x = \rho_x/\rho_g$, the relative distance $\bar{x} = x/d_0$, and the density $\bar{\rho} = \rho_l/\rho_g$.

In the second stage of calculation, the motion of the head part of the jet in the medium is considered. We use the general relation obtained in the classical theory of cumulative jet flow [7]

$$\Delta l_t = \Delta l_S\sqrt{\rho_S/\rho_t}, \tag{8}$$

where the depth Δl_t of the hole made in a target (the density of the target material is ρ_t) is related to the length Δl_S of the part of the jet of density ρ_S which is spent on penetration. In our case, the target is a gaseous medium of density ρ_g and the projectile is a sequence of portions of the axial flow with local density ρ_x. The process of "penetration into the target" is identified with the motion of the frontal surface of each leading part of the jet in the gas, and the "expenditure" of the jet material is associated with the lateral spreading and nonlongitudinal motion of the material. The velocity V of this contact cross section downstream from the nozzle varies all the time. In the region close to the nozzle, this velocity is close to the exhaustion velocity of the liquid u_0, since the densities of the medium and jet materials are not commensurable here. However, as ρ_x and u_x decrease, the contact-point velocity also decreases, and at all stages of the process the velocity V is lower than the velocity u_x of the flow that enters the interaction region.

The trajectory of the frontal surface of the jet in the space x–t is uniquely determined by the conditions of the process and is a physically realistic object, but it is possible to imagine the formal existence of a certain "velocity field" $V_x(x, t)$, which describes the passage of the contact fronts through each elementary part of the jet. These velocities correlate with the local flow velocity u_x in agreement with the law of cumulative action (8), and this velocity flow in dimensionless form can be described by the equation

$$\bar{V}_x = \bar{u}_x/(1 + \sqrt{1/\bar{\rho}_x}). \tag{9}$$

Figure 2 shows in relative units the trajectories of the longitudinal components of the motion of jet elements (solid curves) and the above-mentioned phase fronts (dashed curves). Only one trajectory (shown by the thick curve), which passes through the origin, has a real physical meaning and describes the process of the head part of the jet moving in space. It follows from here that the basic dependence of the normalized length of the jet $\bar{L} = L/d_0$ versus the normalized time $\bar{t} = t/\tau$ can be obtained from the following equation with account of (5)–(7) and (9):

$$\bar{t} = \int_0^{\bar{L}} (\bar{V}_x)^{-1}\,d\bar{x}.$$

The characteristic time scale τ is the unique formal combination d_0/u_0 with the appropriate dimensionality, which has no physical meaning.

Until now, the jet was considered in the one-dimensional approximation: neither the suction of air from the ambient space by the axial flow nor the motion of the mixture to the sides of the head part of the jet were related to the evolution of the longitudinal components of the flow velocity, and the prescription of the angle β only weakly affects ρ_x and u_x, i.e., the parameters that also characterize the longitudinal flow. In this formulation, it is possible to calculate only the jet length $L(t)$. Neither the maximum diameter of the jet D, nor the location l_m of the cross section in which this diameter is observed, nor the root angle of the jet α can be determined without considering the radial and circulation flows in the region of interaction between the axial flow and the ambient medium. A rigorous theoretical analysis of such spatial and, moreover, nonstationary flows is difficult; therefore, to calculate D, l_m, and α, it is reasonable to use the characteristics of the known canonical structure — a vortex ring [8].

It is shown [1] that the flow character in the head part of the jet in the developed stage of the process ($L > 70d_0$) corresponds to that observed for a vortex ring in the period of its formation [9]. Indeed, high-speed photography shows [10] that the gas–liquid mixture displaced from the interaction region to the sides of the axial flow does not fully hang in the ambient medium, as in the classical cumulative flow. Performing a circular motion, part of this liquid again enters the axial flow, which is a typical feature of the vortex ring. Thus, there is no principal difference between the hydrodynamic process in the region of interaction of the jet and the ambient medium represented as following the quasicumulative mechanism [10] or corresponding to the vortex-ring flow. The differences are observed only at the periphery of the jet, but they affect only the shape of the shell. We note that such an approach to flow consideration in the region of interaction of the head part of the jet and the ambient medium was used by Buzukov [11], which allowed him to calculate the flow characteristics that are in agreement with experimental results.

Figure 3 shows the above-described flow structure in the head part of the jet. In this representation, we can assume that the jet length L is determined by the location of the frontal surface of the vortex body, and the location of the vortex core is determined by the cross section of the jet in which its maximum diameter D is observed, i.e., by the parameter l_m. Of particular importance is the fact that the evolution of the vortex ring obeys the principle of self-similarity [12]. This means that a certain relationship is always observed between the transverse and longitudinal diameters of the vortex D and D_x and the vortex-core diameter d_r. Therefore, if we could relate at least one of these parameters to the initial conditions through the results of an independent experiment, we could consider the problem of the characteristics of a pulse high-speed jet of a dispersed liquid, which propagates in a gaseous medium, to be solved in the third stage.

Buzukov [9] studied the dynamics of the formation of a vortex ring. It is shown that the vortex-core diameter immediately after the establishment of a typical flow (at a distance of $\sim 0.7D_x$) is greater than the nozzle diameter by 10–12% for a wide range of Reynolds numbers. Thus, for our conditions we can assume that $d_r = 1.1d_x$, where the current diameter of the axial jet d_x is determined in its cross section that coincides with the vortex-core position at a given time, i.e., at a distance l_m from the nozzle exit. Taking into account this assumption and the results of [9], we can write the following relations, which form a closed system of equations and from which we can determine all the lacking characteristics of the jet:

$$d_r = 1.1d_x, \quad D = 1.6d_r, \quad D_x = 0.9d_r, \quad l_m = L - 0.5D_x, \quad d_x = d_0 + 2l_m\tan(\beta/2). \tag{10}$$

The root angle of the jet conicity can be evaluated from the following formula whose terms are found from the results of solution of (10):

$$\tan(\alpha/2) = (D - d_0)/2l_m. \tag{11}$$

It should be taken into account that the calculation using Eq. (11) determines only the lower limit of α, since the body of the jet is not strictly conical, but somewhat barrel-shaped [1]. Since in most cases [4, 13] the conicity of the jet (the "root" angle) is measured and described directly near the nozzle, where it has the maximum value, the parameter calculated using Eq. (11) can be close to the frequently registered value or slightly lower.

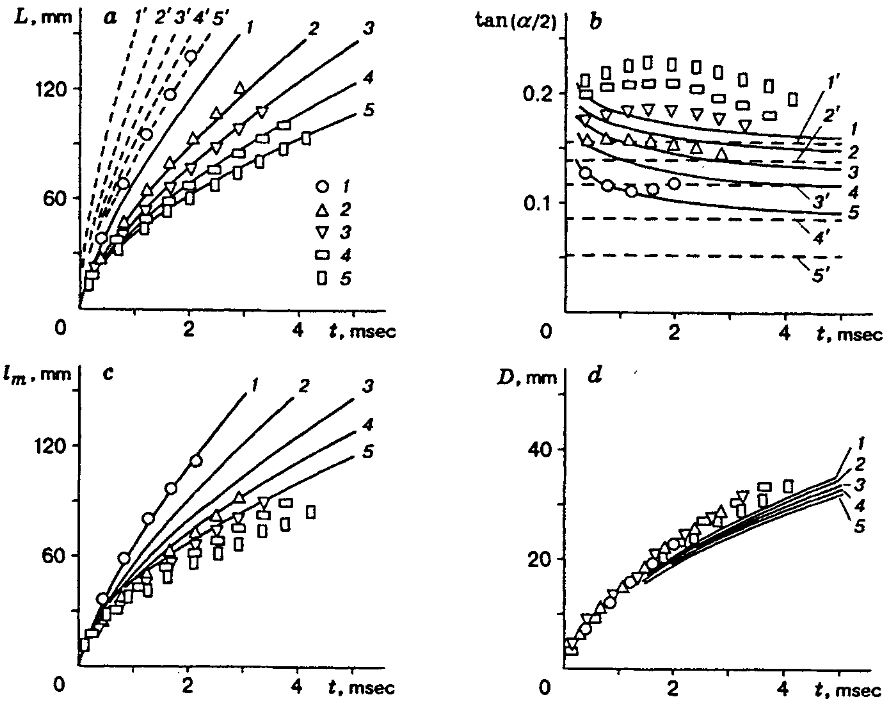

Fig. 4

Comparison of Numerical and Experimental Data. The solid curves in Fig. 4 show the main geometrical characteristics of the jet versus the time t, which were calculated using the proposed technique: the jet length L (a), the jet angle $\tan(\alpha/2)$ (b), the position of the maximum cross section l_m (c), and the maximum diameter D (d); the points refer to the experimental data [11]. The first two graphs also show the calculation results obtained using Lyshevskii's formulas [1, 13], which are usually used in solving engineering problems (dashed curves). The initial parameters used in calculations were chosen to be close to the test conditions [11]: $d_0 = 0.3$ mm, $u_0 = 200$ m/sec, $\rho_l = 810$ kg/m^3 (summer diesel fuel), and the gas density $\rho_g = 10$, 20, 30, 40, and 50 kg/m^3 (curves 1–5 and $1'$–$5'$' and the corresponding points 1–5).

Good agreement of experimental and calculated data is observed as a whole for the main parameter that characterizes the process of evolution of a fuel–air jet, its length $L(t)$ (Fig. 4a). Only a comparatively small difference (up to 15%) is observed for a low (10 kg/m^3) density of the medium, the experimental results lying higher than the calculated data. This nonsystematic disagreement can be explained as follows. It is shown [14] that, when a liquid fuel is injected into a gaseous medium with pressure up to 1 MPa, the axial jet of the mixture, which has a small divergence angle [see Eq. (5)], is divided into several parts because of the hydrodynamic instability developed in it. Each of them begins to interact with the medium located on its way in accordance with the quasicumulative mechanism. Since the motion of each next part of the jet occurs in the wake of the previous part, the total range of the jet increases. The same effect is observed at a so-called "interrupted" injection [15]. Lyshevskii's formulas yield values of L which are higher than experimental data by a factor of 2–2.5. There is no unambiguous explanation to this quite significant disagreement at the moment. However, since this disagreement is stable and remains at a constant level irrespective of the test conditions, we can assume that it is related to an incorrect determination of the empirical coefficients [13]. This is indirectly evidenced by the fact that some researchers (see, e.g., [16]) give different coefficients.

A qualitatively different picture is observed in comparison of the calculated and experimental data on the jet angle α (Fig. 4b). Here, vice versa, the best agreement is observed for low densities of air, whereas for high densities of the medium the measured values of α are greater than the calculated results: the maximum difference in the parameter $\tan(\alpha/2)$, equal to 25%, is observed for $\rho_g = 50$ kg/m^3 ($t = 2$ msec). If this difference tends to smoothing with decreasing ρ_g, the calculation results [13] are lower than the experimental values by a factor of 1.5–2. Since the angle α is determined as the "root" angle [13], i.e., it is definitely greater than the angle calculated by formula (11) or the measurement technique [11], the difference can become even greater. As in the case of the jet length L, possibly, the empirical coefficient [13] should be corrected here.

Figure 4c and d shows the functions $l_m(t)$ and $D(t)$ for different densities of the medium. It follows from Fig. 4c that, despite the qualitative agreement between the experimental and calculated data, there is some discrepancy between the quantitative values: for high densities, the measured l_m are lower by 20–25% than the calculated values. Only for $\rho_g = 10$ kg/m^3 do the results practically coincide. This difference can be explained by the following. In accordance with the model proposed, the flow in the head part of the jet is identified with that observed in a vortex ring. To determine its basic geometrical characteristics, the longitudinal and transverse diameters D_x and D, we used system (10), in which the values of the coefficients are valid only for autonomous vortices with a completely closed flow. However, in our case, the vortex-like head structure (see Fig. 3) is continuously supplemented by a new mixture through the axial flow, which enters this structure. Part of the gas–liquid mixture is shed from the side surface of this structure to the ambient medium; this process is also continuous, but more intense than in an autonomous vortex. Such a circulation flow is half-open from the back side. It can be logically assumed that the cross section of the jet in which the jet has the maximum diameter can be moved upstream (this point is marked by an asterisk in Fig. 3). Accordingly, the diameter D is slightly greater than that calculated by Eq. (10). Nevertheless, it is not possible to propose any mechanism for introducing some corrections to Eq. (10), since a more detailed study of the flow structure of the gas-droplet mass in the head part of the jet is needed. Until now, no specifically oriented studies have been conducted.

Figure 4d shows the measured and calculated results for the jet diameter D. As was assumed, the calculated values of D are everywhere higher than the experimental data by approximately 10%. The most important result is the weak dependence of $D(t)$ on ρ_g. Such an unusual behavior of this curve was observed experimentally for the first time and explained by Buzukov [11]. Thus, this circumstance indicates additionally that the proposed method is adequate for calculating the parameters of a high-speed liquid jet with pulse injection into a gaseous medium.

Conclusions. The considered model of evolution of pulse gas–liquid jets corresponds as a whole to the mixing processes in diesel engines and is only the first approximation for the solution of a more general problem, since the results obtained are only estimates. Nevertheless, the theoretical description of the process adequately reflects its essence, which is evidenced by good qualitative and quantitative agreement of numerical and experimental data. It is important that the formulas do not contain empirical coefficients, which should be introduced to obtain satisfactory numerical results [we do not mean here the coefficient A in formula (5), which is not directly connected with the present problem, but characterizes the intensity of cavitational destruction of the liquid at sudden unloading and is mainly determined by the specific features of the physicochemical structure of the material]. Comparatively small quantitative discrepancies between the numerical and experimental results can be given a physically grounded explanation. These discrepancies can be eliminated by introducing no more than 25% allowances to the formulas in certain ranges of the initial conditions.

The next stage of the work can be the improvement of the numerical scheme for predicting large-scale inhomogeneities in the distribution of the liquid component in the jet. Their appearance is primarily connected with a nonuniform exhaustion of the liquid from the nozzle.

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