Interaction of a liquid jet with a co-current gas flow inside the nozzle and under ejection into vacuum

V G Prikhodko, V N Yarygin, I V Yarygin*
Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia
*E-mail: yarygin@gorodok.net

Abstract. The structure of a gas droplet flow arising under gas outflow with liquid jet injected into it from a supersonic nozzle into vacuum is studied experimentally. Possibility of the flow structure control in order to obtain droplets of a certain size, composition, and velocity, is considered. The liquid was injected into the co-current gas flow in the prechamber of the supersonic nozzle and then flowed out into the vacuum chamber in the form of a gas-droplet jet. Using the developed technique of droplet deposition on paper substrates, the effect of the Reynolds number of the gas and the pressure in the vacuum chamber on the angular distribution of droplet phase behind the nozzle exit is investigated.

1. Introduction
Currently gas-droplet flows are widely used in various heat and mass transfer apparatus and devices. It is known that the addition of even a small amount of the droplet phase to the cooling flow significantly increases the cooling efficiency due to the use of the phase transition heat under droplets evaporation [1]. Fundamentally such studies are carried out at relatively low, subsonic velocities of gas-droplet flows and at pressures equal to atmospheric and higher [2]. At the same time, for a number of scientific and practical applications, supersonic gas and vapor-droplet flows formed under the outflow of liquids and gas-liquid mixtures into vacuum are of great interest. From the fundamental point of view the study of physical processes and phenomena accompanying outflow of liquids into vacuum: instant boiling, disintegration into droplets, phase transitions on the surface and inside droplets, interaction of droplets with supersonic flow, etc. is of great importance. In practical terms, the outflow of liquids into vacuum is of interest, in particular, for a number of vacuum technologies, as well as for space applications from the point of view of spacecrafts contamination at operation of drainage devices, attitude control thrusters, propellants refueling systems, etc. [3]. Despite a certain scientific interest to this problem, the number of studies concerning outflow of liquids and gas-liquid mixtures into vacuum is very limited.

There are two different approaches for creating a gas-droplet flow inside the nozzle. The first method involves the use of injectors to spray liquid onto the surface of the nozzle prechamber. In this case, one part of the liquid moves in the form of a near-wall film along the nozzle wall, and another part fall into a gas flow, further forming a complicated flow structure behind the nozzle. This method of liquid supply is used, in particular, in rocket engines for nozzle walls cooling. The second method of creating a gas-droplet flow involves spraying a liquid inside the nozzle in its axial region. This method is used when creation of a gas-droplet jet with no need of the nozzle walls cooling is required. In this paper the processes of heat and mass transfer in a gas-droplet flow arising under the
outflow of a gas jet and a liquid injected into it from a nozzle into vacuum are investigated experimentally. In particular, the possibility of controlling the structure of a gas-droplet flow in order to obtain droplets of a certain size, composition, and velocity is studied. The liquid was injected into the co-current gas flow inside the prechamber of the supersonic nozzle and then flowed out to the vacuum chamber in the form of a gas-droplet jet. The majority of liquid in this method enters the gas flow, and only an insignificant part of liquid enters the nozzle wall.

In this work we deal with the so-called strongly underexpanded or nonisobaric jets characterized by the presence of a free supersonic expansion region (jet core) and regions of the outflowing gas interaction with the surrounding gas (mixing layers along the jet boundary, oblique and breakdown shock waves). Currently this class of flows is studied well, mainly in connection with rocket and space applications. It is shown that for the zone of mixing with the surrounding gas, the zone of shear flows behind the Mach disk and the core of the flow, the Reynolds number $Re_L = Re_*/\sqrt{N}$ can be taken as the determining one, which allows to classify the flow by type (here $Re_*$ is the Reynolds number determined by the parameters in the critical cross-section of the nozzle, $N = p_0/p_\infty$ is the pressure drop from the nozzle prechamber to the surrounding space). The following flow regimes classification is proposed [4]:

1. $Re_L > 10^4$ – the flow regime in the mixing layer is turbulent;
2. $10^3 < Re_L < 10^4$ – transition from laminar to turbulent flow in the mixing layer;
3. $10^2 < Re_L < 10^3$ – the flow regime in the mixing layer is laminar;
4. $Re_L < 10^2$ – transition from laminar flow to regimes with rarefaction effects;
5. $Re_L < 10$ – transition to the scattering regime, the shock waves degenerate in density.

Thus, it can be argued that if the flow regime inside the nozzle is completely determined by specifying or choosing the Reynolds number $Re_*$, then the flow regime in the jet behind the nozzle under gas outflow into vacuum depends for the chosen $Re_*$ on the pressure in the surrounding space, or, more precisely, on the pressure drop from the nozzle prechamber to the surrounding space pressure as well.

The main objective of this study was carrying out experimental investigations in order to understand how the change in the flow regime parameters of the gas and liquid affects the distribution function of the droplet phase behind the nozzle exit under outflow into vacuum.

2. Experimental setup and measurement technique

The experiments were carried out at the vacuum gas-dynamic complex of IT SB RAS. The working section was installed inside the vacuum chamber. Gas was supplied through an electromagnetic valve and a flow diaphragm, liquid – through a nozzle and a capillary tube with a diameter of 1 mm, which could move along the axis of the nozzle, taking up fixed positions relative to the nozzle exit, which made it possible to study the process of liquid interaction with gas at sub- and supersonic relative velocities. The test section is shown in figure 1. In this work, using the developed technique [5], the spatial structure of the droplet phase flow behind the nozzle exit was investigated, and its visualization was carried out with the help of illumination by halogen lamps and a laser.
The experiments were carried out in the range of Reynolds numbers $Re_*$ from $3\times 10^4$ up to $4\times 10^5$, while the pressure in the vacuum chamber (surrounding space) was independently regulated in the range from 1 up to 1300 Pa, and the flow regime in the mixing layer was laminar. The obtained experimental data on gas density change in the jet allowed us to calculate dynamic effect of the gas flow on droplets of various dimensions. The quantitative measure of such an impact is the Weber number equal to $We = \frac{\rho V^2 d}{\sigma}$ (where $\rho$ – gas density, $V$ – gas velocity, $d$ – droplet diameter, $\sigma$ - liquid surface tension coefficient), which characterizes the ratio of dynamic pressure forces to surface tension forces. Estimations have shown that the largest values of the Weber number ($We \approx 200$) and, accordingly, the greatest effect of the co-current gas flow on the droplets takes place inside the nozzle. Behind the nozzle the dynamic effect of the gas flow on droplets decreases rapidly with increase of distance from the nozzle exit, primarily due to gas density reducing.

3. Results and discussion
The influence of pressure in the surrounding space on the droplet phase flow structure is illustrated in figure 2, which shows the data on visualization of the droplet phase flow structure for two outflow modes, differing only in the values of the surrounding pressure $p_\infty$ (pressure in the vacuum chamber),
while the Reynolds number $Re_\ast$ in both cases was the same. Figure 2 shows a significant difference in the flow structure of the droplet phase: with the increase of surrounding pressure, some structures appear behind the nozzle exit, resembling an underexpanded jet. These data confirm the conclusion that the flow in the jet is determined not only by the nozzle parameters, but parameters of the surrounding space as well.

![Figure 2. Visualization of droplet phase flow structure. $a - p_\infty = 10$ Pa, $b - p_\infty = 1300$ Pa.](image)

To measure the angular distribution of the droplet phase behind the nozzle exit, a technique of droplets deposition on paper substrates fixed at a certain radius around the nozzle was developed [5]. General view of paper substrates with traces of droplets, obtained in experiments at three different stagnation pressures $p_o$ in the nozzle prechamber is shown in figure 3.

![Figure 3. General view of paper substrates. $p_\infty = 10$ Pa. 1 – $p_o = 130$ kPa, 2 – $p_o = 13.5$ kPa, 3 – w/o gas.](image)

From figure 3 one can see that at large pressure $p_o$ (and, accordingly, Reynolds $Re_\ast$ and Weber $We$ numbers), a rather narrow flow of fine droplets is observed, approximately from $-25$ up to $+25^\circ$ relative to the jet axis, and with $p_o$ decrease the flow of droplets become wider and droplets larger. This is especially noticeable on the third substrate (outflow without a co-current gas flow), where traces of individual large droplets are observed in the peripheral region of the flow. Subsequently, paper substrates were processed using a specially developed program. The angular distributions of the droplet phase behind the nozzle exit obtained by processing the substrates from figure 3 are shown in figure 4. The arising of the central region of the droplet phase flow, as well as an increase in the droplet ejection angle with a decrease in the gas flow rate, is clearly observed. Thus, deposition on a substrate gives a visual representation of the gas-droplet flow structure formed under the joint outflow of gas and liquid into vacuum.
Figure 4. Angular distribution of droplet phase. \( p_c = 10 \text{ Pa} \), \( 1 - p_o = 130 \text{ kPa} \), \( 2 - p_o = 13.5 \text{ kPa} \), \( 3 - \text{w/o gas} \).

4. Conclusion
The process of gas outflow with a jet of liquid injected into it from a supersonic nozzle into vacuum and background gas is studied experimentally. The influence of both the parameters of the gas flow and the pressure in the surrounding space on the droplet phase flow structure behind the nozzle exit is shown. The developed technique of droplet deposition on paper substrates gives a visual representation of the droplet phase angular distributions behind the nozzle exit and the possibility of controlling them by changing the Reynolds number of the gas flow.

References
[1] Francois M, Wei S. 2002 Progress in Aerospace Sciences 38 275-304
[2] Deich M E, Filippov G A 1981 Gasdynamics of two-phase medium (Moscow: Energoizdat)
[3] Yarygin V N, Prikhodko V G, Yarygin I V, Gerasimov Y I, Krylov A N and Skorovarov A Y 2018 Journal of Physics: Conference Series 1105 012079
[4] Avduevsky V S, Ivanov A V, Karpman I M, Traskovsky V D, Yudelovich M Y 1971 Soviet Physics. Doklady 197(1) 46-49
[5] Prikhodko V G, Yarygin I V, Vyazov Yu N 2019 Interfacial Phenomena and Heat Transfer 7(2) 105-111