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Near-wall liquid film ejection with co-current gas flow from nozzle into vacuum

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ABSTRACT

The recently discovered phenomenon of near-wall liquid film rise against gravity on an external surface of a nozzle under joint ejection with co-current gas flow into vacuum is studied experimentally for a variety of liquids and ejection regimes. It is shown that co-current gas flow parameters, pressure in surrounding space (in vacuum chamber) and physical properties of liquid (primarily saturated vapor pressure and heat of evaporation) have the main influence on behavior of a near-wall film at the exit edge of the nozzle. Quantitative data on height of liquid film rise for different liquids and different conditions of ejection are obtained. Possible theories that account for the film rise against gravity on the external surface of the nozzle are discussed.

1. Introduction

Expansion of liquids and gas–liquid mixtures into vacuum is of great interest both from the fundamental and practical points of view. From the fundamental science perspective studies of physical processes and the phenomena accompanying expansion of a liquid into vacuum – instant boiling, disintegration into droplets, phase transitions on surfaces and inside droplets, interaction of droplets with a supersonic gas flow, etc. are important. For practical applications ejection of a liquid into vacuum is of interest in particular in the field of space technology, where a problem of space vehicle surface contamination by orientation thrusters, drainage devices, and refueling systems is of great importance [1–3].

Gas jet expansion into vacuum from nozzles and cylindrical channels has been studied in numerous experimental and theoretical works. A list of many important contributions can be found in review [4]. Here we mention the most relevant contributions. In Ref. [5] it was demonstrated that initially continual gas phase flow pattern inside the nozzle and in its vicinity becomes transient in the near field of the jet and free-molecular in the far field of the jet. In Ref. [6] gas backflows under jet expansion from supersonic nozzle into vacuum appearing due to boundary layer were studied. Results of numerical simulation of gas backflows under expansion from supersonic nozzles into vacuum were presented in Ref. [7]. Sharp temperature drop under gas expansion from short tubes was demonstrated numerically in Refs. [8,9].

However the problem of joint high velocity gas flow with near-wall liquid film has not been studied systematically. Such a flow has a number of special features. One such feature is appearance of the gas-droplet flow upon joint ejection of the liquid film and gas into vacuum. Since the continual flow pattern under expansion into vacuum changes to transient and eventually to free molecular one can expect the influence of non-equilibrium phenomena and rarefaction on interaction of droplets with the supersonic rarefied flow. Another special feature of the problem is instant overheating of the liquid in vacuum due to the fact, that vacuum chamber pressure is much lower than liquid saturated vapor pressure. This leads to explosive disintegration of liquid into droplets.

In our previous experiments we studied problem of external contamination of space vehicles (including the ISS) surfaces by jets of orientation and control thrusters, in which a fuel film is used for nozzle walls cooling. Fuel was modeled by ethanol because its main physical properties (density, saturated vapor pressure, specific evaporation heat, viscosity, surface tension) are close to unsymmetrical dimethylhydrazine, which is currently used as a fuel for ISS orientation thrusters.

It was discovered that under ejection into vacuum, near-wall liquid film moving down on an inner surface of the nozzle not only breaks up into droplets at the exit edge of the nozzle but also emerges on the external surface of the nozzle, moving backwards

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on it, even against gravity [10]. Such behavior leads to contamination of solar panels, antennas, port holes and poses a great danger to space vehicles crew during space walks [2]. Minimization of such contamination is an important and challenging technical problem.

At the same time it must be noted that the discovered effect of liquid film rise on the external surface of the nozzle is of special interest as a new physical phenomenon. This paper is concerned with experimental study of this effect for liquids which significantly differ by their physical properties from ethanol.

2. Experimental setup

Experiments were carried out on a VIKING vacuum gas-dynamic setup of the Kutateladze Institute of Thermophysics [11]. The large volume of the working chamber (150 m^3) allowed to carry out operation in the pulse mode with high flow rates of gas and liquid. Since the amount of liquid in one pulse was rather small, liquid evaporated quickly without posing any difficulties for vacuum pumps.

The nozzle (brass cylindrical tube with 5 mm diameter, 20 mm length, 1 mm wall thickness and rounded exit edge) was mounted vertically in the vacuum chamber, with exit part facing downwards. The liquid entered through a circular gap of 0.1 mm width into stagnation chamber of the nozzle and moved down the nozzle walls as a film. Simultaneously, gas was blown through the nozzle. At the nozzle exit, a freely expanding gas jet with dispersed liquid droplets was formed.

Air was used as working gas, and ethanol, dodecane, Freon-11 and water as working liquids. Their physical properties are shown in Table 1. Dodecane and Freon-11 were chosen as liquids with many similar physical properties but with much lower and higher saturated vapor pressure as compared to ethanol respectively. Water, which has high heat of evaporation, was chosen as working liquid because of a number of important applications in the field of aerospace technologies. Although a number of papers studied water injection into vacuum from tubes accompanied by droplet formation and freezing [12–14] we found no studies on ejection of water in the form of near wall film.

Typical experimental conditions were as follows. Required pressure in the range from 1 Pa to 10^5 Pa was set in the vacuum chamber. Filtered and dehydrated compressed air was fed into stagnation chamber through flow diaphragm 2 mm in diameter. In all the experiments the conditions were created for the flow through the diaphragm to be at sonic velocity. In experiments with dodecane, ethanol and water gas flow rate was equal to 3.8 g/s. In experiments with Freon in order to avoid liquid boiling inside the nozzle gas flow rate was higher – at about 8 g/s. Stagnation chamber pressure was measured by the pressure gauge and was in the range from $8\cdot10^4$ to $1.2\cdot10^5$ Pa in experiments with dodecane, ethanol and water and in the range from $1.7\cdot10^5$ to $1.8\cdot10^5$ Pa in experiments with Freon.

Table 1
Physical properties of working liquids.

Parameter	Units	Ethanol C_2H_5OH	Dodecane $C_{12}H_{26}$	Freon-11 CCl_3F	Water H_2O
Saturated vapor pressure at 20 °C	kPa	5.86	0.0097	88.92	2.31
Dynamic viscosity at 20 °C	Pa s, 10^{-3}	1.2	1.492	0.44	1.002
Density at 20 °C	kg/m^3, 10^3	0.79	0.75	1.49	1
Surface tension at 20 °C	N/m, 10^{-3}	22.8	25.5	18.6	72.8
Melting point at 100 kPa	°C	−114.5	−9.55	−110.5	0
Boiling point at 100 kPa	°C	78.3	216.3	23.8	100
Heat of vaporization at 100 kPa	kJ/kg	840	360	184	2256

Volume flow rate of liquids was equal to 0.4 ml/s, and mass flow rate was a function of liquid density and was within the range from 0.3 g/s for dodecane to 0.6 g/s for Freon. Initial temperatures of gas and liquid were equal to 300 K. Experiments were carried out in the pulse mode. Typical time of ejection was 5 s. Meanwhile settling time was less than 1 s, and pressure rise in vacuum chamber was in the range from 12 to 25 Pa. Time interval between consecutive shots was about 10 min. This was enough time for the nozzle exit edge temperature reduced during the shot to return back to normal. Photographic recording during experiments was performed through the side porthole of the vacuum chamber.

3. Experimental results

Snapshots of near-wall film ejection process into vacuum chamber with initial pressure of about 1 Pa for ethanol, dodecane, Freon and water are shown in Fig. 1(a–d). Ejection process into chamber with atmospheric pressure for Freon is shown in Fig. 2. Flow patterns during ejection into atmosphere for ethanol, dodecane and water were almost indistinguishable. One can see that the ejection of near-wall liquid film into vacuum and into atmosphere is drastically different. Under ejection into atmosphere the usual gas-droplet flow takes place, while under ejection into vacuum near-wall liquid film emerges on the external surface of the nozzle, moving backwards on it against gravity.

The snapshots in Fig. 1 show the maximum recorded film rise. A special feature of water near-wall film ejection into vacuum is formation of the ice layer on the external surface of the nozzle. Fig. 3 shows height of liquid film rise versus pressure in vacuum chamber. Let's consider the results obtained in more detail.

3.1. Dodecane

As we can see from snapshots in Fig. 1a and data in Fig. 3 height of dodecane film rise is the greatest in comparison with film rise of ethanol and Freon. Dodecane in comparison with ethanol and Freon has the smallest saturated vapor pressure (see Table 1). Though saturated vapor pressure of dodecane at the room temperature of 9.7 Pa is approximately one order of magnitude higher than initial pressure in the vacuum chamber equal to 1 Pa it doesn't lead to explosive disintegration of film into droplets. Apparently, it is caused by liquid film cooling during its motion with co-current gradient gas flow inside the nozzle. Thus the value of saturated vapor pressure of liquid also decreases.

3.2. Ethanol

Saturated vapor pressure of ethanol at room temperature is equal to 5.9 kPa that is more than two orders of magnitude higher than saturated vapor pressure of dodecane. Therefore under ejection into vacuum chamber with pressure of about 1 Pa ethanol film becomes instantly overheated. This leads to partial disintegration of liquid film into droplets during its movement on the external surface of the nozzle. The process of intensive droplet detachment from external surface during experiments with ethanol is shown in Fig. 1b.

3.3. Freon 11

Saturated vapor pressure of Freon is close to atmospheric pressure. Therefore under ejection of Freon into vacuum the effect