On the near wake structure of a supersonic coaxial gas-liquid jet

S V Poplavski and A Yu Nesterov
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 4/1 Institutskaya str., Novosibirsk 630090, Russia
s.poplav@itam.nsc.ru

Abstract. The work is devoted to a complex experimental study of the near wake of supersonic coaxial gas-liquid jets with a high concentration of the dispersed phase. At the various liquid flow rates, wave structure of a gas phase was visualized, droplet velocity profiles were obtained by the LDA method, and the spray concentration was measured. The effect of the liquid phase on the supersonic underexpanded jet was studied, in particular, a change in the general wave structure, Mach disk transformation, etc. A gas velocity profile was obtained in a two-phase core of a gas-liquid jet by the method of droplet velocity profile correction taking into account their velocity relaxation.

1. Introduction
Devices for spraying liquids - nozzles - has many technological applications: coating, medicine and pharmacology, the chemical and food industry, propulsion engineering, furnace burners, modern fire extinguishing systems, etc. Among various kinds of nozzles, there is a class of pneumatic ones; they are mainly used for burning wastes in the oil industry, but can be used in any technology that requires a finely dispersed spray with large liquid flow rate. In these nozzles, a high-speed gas flow is used to preliminarily destroy the liquid and form the spray jet. This allows one to provide dispersion (~ 10 microns) acceptable for the efficient spray combustion at a flow rate of up to several cubic meters per hour [1]. A number of issues of the optimal design of such devices remain unresolved, in particular with regard to supersonic gas regimes relevant for these purposes. However, the study of high-flow nozzles is complicated by the fact that, due to the high concentration of the spray, traditional tools and methods, such as the Pitot tube and hot-wire anemometers, are not applicable. Due to the opacity of the gas-liquid jets, visualization, PIV and other optical diagnostics are also excluded. Mathematical modeling of gas-liquid flows is limited by the volume concentration of the dispersed phase $\beta < 10^{-4}$ [2], which is two orders of magnitude less than the real spray dense of high-flow nozzles. For the development and verification of computational models of dense gas-liquid flows, reliable, and methodically verified experimental data on a wide range of physical parameters are needed. Thus, this section of the dynamics of two-phase media does not yet have a sufficient methodological base for either experimental or mathematical modeling.

Due to the complexity of the processes, it is advisable to carry out studies of the mechanisms of decay of a liquid jet and secondary destruction of droplets in a simplified formulation with model objects. One of these objects is a coaxial gas-liquid jet with a fluid supply through the nozzle exit: it has central symmetry and is available for investigation from the moment the liquid enters the gas stream. According to previous studies, the destruction of droplets in such a system occurs in the region...
of maximum velocity gradients, namely, in the near wake [3]. Dispersion of liquid is most effective in supersonic jets when droplets interact with a system of jumps that supposedly penetrate into a two-phase core in the near wake of a supersonic underexpanded gas jet.

A comprehensive study of the processes in the core of a supersonic gas-liquid jet, their influence on the flow structure and spray dynamics are the key research challenges. Along with this, it is necessary to develop new methodological approaches to the study of such systems. This paper presents the results of an experimental study of the structure of the near wake of a supersonic gas-liquid jet, obtained on the basis of new approaches and data on the dynamics of the gas phase and droplets.

2. Experimental setup and diagnostics

The experiments were carried out on “Gas-liquid stand” setup of ITAM SB RAS. The setup allows conducting investigations of gas-liquid jets in the range of liquid flow discharge from 10 to 5000 l/hr and the pressure in the pre-chamber can be up to 8 atm. The gas-liquid stand 1 (figure 1) comprises a nozzle unit 2, where the nozzle was fixed with possibility of vertical movement, a receiving tank 3 for used liquid, and instruments for controlling flow parameters of gas and liquid. The atomizer constitutes convergent nozzle with input and output diameters 19 and 14 mm respectively (figure 2) with the central tube 2 mm in diameter for supply of liquid along the jet axis.

![Figure 1](image1.png)

**Figure 1.** Gas-liquid stand: 1 – jet module, 2 – nozzle unit, 3 – receiving tank, 4 – liquid and gas channels, 5 – elements of diagnostics.

![Figure 2](image2.png)

**Figure 2.** Sketch of the atomizer: 1 – body, 2 – outlet convergent section, 3 – the pipe for central supply of liquid.

In the present work we use the complex of optical methods for gas-liquid flow diagnostics:

- Flow visualization (shadow method, AVT visualization techniques [4]) for registration of jet structure;
- Malvern Spray Tec analyser for determining the spray dispersity;
- PIV diagnostics of gas flow velocity field;
- Laser Doppler anemometer with direct spectral analysis [5, 6] for droplets speed determination.

The experimental setup, the complex of diagnostics and the parameters of the jet in the different regimes are described in [3]. One of the important parameters of the gas-liquid jet is a concentration of the spray, it influences on the interphase heat transfer and the speed of sound in two-phase medium [7]. Note that the presence of a liquid with the volume fraction $\beta > 10^{-6}$ in the flow leads to changes in the profile of gas velocity. So the data of PIV in pure gas flow is inapplicable to two-phase medium. For determining the gas velocity $U(x)$ in two-phase core of the jet a method of data correction for velocities of liquid $V(x)$ was used to take into account the velocity relaxation. In [8] it is shown that the profile of gas speed $U(x)$ can be calculated from the liquid velocity $V(x)$ using the equation:
\[ U(x) = V(x) \pm \sqrt{\lambda \cdot V(x) \cdot \left| \frac{dV(x)}{dx} \right|} \cdot \frac{4 \rho_p}{3 \rho C_D}, \]

(1)

\[ C_D(\text{Re}) = \frac{24}{\text{Re}} + \frac{4}{\sqrt{\text{Re}}} + 0.004\text{Re}^{0.44} \]

(2)

Here \( \lambda \) is the velocity relaxation length of particles, the plus sign “+” is used for the case \( dV/dx > 0 \), and the minus sign “–” is used for the case \( dV/dx < 0 \). \( d \) and \( \rho_p \) are the size and the density of the particles, \( C_D \) is the particles drag coefficient assuming the characteristic density of gas \( \rho \approx \text{const.} \)

In [9], this approach was used to correct the gas velocity field obtained by the PIV method in a supersonic underexpanded jet. Here, this method was applied to the droplet velocity profiles obtained by the LDA method to calculate the gas velocity profile. The correction was carried out in two stages:

- Preliminary correction with estimated value of \( \lambda \) gives approximate gas velocity profile \( u(x) \) in two phase core;
- Refined correction performed according to \( \text{Re} \) number for the relative velocity of gas and drops \( V(x) - u(x) \).

3. Results and discussion

3.1. The effect of the liquid phase on the wave structure of the jet

The experiments were carried out for the modes Npr = 6 and 8, and the liquid discharges 20 and 300 l/h (5.6 and 83 g/s). As the liquid we use water, dispersing phase is air. The supersonic underexpanded jets with well-studied wave structure are generated on these mods without liquid [9]. In our case the flow is somewhat more complex because of the central body in the nozzle [3], but these changes are small in comparison with perturbation caused by the presence of liquid.

The flow was visualized by the shadow method without liquid and with the introduction of its small quantities, while part of the jet remains transparent, where the wave structure can be observed. Shadowgrams of the jet without liquid and at small liquid consumption are presented in figures 3 and 4.

![Figure 3](image-url)

Figure 3. Shadow pictures of the jet in the Npr6 mode in the absence of liquid (a), at low liquid flow rates (b, c) and at the liquid flow rate of 20 l/h (d).

It is seen that in the presence of a liquid, the pattern of jumps changes significantly: the Mach disk bends upstream, the shift of the jump is also provided by a shift upstream triple point and deformation of the general structure. The triple point shifts in comparison to pure gas is from 18 to 16 mm from the
nozzle in Npr6 mode (in figure 3c) and from 22 to 20 mm in Npr8 mode (see figure 4c). The probable position of the jump on the axis of the jet is 4–5 mm upstream. With a liquid discharge of 20 l/h, the Mach disk looks like a bow shock on a cloud of particles [10,11] (figure 3d and figure 4d) and shifts even higher. The bow shock is formed because of an increase in the particle concentration. This happens due to the deceleration of the droplets at the boundary of the first cell, and because of the recirculation zone presumably formed here [12]. Thus, a complex picture of the gas flow is observed, leading to high velocity gradients, this has a great influence on the destruction of droplets and requires a more detailed consideration.

Figure 4. Shadow pictures of the jet in the Npr8 mode in the absence of liquid (a), at low liquid discharge (b, c) and at the liquid consumption of 20 l/h (d).

3.2. The dynamics of gas-liquid jet
The restructuring of the flow depending on the liquid discharge can also be traced by the droplets velocity profiles. Figures 5 and 6 shows these profiles along the jet axis. Their characteristic feature is a sharp drop in droplets velocity in the region from 10 to 20–25 mm, followed by a monotonic increase up to velocity relaxation in a decelerating gas flow at distances greater than 100 mm [3].

Figure 5. Profiles of the droplets velocity along the axis in the near wake of jet at various liquid consumption, Npr6.

Figure 6. Profiles of the droplets velocity along the axis in the near wake of jet at various liquid consumption, Npr8.

This type of profiles is observed at all liquid consumptions; there are differences only in the quantitative characteristics and the Mach disk position. It shifts toward the nozzle with increasing
concentration, which can be seen from the velocity maximum position. Thus, in this range of the parameters, the flow pattern is noticeably different from the pure gas jet.

Figures 7, 8 show the profiles of the velocity and spray concentration in the near wake, as well as the flow shadow pattern for a liquid flow rate of 20 l/h, modes Npr6 and Npr8. It can be seen that the volume concentration before the Mach disk drops to values of $3 \times 10^{-3}$ in the Npr6 mode and $10^{-3}$ in Npr8 one; behind the jump, the concentration increases significantly with a subsequent decrease to the same values and even lower in the region of jet acceleration. In both modes, a characteristic flow pattern with the likeness of a bow shock is observed. In the Npr8 mode, the effect of the expansion of the two-phase region just behind the jump is noticeable.

Figure 7. Droplets velocity profile, concentration and shadow flow pattern in Npr6 mode, Q = 20 l/h.  

Figure 8. Droplets velocity profile, concentration and shadow flow pattern in Npr8 mode, Q = 20 l/h.

Figure 9 shows the results of the correction of the droplet velocity profile for the Npr6 mode. It is seen that the obtained velocity profile is close to the characteristic structures of the underexpanded supersonic jet of pure gas, but the velocity behind the Mach disk becomes negative. Apparently, this is due to the presence of a recirculation zone behind the Mach jump with a countercurrent near the jet axis [12], which leads to an intensive deceleration of droplets in this region.

Figure 9. Experimental droplets velocity and calculated gas velocity, Npr6, Q = 180 l/h.  

Figure 10. Mach numbers in a two-phase jet core, Npr6, Q = 180 l/h.
In figure 9 periodic velocity gradients is seen that correlate with the position of the jumps in the gas jet periphery. A significant decrease in the gas velocity in the two-phase jet core is observed in comparison with a purely gas one: the maximum velocity was ~ 240 m/s, while for a gas jet it was ~ 430 m/s. In this case, the flow remains supersonic due to a drop in the speed of sound in a two-phase medium, the graph of the Mach numbers on the axis of the jet is shown in figure 10. It can be seen that, despite a strong drop in the gas velocity, the Mach number before the jump is about 1.5-2. Due to the deceleration of the gas in the two-phase core of the jet and the growth of the speed of sound of the medium downstream, only one compression wave (Mach disk) is reproduced in the gas-liquid jet. Nevertheless, the flow retains the periodic gradient for 5-7 calibers due to the influence of supersonic structures at the periphery.

4. Summary
The paper presents the results of a comprehensive experimental study of the near wake of a supersonic coaxial gas-liquid jet at various liquid consumptions. The change in the wave structure in the presence of a liquid is studied, and the degeneracy of the Mach disk into a conical jump is shown. The velocity and concentration profiles of droplets in two-phase core of the jet are obtained. Using the correction algorithm of the droplets velocity, the gas velocity in two-phase jet core was calculated. The presence of a gas velocity jump of the “reverse step” type with a negative velocity region and periodic gradient structures downstream were observed. An assumption is made about the existence of a recirculation zone in the gas phase behind the conical shock wave.

Acknowledgements
The research was carried out within the framework of the Program of Fundamental Scientific Research of the state academies of sciences in 2013-2020 (project No. AAAA-A17-117030610137-0).

References
[1] Vitman L A, Katsnelson B D and Paleev I I 1962 Atomization of liquid by nozzles (Moscow, Leningrad: Gos. Energ. Izd.) p 265
[2] Varaksin A Yu 2013 High Temperature 51 377–407
[3] Boiko V M, Nesterov A Yu and Poplavski S V 2019 Termoph. Aeromech. 26 385–98
[4] Boiko V M, Orishich A M, Pavlov A A and Pikalov V V 2009 Methods of Optical Diagnostics in Aerophysical Experiments (Novosibirsk: Novosib. Gos. Univ.) p 450
[5] Boiko V M, Poplavski S V, Nesterov A U, Kondratev S V, Morozov A A and Potekhin A K 2017 AIP Conference Proceedings 1893 020015
[6] Boiko V M, Nesterov A Yu and Poplavski S V 2018 AIP Conference Proceedings 2027 040008
[7] Deich M E and Filippov G A 1981 Gas Dynamics of Two-Phase Media (Moscow: Energoizdat) p 472
[8] Boiko V M, Pivovarov A A and Poplavski S V 2013 Comb., Expl., Shock waves 49 548–54
[9] Boiko V M, Zapiagaev V I, Pivovarov A A and S V Poplavski 2015 Comb. Exp. Shock Waves 51 587–96
[10] Boiko V M, Papyrin A N and Poplavski S V 1993 Comb. Expl. Shock Waves 29 389–94
[11] Boiko V M and Poplavski S V 2009 Comb. Expl. Shock Waves 45 198–204
[12] Zapiagaev V I, Boiko V M, Kavun I N, Kiselev N P and Pivovarov A A 2016 AIP Conference Proceedings 1770 030029