Near-wall liquid film flows for space applications

V N Yarygin¹, V G Prikhodko¹, I V Yarygin¹, Yu I Gerasimov², A N Krylov² and A Yu Skorovarov²

¹ Kutateladze Institute of Thermophysics SB RAS, 1 Lavrentiev Ave., Novosibirsk, 630090, Russia
² Korolev Rocket and Space Corporation ENERGIA, 4a Lenin Str., Korolev, Moscow area, 141070, Russia

E-mail: yarygin@itp.nsc.ru

Abstract. In this paper we present results of model experiments on interaction of near-wall liquid film with co-current gas flow inside supersonic nozzle under operating conditions of the International Space Station orientation thrusters. Wave pattern characteristics of films are studied with the help of coaxial capacity-type probes and data on the film local parameters – its thickness and velocity are obtained. It is shown that under the experimental conditions the co-current gas flow exerts strong dynamic impact on near-wall liquid film, leading to intensive wave formation and detachment of droplets by co-current gas flow. It is demonstrated that Weber number can be accepted as the main similarity criterion defining the nature of near-wall liquid film interaction with co-current gas flow under conditions considered.

1. Introduction

Among numerous applications of near-wall liquid flows their use for cooling heat-stressed elements and devices is of special importance. A case in point is liquid-propellant rocket engines used as orientation thrusters at the International Space Station. These bipropellant thrusters use self-igniting components – dinitrogen tetroxide (amyl) and unsymmetrical dimethylhydrazine (UDMH). For protecting combustion chamber walls and supersonic nozzle against high-temperature (over 3000K) combustion products a near-wall propellant film (usually UDMH) is formed. Though currently many papers present the research results for near-wall liquid films including gravitational as well as moving under the influence of gas flow, the number of publications on liquid film flows under conditions of high-velocity and, in particular, supersonic co-current gas flow is limited [1]. One of the main features of near-wall film behavior under considered conditions is strong influence of high-velocity co-current gas flow on local parameters of the film inside the supersonic nozzle as well as under expansion into vacuum. Another important phenomenon takes place at the interaction of near-wall film with gradient gas flow. Significant drop in static pressure in the flow (approximately 30 time for the nozzle with Mach number M = 3, used in our experiments) can result in a situation where static pressure in the flow above the film becomes lower than the saturated vapor pressure of liquid. This can cause boiling up and evaporation of the film and appearance of transversal vapor stream from the film into the boundary layer. This vapor stream, by analogy with gas blowing through a permeable wall into boundary layer can affect the value of interphase friction, resulting in reduction of shearing stress at gas-liquid boundary in comparison with gas interaction with a film without its boiling and evaporation. Up to date virtually no results have been published that would give accurate and
confirmed data on the shearing stress at the gas-liquid phase boundary under conditions of high relative velocities of co-current gas flow. This phenomenon can be partially explained by the fact that currently there are no approaches to direct measurements of friction value at the interphase boundary, especially under conditions of intensive wave formation, droplets detachment from film surface and liquid film boiling and evaporation.

Our previous paper presents the results on gas-droplet flow, arising under expansion of near-wall liquid film with co-current gas flow from supersonic nozzle in vacuum [2]. There the extensive experimental data are given for outside the nozzle. In this work we present results of experimental study of near-wall liquid film interaction with gas flow inside the supersonic nozzle. Our study is invigorated by the problem of external contamination of spacecrafts, including the International Space Station, by exhaust plumes from orientation thrusters, in which the fuel film is used for cooling the nozzle walls. With the help of coaxial capacity-type probes wave characteristics of films are studied and the data on its local parameters, thickness and velocity, are obtained.

2. Experimental setup and measurement techniques

Model experiments were carried out at the VIKING facility of Vacuum gas-dynamic complex of the Institute of Thermophysics SB RAS [3]. This experimental facility with a 150 m³ working chamber provides wide range of possibilities for conducting experiments in pulse and continuous modes. Currently there are many methods for measuring local characteristics of near-wall films, the most important of which is thickness. In our work the measurements of local parameters of near-wall liquid film (film thickness and velocity) were performed with the help of capacity-type probes [4]. The scheme of the model nozzle with probes is shown in figure 1.

In our experiments we used coaxial capacity-type probes with external electrode diameter of 1.6 mm, and the internal one of 0.5 mm, which were flush-mounted on the internal surface of the nozzle. For film thickness measurement four probes were placed at 90° interval over the nozzle perimeter at a 2 mm distance from the nozzle lip, and their readings were averaged. Upwards from one of the probes an auxiliary probe was located at a 5 mm distance. This pair of probes was used for velocity measurements. Probes sampling frequency was 1 kHz. Special attention in our experiments was paid to measurement accuracy. Details on measurement methodologies, including probes calibration, are given in [2]. An important part of experiment set up is the choice of key parameters of a supersonic model nozzle – Mach number, type of gas and liquid for near-wall film formation. In our studies, we assume the concept of modeling by the typical angle of jet divergence $\Theta$ determined in terms of the relative jet impulse $J$ [5]:

$$\Theta = \arctg \left( \frac{1-J}{J} \right)^{0.5}, \quad J = \left( \frac{1}{\gamma M_a^2} \right) \left( 1 + \frac{2}{(\gamma - 1) M_a^2} \right)^{-0.5},$$

where $J = J_a/GV_{max}$, $J_a$, $G$, $V_{max}$ is the gas impulse at the nozzle exit cross-section, gas flow rate, and
maximum gas velocity, respectively. In this approach, it is necessary to reproduce the value of the relative impulse of real thruster experimentally. Supersonic nozzle with geometrical Mach number $M = 3$ (throat diameter – 10 mm, exit cross-section diameter – 20 mm) was used in experiments as model nozzle, ethanol – as working liquid (physical properties of ethanol and UDMH, such as viscosity, saturated vapor pressure, surface tension, heat of evaporation are rather close), and purified air – as working gas.

3. Results and analysis
In analyzing experimental results we considered not only Re number of the gas flow but also We number. From the general point of view it is clear that for the specified nozzle and working liquid an interaction of co-current gas flow with near-wall liquid film inside the channel is defined by parameters of co-current gas flow and near-wall liquid film. Reynolds $Re_{gas}$ and Weber $We$ numbers of gas flow as well as Reynolds number $Re_{liq}$ of near-wall liquid film can be chosen as the corresponding similitude parameters. These similitude parameters for gas flow are connected by the relation

$$We = Ca \cdot Re_{gas} = \frac{\eta \cdot V}{\sigma} \cdot \frac{\rho \cdot V \cdot L}{\eta} = \frac{\rho \cdot V^2 \cdot L}{\sigma},$$

where $Ca$ is the capillarity number characterizing a ratio between viscous friction and surface tension; $\eta$ is the dynamic viscosity of gas; $\sigma$ is the surface tension coefficient of liquid; $\rho$ is the gas density; $V$ is the gas velocity; and $L$ is the characteristic dimension. Although only Reynolds number would be enough to characterize gas flow, Weber criterion that takes into account a ratio between dynamic pressure forces and surface tension has been added as characteristic parameter. At small Weber numbers ($We < 1$) the co-current gas flow doesn't exert strong dynamic impact on near-wall liquid film, leading only to the loss of stability and transition to wave character of film flow. However under increased Weber number ($We > 2$) the gas flow begins to exert strong dynamic impact on near-wall liquid film, leading to intensive wave formation, detachment of droplets from an interphase surface and their entrainment by co-current gas flow [6]. In our experiments the maximum values of Weber number reached 160, therefore, it was possible to expect strong impact of co-current gas flow on near-wall liquid film. This assumption was further confirmed by experiments.

Example of film thickness measurements by two consequently located probes for time interval from 1.4 up to 2 seconds are presented in figure 2.

![Figure 2. Liquid film thickness measured by two probes.](image-url)
The moment of liquid film registration by probes is observed clearly. It can be seen that the surface of the film has a repetitive wave structure with abrupt forward front and the following low-sloped part with smaller waves on it. It is also possible to see that liquid films are thin, and amplitude of waves on their surface is of the order of the film thickness. These measurements allowed us to obtain experimental data on average thickness and velocity of the film forward front as well as velocity of waves on an interphase surface. The corresponding results are presented in figures 3 and 4 as the function of gas Reynolds number. In these experiments liquid flow rate was 1 g/s, and gas flow rate varied from 2 up to 22 g/s. Though some dispersion of experimental data is observed, in general they correlate well with Reynolds number of gas flow.

The obtained experimental data on near-wall liquid film average thickness and velocity near the exit cross-section of the nozzle allowed us to determine the liquid flow rate at the nozzle lip. Taking into account the known initial liquid flow rate we were able to estimate the amount of liquid detached from the film surface and carried away by co-current gas flow. As it was already mentioned above, detachment of droplets from near-wall liquid film surface should happen at $W_e > 2$. The strongest dynamic impact of co-current gas flow on near-wall liquid film should take place in the critical cross-section of the nozzle where shearing stress at interphase border has maximum value. On the basis of

![Figure 3. Dependence of liquid film thickness on Reynolds number $Re_{gas}$.](image3.png)

![Figure 4. Dependence of liquid film velocity on Reynolds number $Re_{gas}$.](image4.png)
this assumption it is possible to conclude that the most intensive detachment of droplets should arise near the critical cross-section. The rest of the film moves to the nozzle lip under the continuing strong impact of the gas flow. The validity of this assumption is confirmed by estimated Weber numbers with maximum values at the critical and output cross-sections of the nozzle of 160 and 40, respectively. The corresponding results on the amount of carried away liquid are shown in figure 5. In our experiments this amount can exceed 50% of an initial flow rate of liquid and correlates with Weber number.

Such a large volume of liquid carried away from interphase surface under considered conditions as well as high values of Weber number are caused, apparently, by physical properties of ethanol (particularly rather small surface tension coefficient).

4. Conclusion
The carried out experiments provide an important insight into the role of a flow background inside the supersonic nozzle in formation of gas-droplet flow under further expansion into vacuum, namely arising of two typical areas of the droplet phase flow – central and peripheral. The peripheral area of the droplet phase flow behind the nozzle exit cross-section in vacuum, which is formed due to disintegration of near-wall liquid at the nozzle exit edge, is of most importance, since it is responsible for contamination of external surfaces near thrusters of the International Space Station. Obtained experimental data are also of interest for the development of theoretical models of near-wall liquid film interaction with supersonic gradient gas flow.

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