On the dispersion of liquid in coaxial supersonic gas jet

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Abstract. The aim of this work was to study the dispersion of liquids in gas jets in connection with the creation of high productivity nozzles. For effective combustion of fuel, systems with intensive air supply to the spray of a liquid are promising. In connection with this, a supersonic coaxial jet was experimentally studied with a central supply of liquid beyond the slit of the confuser nozzle at the modes Npr = 4 and Npr = 6. New data are obtained on the structure of the gas-liquid jet: the gas velocity field, the shadow visualization of the geometry and wave structure of the jet with and without liquid, the velocity profiles of the liquid phase, the dispersion of the droplets. The spatial distribution of the concentration of the spray was first determined. From these data, the parameters of the dispersion processes are obtained in terms the We numbers. A physical model of a supersonic coaxial gas-liquid jet with a central fluid supply is proposed.

1. Introduction

Dispersing of liquids is an important component of a wide range of technological processes in many industries. These are modern fire-fighting systems, chemical treatment of machine parts and application of polymer coatings, fuel injectors, irrigation systems in agrotechnics, pharmacology, medical sprays, etc., A whole complex of other physical processes takes place here in addition to the proper dispersion of the liquid: drop and gas velocity relaxation, intense interfacial heat transfer, phase transitions, and droplet coagulation [1]. Basic data on the aerodynamic destruction of single drops were obtained in shock waves and flows with jumps of gas dynamic parameters [1-4]. These metabolic processes are also inherent in large-scale atmospheric phenomena of transport and evolution of the water state in rain clouds and storm fronts [5]. Experimental data on the structure and dynamics of gas-liquid flows are critically important for verifying the numerical modeling of liquid dispersion in gas jets [6]. Thus, the relevance of the study of nonequilibrium gas-liquid systems is not limited to technical applications. The study of dispersion of liquids and the dynamics of sprays in gradient gas flows is a fundamental item within the framework of the problem of interphase heat-mass transfer in nonequilibrium heterogeneous systems of technogenic and natural origin.

Many of the above applications use so-called pneumatic nozzles, for example, in the oil industry for high flow burners (~ 1m³/h). They are used to incinerate oil waste in unconfined fields to avoid spillage to the ground. For spraying liquids with high flow rates, the most promising ones are pneumatic nozzles, and in particular nozzles like Y-jet [7]. There the primary decay of the liquid occurs in the mixing chamber by means of lateral gas jets, followed by secondary breaking up when it flows out of the mixing chamber. The velocity lag of the drops from the gas is an important condition for their secondary destruction, which provides the necessary Weber number for the required dispersion. This determined the choice of supersonic gas flow regimes in this paper and the feed of liquid along the axis of the jet beyond the nozzle cut for a more detailed observation of the disintegration of the liquid jet. Such a configuration gives a coaxial jet with a supersonic gas shell and
a gas-liquid core. This is a complex flow with a large number of parameters, a study of it has not been carried out yet. The structure of two-phase core of a gas-liquid jet is the subject of this study.

2. The destruction of a fluid in a coaxial gas flow and the characteristics of a gas-liquid jet

Hypothetically, the destruction of a jet of liquid in a coaxial gas flow occurs in two stages according to the following scheme. The interphase boundary instability develops with a sufficient difference in the velocity of the gas and the liquid jet, leading to a primary disintegration of the liquid into fragments of various shapes and sizes [8] (Figure 1). The subsequent secondary drop decay takes place according to one of the known aerodynamic mechanisms depending on the Weber number \( \text{We}=\frac{\rho u^2 d}{\sigma} \), \( \rho \) and \( u \) – are the density and relative velocity of the gas, \( d \) and \( \sigma \) are the size and surface tension of the drop.

1. vibrational breakup: 
   \( \text{We} \approx 12; \)
2. bag breakup: 
   \( 12 < \text{We} < 50; \)
3. bag-and-stamen breakup: 
   \( 50 < \text{We} < 100; \)
4. sheet stripping: 
   \( 100 < \text{We} < 250; \)
5. wave crest stripping: 
   \( \text{We} > 250; \)
6. catastrophic breakup: 
   \( \text{We} > 250. \)

**Figure 1.** Disintegration of a liquid jet in a coaxial gas jet [8] and mechanisms of secondary drops breakup depending on the Weber number \( \text{We} \) [4].

With regard to the breakup mechanisms of droplet destruction (4 and 5 in Figure 1), in [2] it was shown by direct observation by the fast-acting shadow method that the change in the mechanism of 4 by 5 occurs at a number \( \text{We} \approx 1000. \) But in gas-liquid jets neither primary nor secondary destruction is not available for direct observation due to the high concentration of liquid. Therefore, there always remain questions about the conditions under the number of \( \text{We} \) of the drops, when they appear in the flow after the primary disintegration of the liquid jet, and what are the mechanisms for the secondary droplets breakup. Somewhat better is the case with the determination of the parameters of the spray at a distance from the nozzle, where the concentration decreases significantly. But here the high-speed lag of the phases is minimal, the dispersion of the drops stops, and the state of the spray is close to the final one. Thus, the final state of the spray in gas-liquid jets depends on the factors that should be attributed to the peculiarities of aerodynamic loading of droplets in practically important but unexplored cases.

In these experiments, the main breaking up of droplets should occur in gradient sections of the flow in supersonic regions of the jet with a characteristic alternation of gas acceleration and braking, where the number \( \text{We} \) is maximized [3]. One of the unexplored questions of the structure of supersonic gas-liquid jets is whether these structures (cells) are preserved in the presence of a liquid. This is the question of the qualitative picture of the jet, and what quantitative parameters of the gas-liquid jet are needed for its exhaustive description.
The question of the required characteristics of a gas-liquid jet can be put in two ways. In the applied statement, it is important what conditions are necessary for the generation of the spray with the required parameters. Such a formulation presupposes the availability of data on the flow in a wide range of parameters that are obtained in academic studies. But here the problem is posed differently: what is the final state of the spray under the given experimental conditions. In both statements of the question the same parameters of the flow are of interest. What is the set of physical parameters of a gas-liquid jet sufficient for its description?

The most substantiated list is provided by the energy approach. It can be shown that in the simplest case without taking into account heat transfer and phase transitions, the energy of the spray $E(x)$ in a unit of time in the cross section $x$ is added from the work of the gas to increase the surface of the liquid $S$ with the free energy $E_S = S\sigma$ and for the growth of the kinetic energy of the droplets:

$$E(x) = \frac{3\pi}{2} v_0 D_0^2 \sigma + \frac{\pi}{8\rho_l} V_l^3(x) D^2(x) \beta(x)$$

Here $v_0$ is the initial velocity of the liquid in the jet with the initial diameter $D_0$, $\sigma$ and $\rho_l$ are the surface tension and density of the liquid, $\beta(x)$ and $V_l(x)$ are the volume concentration and droplet velocity, $d(x)$ is droplets size at the distance $x$ from the nozzle, $D(x)$ is the diameter of the two-phase jet core. Thus, to describe the state of the spray, the following data are needed: the geometry of the main jet structures and, in particular, $D(x)$, the liquid dispersion $d(x)$, the gas and liquid phase velocities $u$ and $V_l(x)$, as well as the volume concentration of the spray $\beta(x)$ along the jet.

3. Experiments and methods of diagnosis

The experiments were performed on the "Gas-liquid stand" installation of ITAM SB RAS, which allows generating high-velocity gas jets with a high concentration of liquid sprays in a wide range of gas velocities. The air jet was formed at the outflow from the convergent nozzle at the modes with nozzle pressure ratio $N_{pr} = 4$ and $N_{pr} = 6$ (Figure 2). Nozzle cut diameter 14 mm.
Figure 2. The wave structure of the near region of a supersonic underexpanded jet at the modes Npr = 4 (a, b) and Npr = 6 (c, d) in the absence (a, c) and in the presence of liquid (b, d); 1 - nozzle cut, 2 - tube, 3 - incoming jump, 4 - reflected jump, 4* - jump near gas-liquid region broadening, 5 - Mach disk, 5* - liquid jet disintegration region, 6 - tail jump on aerodynamic track behind central body, 7, 8 - jumps similar to 4*.

The parameters of the gas-liquid jet were studied by four optical methods.
1. Shadow visualization for recording the geometry and wave structure of the jet.
2. PIV method for recording the gas velocity field.
3. Laser Doppler anemometer (LDA) with direct spectral analysis [9, 10] on the basis of the WS-7 spectrum analyzer [11, 12] for measuring the velocity of the spray particles.
4. The Malvern "Spray Tech" device for recording the dispersity of the spray.

Shadow visualization was performed by a system of two TAL-125R telescopes, a 125 mm lens diameter, a focal length of 1125 mm. The images were recorded with a digital camera with an exposure of 125 μs. Shadow images of the jet at a distance of 300 mm from the cut of the nozzle are obtained. Figure 2 shows a shadow visualization of the near field of a supersonic underexpanded jet from a convergent nozzle (1) with a central tube (2) in the absence and presence of a liquid. Here, the main wave structures of the gas jet are seen: a hanging (coming) jump (3), a reflected jump (4), and a Mach disk (5) with Npr = 4 (Figure 2a) and Npr = 6 (Figure 2c).

The complex used basically meets the diagnostic requirements shown in the previous section, except for measurements of the spray concentration $\beta$. As will be shown below, this parameter can also be indirectly determined from the master data.

4. Concentration of the spray
Estimation of the volume concentration of the spray $\beta$ in the gas-droplet jet was carried out according to the following procedure. Within the framework of linear optics, it can be shown that for a known optical path $L$ in a suspension of particles with a size $d$, the dispersion medium becomes opaque to the parallel beam if the concentration is $\beta \geq 2d/3L$. Consequently, on the transparency boundary, we have:

$$\beta = \frac{2d}{3L}$$

(2)
The dispersion composition of the spray in the jet was studied by the Malvern "Spray Tech" serial device, which operates on the principle of analyzing the angular scattering of light on droplets. The available dispersion data refers to \( x > 10 \text{ mm} \) near the axis of the jet, and are \( d \approx 12 \mu m \) for the Npr4 regime and \( d \approx 7 \mu m \) for the Npr6 regime, and no significant variability is observed along the jet. But flow regimes with bimodal dispersion of the spray were detected.

Instrumental control of the thickness of the two-phase region \( L \) at the transparency boundary is based on the determination of the transmission pattern of light on shadow images in arbitrary sections of the jet. Passage profiles are the result of digital photometry on a given segment of a two-dimensional digital brightness field (shadow image). They can be obtained by various programs for processing graphic data; here we used the program "Image Pro".

The measured diameter \( D(x) \) and the thickness of the translucent region \( \delta(x) \) allow us to estimate the optical thickness \( L(x) \) as a chord of the circular section of the jet of radius \( R = D/2 \), provided this chord is tangent to the coaxial circle of radius \( r = R - \delta \) (radius of the opaque jet core):

\[
L(x) = 2\sqrt{2R\delta - \delta^2} = 2\sqrt{D(x)\delta(x) - \delta^2(x)}
\]

\( \text{(3)} \)

Figure 3. a) The volume concentration of the spray \( \beta \) at the transparency boundary of the supersonic coaxial gas-liquid jet according to (2), (3); b) the average volume concentration of the spray \( \beta_{ev} \) in the cross sections \( x \) of the coaxial supersonic gas-liquid jet according to (4); 1 – Npr=4, 2 – Npr=6.

Figure 3a shows the results of calculating the volume concentration \( \beta \) for the measured values of \( D(x) \) and \( \delta(x) \) at different sections \( x \) along the jet. The estimation of the average concentration of the spray is obtained from the considerations of conservation of liquid mass along the jet. Namely, for a known flow of liquid \( Q_0 \) into the flow (in the given experiments \( Q_0 \approx 5 \times 10^{-5}, \text{ m}^3/\text{s} \)), the average concentration of the spray \( \beta_{ev} \) in an arbitrary section of diameter \( D(x) \) is expressed as follows:

\[
\beta_{ev}(x) = \frac{4Q_0}{\pi D^2(x)V(x)}
\]

\( \text{(4)} \)

Here \( V(x) \) is the velocity of the spray particles in the cross section \( x \). The velocity profile \( V(x) \) is obtained by the LDA method. The average concentration profile along the jet \( \beta_{ev}(x) \), calculated from (4), is shown in figure 3b.

5. Discussion of results

From the comparison of Figure 3a and Figure 3b, one can see, firstly, that two different approaches give a similar profile of the spray concentration in \( x \), and this confirms the structure of the flow as a
whole. Secondly, with the general trend of decay, the average concentration is more than an order of magnitude greater than the concentration at the transparency boundary in the entire range of $x$ studied. This suggests that the bulk of the liquid is concentrated in the jet core and is the supplier of a finely dispersed spray at its periphery over the entire apparent extent of the jet. The sharp decrease in the mean concentration, as well as the local one, ends in the region $x \sim 100\text{-}120$ mm, but the shadow visualization does not show any noticeable features in this section of the jet. There is only a feature of the velocity profile of the spray (figure 4a), namely, at $x \sim 120$ mm, a droplet speed maximum of $\sim 250$ m/s is observed with Npr4 and $\sim 320$ m/s with Npr6.

The deceleration of the spray behind the point of maximum droplet velocity ($x > 120$ mm) is a consequence of the gas braking due to the loss of dispersion of the liquid phase and the acceleration of the crushing products. It is also seen from Figure 4a that the greatest acceleration of a drop is experienced at the initial portion of the jet, where the maximum phase velocity difference occurs. The magnitude of the droplet acceleration and the character of its variation with respect to $x$, obtained by differentiating the velocity approximation, are shown in Figure 4b.

The obtained data on the main parameters of the gas-liquid jet allow us to draw indirect conclusions about the mechanisms of secondary destruction of droplets in the flow. The known velocity of the gas and droplets enables to estimate the We number of the gas-liquid flow at different modes and at different points of the spray. Figure 5 shows the distribution of the number We along the axis of the jet in various modes. Taking into account the effective Weber numbers of $12 < \text{We} < 100$, we can assume that the secondary crushing mechanism is a "bag" (the 2-nd or 3-rd type in Figure 1). It is for this type of crushing of droplets that the bimodal structure of the dispersed composition of the crushing products takes place. The lower boundary of the numbers We for the destruction of liquid by aerodynamic mechanisms is shown in the graph of the horizontal line.

**Figure 4.** a) Speed profiles of spray particles along the axis of the jet (LDA method); 1 - Npr4, 2 - Npr6, points - experiment, curves - approximation by a polynomial of the 5th degree; b) acceleration of spray particles along the axis of the jet; 1 - Npr6, 2 - Npr4, curves - differentiation of velocity approximation in Figure 4a.
6. Conclusion

The supersonic coaxial jet was experimentally studied with a central supply of liquid beyond the confuse nozzle at the modes with nozzle pressure ratio $N_{pr} = 4$ and $N_{pr} = 6$. At the first time the energy principle has been formulated to determination efficient set of physical parameters of gas-liquid jets. According to this approach, data on the jet structure, gas and liquid velocity profiles, the dispersion composition and concentration of the spray have to be obtained. One-moment local measurements of the velocity and size of droplets in saturated gas-liquid flows were performed for the first time. A method is proposed for estimating the liquid concentration in a jet by shadow imaging, supplemented with data on the dispersed composition and the speed of the spray. Flow regimes with bimodal dispersion of the spray were detected. The role of the “bag breakup” mechanism in the formation of the bimodal structure of droplet size distribution is revealed.

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