Experimental study of droplet detachment from liquid film surface by a co-current flow inside the nozzle stagnation chamber

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Abstract. The paper presents the results of an experimental study on the interaction of near-wall liquid film with the co-current gas flow in the convergent channel. Conditions for transition (co-current gas flow velocity and liquid flow rate) of near-wall liquid film from annular flow mode to annular-dispersed flow accompanied by a detachment of droplets from the interface are elucidated.

1. Introduction

The annular-dispersed regime of two-phase gas-liquid flow in pipes and channels is one of the basic flow modes in various devices. This flow takes place in nozzles of liquid rocket engines whose walls are cooled by a near-wall liquid film of fuel. For thermal designs of various devices with annular-dispersed flows, it is important to know the characteristics of drop entrainment, i.e. detachment of droplets from near-wall liquid film surface by the co-current gas flow. Experimental study results [1] show that the amount of liquid detached in the form of droplets and moving into the core of two-phase flow can reach up to 50-80% of the total mass flow rate of liquid at the channel inlet. Obviously, such droplet entrainment significantly affects the heat and mass transfer characteristics in a channel or nozzle. Neglecting the entrainment of droplets in calculations can give at least an inaccurate result.

It is necessary to take into account the interaction of co-current gas flow with near-wall liquid film and droplets not only for internal two-phase flows in channels of various geometries but for calculating external flows as well, for example, in studies of jets behind nozzles of rocket engines. Thus, while investigating the structure of jets behind the control and orientation thrusters of the International Space Station (ISS), one of the crucial tasks is obtaining the spatial distribution of incomplete combustion products of fuel (ICP). It is shown [2] that under jet outflow into the vacuum, backflows, i.e. flows at angles over 90 degrees, including backflows of droplet phase, may occur. These backflows cause contamination of external surfaces of the ISS, which is a negative factor. These studies [2] also show that the spatial distribution of the droplet phase in a free jet depends on the history of near-wall liquid film interaction with co-current gas flow inside the nozzle and under ejection into the vacuum.

Currently, there are no exact analytical expressions for calculating droplet entrainment, but there are experimental approximation dependences. Almost all the approximation formulas include explicit or implicit values, such as critical gas velocity or critical liquid flow rate at which droplet detachment begins, and the two-phase flow transforms from purely annular to annular-dispersed flow mode. These
critical values are required for accurate calculation of droplet entrainment and heat and mass transfer parameters.

The best-known studies of two-phase flow consider flows in a pipe or channel. Alternative geometry is discussed in paper [3], in which the results of flow calculations taking into account detachment and deposition of droplets in the convergent nozzle are presented. Namely, the nozzle in this paper has a simple shape of a smooth transition from a large diameter tube to a small diameter tube. The experimental pressure and liquid film thickness measurement data published for this design were used to verify the calculation results.

This paper presents the experimental results obtained for the convergent part of a supersonic nozzle at the critical flow rate.

The nozzle geometry is taken from studies of the ISS surface contamination with gas-liquid flow ejecting from the supersonic nozzle into a vacuum [2, 4]. The objective of the work is to understand the conditions at which droplets begin to detach from near-wall liquid film under co-current gas flow. We used the subsonic part of the model nozzle shortened to the critical section, described in [5].

2. Test section and measurement technique
The experimental design and sketch of the nozzle with characteristic dimensions are shown in Fig. 1. Air from compressor 1 was accumulated in high-pressure tank 3 and then passed through filter 5 into a gas pipeline. The solenoid valve 6 opened the gas supply to the nozzle pre-chamber, in front of which the diaphragm 12 with a diameter of 2 mm was installed. Liquid (ethanol) under excess pressure of about 20 kPa was fed into the nozzle 10 through a circular gap of 0.1 mm width, formed by a cylindrical insert and pre-chamber wall. Injectors 11 were used as valves for opening and closing liquid supply.

The gas flow rate in the experiments was controlled by changing gas pressure in tank 3. The pressure was recorded using sensor 4. The liquid flow rate was set out by several nozzles 11 and measured using the measuring tube 9. The gas pressure in the pre-chamber was measured using the sensor 7. Solenoid valves were controlled by computer. The same computer recorded signals from all sensors.

![Figure 1. Sketch of the test section.](image)

The flow mode transition in the nozzle from purely annular to gas-dispersed flow was determined by changing heat transfer conditions of the body mounted in the jet behind the nozzle. Evaporation of droplets deposited on the surface requires additional heat; according to the data in the paper [7], even a
small number of droplets in the flow significantly reduce the temperature of the adiabatic wall. These promising results provided sufficient sensitivity to the chosen method for experimental measurements.

Small (about 2.8×1.2×1 mm in size) semiconductor temperature sensor LM50 was used as the streamlined body in experiments. The sensor had sufficiently high sensitivity, built-in preamplifier, and was provided with factory calibration from -40 up to +125 °C. The choice of the sensor was due to a compromise between small enough size not to perturb the flow, and, at the same time, considerable enough to capture and evaporate a noticeable number of droplets. The disadvantage of the sensor was its response delay (response time was about 1 s), but it did not prevent from noticing the change in temperature under the transition of the flow mode. The results of test experiments confirmed the possibility of using temperature sensors to diagnose the appearance of the droplet phase in gas flow.

The sensor was fixed with glue to the tip of the medical needle and could be mounted on the flow axis at different distances from the nozzle. To determine the critical gas velocity, the sensor was mounted at a distance X ≈ 7.5 mm from the nozzle outlet cross-section. This slightly exceeded the distance X = 5.6 mm: the point of the nozzle conical (outlet) part generatrices intersection at the axis.

The following parameters were recorded in experiments: time, temperature sensor readings, and pressure in the gas tank, the nozzle pre-chamber, and the surrounding space. Initially, gas was at room temperature. Since the diameter of the nozzle outlet cross-section was 5 times larger than the diaphragm, the flow in the nozzle was subsonic; stagnation pressure practically did not differ from atmospheric pressure and was considered constant. Mass flow rate and velocity of gas were calculated at atmospheric pressure conditions by a gas pressure change in the tank of the known volume. The ethanol flow rate was recorded by the liquid level change in the measuring tube.

The plan of the experiment was as follows: the gas tank was filled with air by a compressor up to the required pressure. The liquid supply pipeline was filled with ethanol up to the top of the measuring tube, and the corresponding injectors were connected to the control unit. According to the plan, the recording of sensor signals was turned on from the computer and the required valves opened. First, the air was fed to the pre-chamber of the nozzle, and then, after a short delay of about one second for establishing the stable gas flow, injectors were opened for several seconds and the liquid was supplied. After a predetermined time, the air supply was terminated, the recorded data were saved, and the described procedures were repeated under other conditions.

3. Results and discussion

Examples of typical measurement results are given in the figures below. The readings of the temperature sensor for different gas and liquid flow rates are shown in Fig. 2, while for different positions of the sensor relative to the nozzle exit – in Fig. 3. At a small gas flow rate (Fig. 2, curves 1 and 2, overpressure in front of the diaphragm of 10^5 and 3×10^5 Pa), the liquid supply to the nozzle does not lead to a noticeable change in the sensor readings. An increase in pressure up to 5×10^5 Pa and above (Fig. 2, curves 3 and 4) leads to a drastic change in the readings: the sensor indicates the presence of droplets in the gas jet flowing around it. Some delay in the sensor response is due to the response delay of the liquid supply system.
Figure 2. Temperature sensor readings for different excess pressure: 1 – 100 kPa, 2 – 300 kPa, 3 – 500 kPa, 4 – 700 kPa. Distance X = 7.5 mm.

The readings of the temperature sensor depending on its position at the axis relative to the nozzle outlet cross-section (from the placement inside the nozzle at a distance $X = -1, -6$ mm and downstream to $X = 21$ mm) are shown in Fig. 3. At the same time, the operational parameters for gas and liquid flows are constant. It is observed that droplets move to the axis of the jet only beyond the nozzle outlet. One can also see that the sensor shows lower temperatures (stronger cooling) with increasing distance from the nozzle outlet, which seems to be due to changes in heat transfer and gas dynamics at sensor streamlining.

Figure 3. Temperature sensor readings at different distances: 1 – -6 mm, 2 – -1 mm (without liquid), 3 – -1 mm, 4 – 7.5 mm, 5 – 21 mm.
The recorded temperature profiles can be visually compared by noting the air pressure at which droplets appeared in the flow. Using this pressure we can calculate gas velocity in the nozzle pre-chamber: the critical velocity for the chosen liquid flow rate. In this approach, the critical velocity is obtained by changing the conventional value \( P = \int_{t_1}^{t_2} T(t) dt \), where \( T \) is the recorded temperature; and \( t_1, t_2 \) are the time points of beginning and end of liquid supply, respectively. If droplets appear in the jet, the sensor indicates lower temperature, and \( P \)-value decreases. The critical velocity is calculated for the conditions at the point with a noticeable (~ 20 - 30%) deviation of the profile \( P(t) = f(Q_g) \) (where \( Q_g \) is the mass flow rate of gas) from the initial value.

The results obtained are presented in Fig. 4, where the values of gas velocity at which detachment of droplets from near-wall liquid film begins, and the flow mode in the nozzle becomes gas-dispersed. At lower values of velocity, droplets are unlikely to appear, and at a higher velocity, a stable finely dispersed gas-droplet flow behind the nozzle is observed.

![Figure 4. Dependence of critical velocity on liquid flow rate.](image)

The measured values (about 13–20 m/s) of critical velocity for annular two-phase flow in the nozzle pre-chamber are of the same order of magnitude as those for steady flow in a channel or pipe [6-8], despite alternative geometry with variable channel cross-section. It should be noted that even for pipes there is no single approximation dependence: different authors may have different values. Thus, at a liquid flow rate of 0.52 g/s, according to the formula in paper [6], the critical velocity \( V \approx 37 \) m/s is obtained, which is proportional to the liquid flow rate raised to a power of -0.75. According to the formula in paper [7], the critical velocity \( V \approx 9 \) m/s is obtained, irrespective of the liquid flow rate. The approximation dependence in paper [8] gives the critical velocity \( V \approx 3.7 \) m/s and proportionality of the liquid flow rate raised to a power of -0.3. The data obtained in this work are somewhere between the indicated values both in terms of critical velocity and in its dependence on the liquid flow rate of the near-wall film.
Conclusions
The interaction of co-current air flow with a near-wall film of ethanol in the convergent nozzle is studied experimentally. The effects of gas flow velocity and liquid flow rate on the transition of flow mode in near-wall film from annular to annular-dispersed with entrainment of droplets from the film surface are investigated. The results obtained could be useful for analyzing the gas-droplet structure of the flow behind supersonic nozzles, including jets behind nozzles of control and orientation thrusters of spacecraft.

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