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EXPERIMENTAL STUDY OF A SUBMERGED SUPERSONIC TWO-PHASE JET

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An optical-laser method was used to measure the size and concentration of liquid drops in a supersonic gas-drop jet.

Solid particles or drops in a gas jet have an significant effect on the jet's turbulence structure [1]. The presence of drops or particles in the jet also seriously complicates experimental studies, mainly as a result of the need to measure the size, concentration, and velocity of the second phase. The set-up of the experiment is somewhat simpler for two-phase jets with solid particles, since the size of the dipserse phase is known. It is possibly for this reason that, beginning with M. K. Laats [2] most investigators have studied mainly two-phase jets with solid particles [3-5] — including a supersonic jet with M = 1.15 [6]. The few attempts that have been made to study subsonic gas-drop jets [7-9] have been characterized by the use of very small nozzles 0.7-1.2 mm in diameter, which has made it more difficult to study the structure of the flow. There is also a scarcity of information on supersonic gas-drop jets, while the use of liquid fuels for external and supersonic combustion [10] is making it important to be able to describe the structure of such flows in detail.

As the first step in the solution of this complex problem, here we attempted an experimental study of a submerged supersonic gas-drop jet flowing from a nozzle with a diameter an order of magnitude greater than the diameter of the nozzles used in [7-9].

Figure 1 shows a diagram of the set-up used to form the supersonic two-phase jet. A two-phase jet is discharged from a supersonic nozzle at M = 1.5 with a diameter of 11.6 mm in the outlet section. The unit used to organize the two-phase fuel—air mixture consists of a set of 15 concentrically arranged pneumatic nozzles. The liquid 1 (in the experiments, kerosine TS-1) is fed through a central pipe in each nozzle, while air 2 is delivered through the annular channels around the pipe, parallel to the liquid flow. The discharge regime was close to the theoretical regime in all of the tests. Here, the discharge of air at the temperature $T^* = 300$ K was $G_a = 0.073$ kg/sec. The initial concentration of liquid was varied within the range $\overline{G}_0 = 0.02$-0.20.

The dispersion and the volumetric concentration of the liquid phase in the jet were measured simultaneously by the methods of low-angle scattering and attenuation of laser radiation. Figure 1 shows a diagram of the equipment, consisting of a receiving block and a beam-generating block. The latter block included a small LG-72 laser. The beam was formed in the laser by two serially-arranged diaphragms 4 and 5. A beam-splitting plate 6 diverted about 10% of the beam's power to photodetector 7, which made it possible to record the intensity of the laser radiation I_0. The radiation scattered by the liquid particles was collected by the lens 8 installed in the receiving block. The radiation then passed through two chan-

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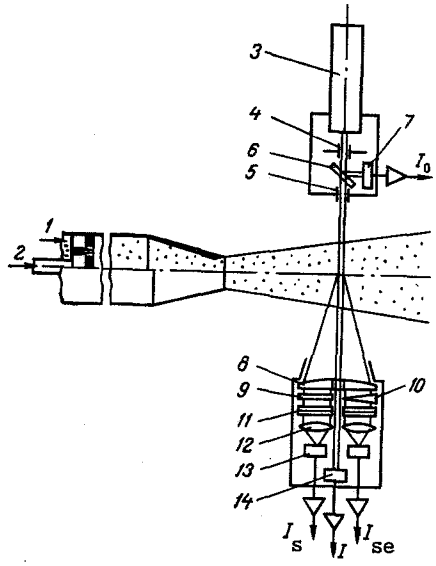

Fig. 1. Diagram of the experimental unit.

nels, each of which contained either a slotted diaphragm 9 or a sectoral diaphragm 10, interference filters 11, and focusing lenses 12 with photodetectors 13. The output signal of the photodetectors was proportional to the intensity of the scattered radiation passing through the slotted I_s and sectoral I_{se} diaphragms, respectively. To record the intensity of the radiation attenuated in the two-phase medium I, the laser beam was directed onto the photodetector 14 through a hole in the lens 8 and the body of the receiving block. The mean diameter of the drops in the liquid phase and their volumetric concentration in the flow were determined from the expressions [9]

$$d_{32} = \frac{3}{8} \lambda \frac{\gamma f}{\delta} \frac{I_s}{I_{se}}, \quad C_v = -\frac{2}{3} \frac{d_{32}}{k_0 L} \ln \frac{I}{I_0},$$

where k_0 is the scattering coefficient. With $\rho = \pi d/\lambda \gg 1$, the scattering coefficient can be given the value $k_0 \simeq 2.0$.

Since the method used here makes it possible to obtain parameters that are averaged over the length of the beam L in the measurement volume, we obtained local values of the concentration of the liquid by recalculating the experimental data in accordance with the familiar Abelian formula [11].

Calibration of the experimental equipment for monodispersed particles of 16, 35, and 72 μm allowed us to reduce the maximum measurement error to 4%. The equipment was moved along the axis and across the jet by a traverse beam with two degrees of freedom.

To compare the character of the change in the concentration of the liquid phase with the decay of the concentration of a passive impurity in a pure gas jet, we measured the field of concentration of an impurity in a submerged supersonic jet with the same parameters at the nozzle edge. As the impurity, we used helium with an initial volumetric concentration of 4.2%. The gas was sampled by a standard method with a small sampling device and was subsequently analyzed on a chromatograph.

Measurement of the mean diameter of the drops both near the nozzle and in more remote sections of the jet showed that, within the experimental error, drop size remains constant in each section. This result is inconsistent with the data obtained in [9] for a coaxial pneumatic nozzle, where coarser drops were seen at the periphery than on the axis of the jet in its initial sections. The difference in experimental findings can be explained by the fact that there is a relatively lengthy stabilizing section between the mixing device and the supersonic nozzle in our tests, with the field of mean drop sizes being fully equalized within this section. At the same time, in [9], the liquid was atomized beyond the nozzle edge in large gas-velocity gradients, which led to a nonuniform distribution of mean drop size in the initial sections of the jet.

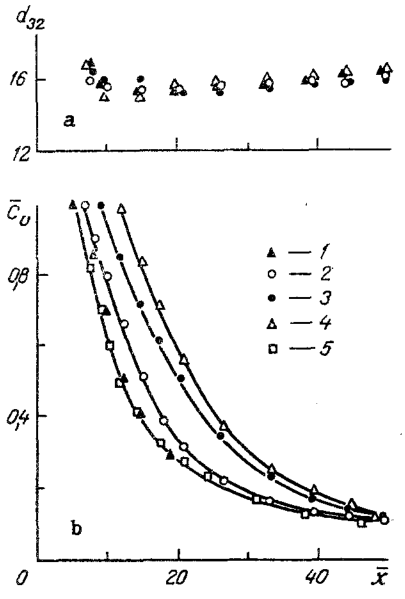

Fig. 2. Distribution of mean drop diameter (a) and volumetric concentration of liquid (b) along the axis of the jet: 1) $\bar{G}_0$ = 0.02; 2) 0.04; 3) 0.10; 4) 0.15; 5) one-phase jet, d_{32}, μm.

Figure 2a shows the axial distribution of the mean diameter of the drops for different values of initial liquid concentration. The large scatter of the data in the initial sections can be attributed to the high optical density of the jet. The results obtained permit us to conclude that within the investigated range of liquid concentration, the concentration has little effect on mean drop size in a supersonic jet. The moderate increase in the diameter of the drop with increasing distance from the nozzle edge is due to the evaporation of fine drop fractions. A similar result was obtained in [9] in subsonic two-phase jets.

Graphs of the decay of the volumetric concentration of the liquid pahse along the jet axis for different values of initial concentration are shown in Fig. 2b. Also shown is the decay of the concentration of the passive impurity in a one-phase supersonic jet.

Within a minimum initial liquid concentration $\bar{G}_0$ = 0.02, the profile of its change along the jet axis nearly (within the experimental error) coincides with the profile of the decay of the passive impurity in the pure gas jet. This indirectly confirms particle slip is negligible in the average motion of particles on the order of 15 μm in size. This conclusion is important for constructing an adequate mathematical model of the flow.

With an increase in the initial concentration of the liquid phase, the decay of concentration is qualitatively the same as in the gas jet, but there is a distinct increase in the length of the initial section and in the range of the jet. These facts must be considered when designing devices which make use of supersonic two-phase jets.

The increase in the range of the jet is accompanied by a decrease in its divergence angle. The latter is connected with a reduction in turbulence intensity. Here, turbulence is "suppressed" by particles of the liquid phase. This fact, valid for subsonic two-phase jets [1], is proved by the data in Fig. 3 to also be valid for supersonic jets. Figure 3 shows the boundaries of jets with different initial contents of liquid. The concentration of the liquid phase at the boundary of the jet was assumed to be equal to 0.01 of its value on the axis in the given section. At $\bar{G}_0$ = 0.02, the boundaries are close to those of the gas jet. The difference increases with an increase in $\bar{G}_0$. The boundary of the two-phase jet is curvilinear. In the initial sections of the jet, where the concentration of liquid-phase particles is high, the suppression of turbulence by the particles is greater than it is in more remote zones. In the more distant sections, the decrease in liquid concentration causes the divergence angle to increase and approach the angle in the gas jet.

The dissimilar effect of drops on mixing of the jet in different sections is confirmed by the data in Fig. 4, which shows dimensionless profiles of liquid-phase concentration at $\bar{G}_0$ = 0.039. In the remove region of the jet ($\bar{x}$ = 49.0), the concentration profile nearly coincides with the Schlichting profile:

$$C_v/C_{vm} = [1-(y/R)^{3/2}]^2,$$

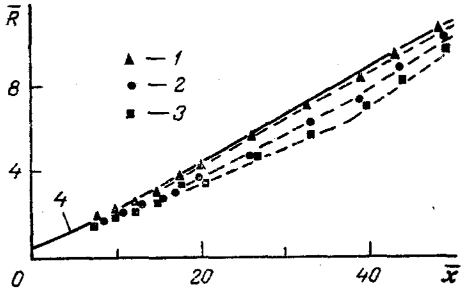

Fig. 3

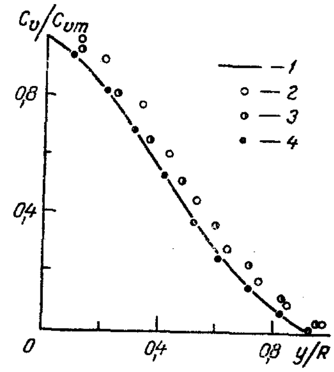

Fig. 4

Fig. 3. Boundaries of two-phase supersonic jets: 1) $\overline{G}_0$ = 0.02; 2) 0.10; 3) 0.20; 4) one-phase jet.

Fig. 4. Transverse profiles of the volumetric concentration of the liquid phase: 1) Schlichting profile; 2) $\overline{x}$ = 7.8; 3) 26.3; 4) 49.0.

while the profile is fuller closer to the nozzle. Similar results were obtained for other values of initial liquid-phase concentration.

Thus, it can be concluded that within the investigated range of parameters, the average characteristics of a two-phase supersonic gas-drop jet are qualitatively the same as those of subsonic jet studied previously. This allows the class of flows examined here to be classified as "medium-disperse quasiequilibrium two-phase jets," [12], which appreciably simplifies the calculation of the parameters of such jets for an entire range of technical applications.

NOTATION

C_v, volumetric concentration of the liquid phase; C_{vm}, value of C_v on the jet axis; C_{v0}, value of C_v at the nozzle edge; $\overline{C}_v = C_v/C_{v0}$; D, nozzle diameter; G_ℓ, discharge of liquid; G_a, discharge of air; $\overline{G}_0 = G_\ell/(G_\ell + G_a)$, initial discharge concentration of the liquid phase; I_0, intensity of the laser radiation; I, intensity of the attenuated radiation; I_s, I_{se}, intensity of scattered radiation passed through the slotted and sectoral diaphgrams, respectively; k_0, scattering coefficient; L, length of the beam in the measurement volume; M, Mach number; R, radius of jet; $\overline{R} = R/D$; T*, stagnation temperature; d_{32}, mean Zauter diameter of liquid drops; x, y, rectangular coordinates; $\overline{x} = x/D$; f, focal distance of lens; γ, angle of sectoral diaphragm; δ, width of slotted diaphragm; λ, wavelength of laser radiation; ρ, diffraction parameter.

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