

# Experimental study of a butanol film motion with a co-current gas flow inside a supersonic nozzle

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**Abstract.** The results of experimental study of the local characteristics of a butanol near-wall film interacting with a co-current air flow in a supersonic nozzle with a geometric Mach number  $M = 3.75$  are presented. The thickness and velocity of the butanol film front as well as waves on its surface in different cross-sections of the nozzle were measured. The role of the boiling process on the film flow inside the nozzle is studied and its effect on the measured film thickness is shown.

## 1 Introduction

The study of a near-wall liquid film interaction with a co-current gas flow is an urgent thermophysical problem. The results of such studies are important for a number of technological processes associated with heat exchangers walls cooling, liquids atomizing and combustion.

The flow of a near-wall liquid film both in the presence of a gas flow (stress films) and without it (gravity films) has been the subject of numerous experimental and theoretical studies. Reviews of such studies are presented, for example, in [1 - 3]. Here we can note the work [4], in which the thickness of the liquid film is measured using the laser refractometry method as well as the wave height, frequency and velocity. In [5] the flow of a liquid film in the presence of a turbulent co-current gas flow is studied. Despite numerous publications, most studies deal with the flow of a liquid film at low subsonic gas flow velocities. Studies of a liquid film flow inside a supersonic nozzle in the presence of a high-velocity co-current gas flow had been carried out at the IT SB RAS [6], but ethanol was used in experiments, which, due to its physical properties, boiled inside a supersonic nozzle in the entire range of Reynolds numbers of gas flow. This work is a continuation of earlier studies, but using butanol as the working fluid, which, due to the lower saturated vapor pressure, made it possible to study the film flow under conditions of a significantly smaller influence of the boiling process inside the nozzle on the measured thickness.

The paper presents the results of an experimental study of the local characteristics of butanol near-wall film under interaction with co-current air flow in the supersonic nozzle with a geometric Mach number  $M = 3.75$ . One of the key features of this work is the high, about 560 m/s, co-current gas flow velocity and, accordingly, high values of the Reynolds and Weber numbers. The main goal of the research was to study the influence of gas flow parameters on the structure and properties of near-wall liquid films, as well as their

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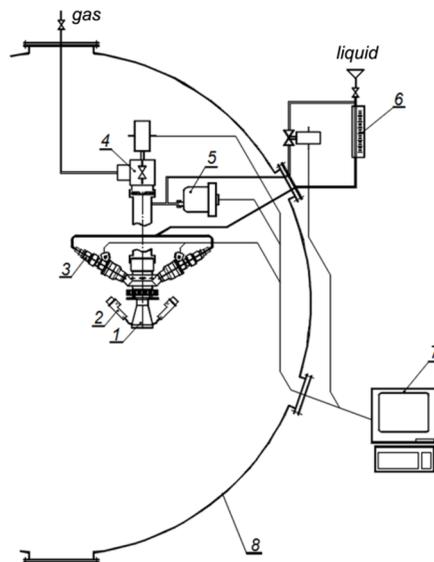
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dynamics along the nozzle wall under outflow into a vacuum. During the experiments, the thickness and velocity of the liquid film were measured, and the influence of heat exchange and mass transfer processes on the nature of interphase interaction was studied.

## 2 Experimental setup and measurement technique

The experiments were carried out at the vacuum gas-dynamic complex of the IT SB RAS in a wide range of defining parameters, in particular the Reynolds number of the gas flow. The drop in static pressure in the gas flow inside the nozzle with  $M = 3.75$  is approximately 2 orders of magnitude. When the gas stagnation pressure in the nozzle pre-chamber is equal to 100 kPa, the pressure in the flow at the exit cross-section is about 1 kPa. The saturated vapor pressure of butanol at room temperature is equal to 665 Pa, therefore, at a gas stagnation pressure of less than 70 kPa, a process of intense evaporation and boiling of the liquid film can be observed near the nozzle exit. The choice of butanol as a working liquid was due to the possibility of studying the film flow inside a nozzle not only in the presence of a gradient gas flow, but also under conditions of both boiling and evaporation of the film or without them. The gas pressure in the nozzle pre-chamber in the experiments varied from 11.9 up to 120 kPa, liquid flow rate – from 0.5 up to 1 g/s, which corresponded to the Reynolds number of gas  $Re_{gas} = 4.6 \cdot 10^3 - 4.9 \cdot 10^4$ , the Reynolds number of liquid  $Re_{liq} = 4.2 - 8.5$  and the Weber number  $We = 3.5 - 20$ , the gas supply time in the experiments was equal to 5 s, the liquid supply time was equal to 3 s.

The schema of the test section is shown in Fig. 1. The test section with supply systems for the working liquid and gas was mounted inside the VIKING vacuum chamber (volume of the chamber is equal to 150 m<sup>3</sup>).



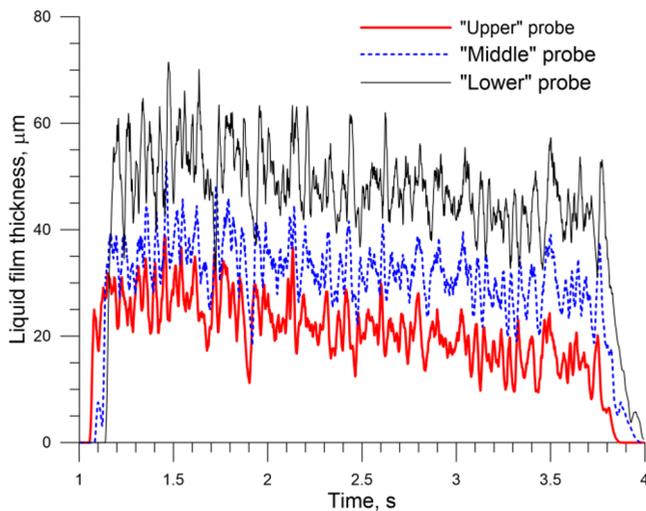
**Fig. 1.** The schema of the test section. 1 – supersonic nozzle, 2 – capacity-type probes, 3 – injectors, 4 – valve, 5 – pressure sensor, 6 – measuring tube, 7 – PC with control unit, 8 – vacuum chamber.

Currently, there are quite a few methods for measuring the local characteristics of wall films, in particular their thickness. The most commonly used optical methods are based on measuring light transmission, light absorption, or reflection from the gas-liquid interface. However, they require the use of transparent channel walls with good optical characteristics, which is often very problematic. In this work, measurements of the

parameters of the near-wall liquid film were carried out using capacitive-type sensors that meter the dielectric conductivity of the medium above the sensor, from which the thickness of the film can then be determined using calibration dependencies. Six capacitive-type probes were installed to the nozzle wall to measure film parameters. Supersonic nozzle with a geometric Mach number  $M = 3.75$  with a conical supersonic part and a critical section diameter  $D = 10$  mm was used in experiments. Four probes were mounted along the perimeter of the nozzle at a distance of 3 mm from the exit cross-section, which measured the thickness of the liquid film and made it possible to assess the uniformity of the liquid film supply into the nozzle. Above one of these probes two more probes were installed at distances of 8 and 14 mm from the nozzle exit cross-section. Three probes located downstream one after another made it possible not only to measure the velocity of the leading edge of the film and waves on its surface, but also to trace the dynamics of changes in the velocity and thickness of the liquid film along the nozzle. The capacity-type probes of 1.5 mm in diameter were embedded flush with the inner surface of the nozzle and did not introduce disturbances into the liquid flow under study. More details of the methodology for measuring liquid film parameters using capacity-type probes are given in [7]. Before starting measurements, the vacuum chamber was evacuated to a pressure below 1 Pa, then the recording of readings from capacity-type probes began and the supply of gas and a wall liquid film to the nozzle pre-chamber was switched on. Also during the experiment, the total liquid flow rate through the nozzle, the gas pressure in the nozzle pre-chamber and the pressure in the vacuum chamber were measured.

### 3 Experimental results and discussion

An example of the film thickness as a function of time, recorded by 3 sensors located in series, is shown in Fig. 2. The stagnation pressure in the nozzle pre-chamber in this experiment was equal to  $p_0 = 2.5 \cdot 10^4$  Pa, and the liquid flow rate was equal to 0.6 g/s. The Reynolds numbers of gas and liquid were equal to  $9.8 \cdot 10^3$  and 5.3, respectively.

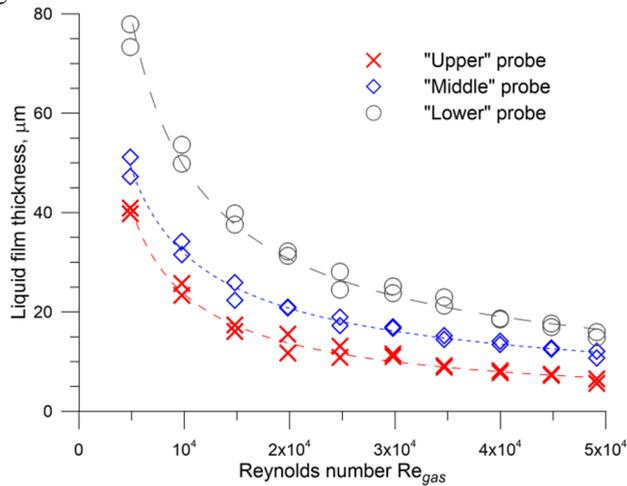


**Fig. 2.** Time diagram of the butanol film thickness.

It can be seen that the moment the film arrives at all probes is clearly recorded, as well as the drop in film thickness to 0 after the liquid supply is switched off. The liquid film has a wave structure, and as it approaches the nozzle exit, the film thickness increases. Based

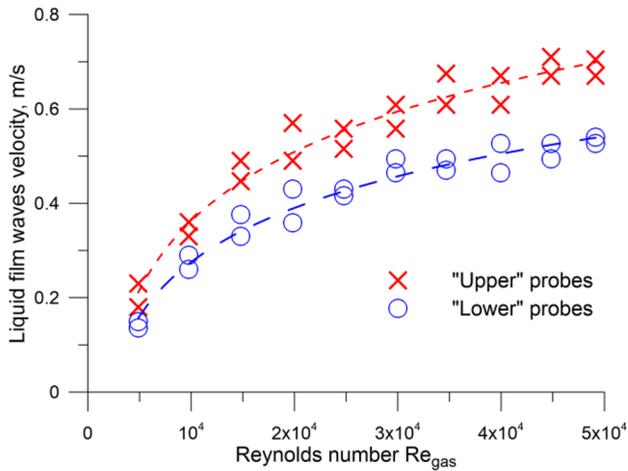
on geometric factors, one would expect that as the film moves inside the nozzle, its thickness should decrease due to an increase in the diameter of the nozzle. An explanation for this effect of increasing thickness may be the process of boiling of the butanol film occurring inside the nozzle. For a supersonic nozzle with a geometric Mach number  $M = 3.75$ , which was used in the experiments of this work, at the realized gas pressure levels in the pre-chamber (above 11.9 kPa), the gas pressure above the film near the exit will be about 120 Pa, which is significantly lower than the saturated vapor pressure of ethanol (about 665 Pa at room temperature). Under such conditions, the butanol film begins to boil inside the nozzle, which causes a strong increase in its thickness due to the formation of vapor bubbles inside the film.

The dependence of the thickness of the butanol film on the Reynolds number of the co-current gas flow in different cross-sections of the nozzle at a liquid flow rate of  $G_{liq} = 0.6$  g/s is shown in Fig. 3



**Fig. 3.** Dependence of the butanol film thickness on the Reynolds number  $Re_{gas}$ .  $Re_{liq} = 5.3$  ( $G_{liq} = 0.6$  g/s)

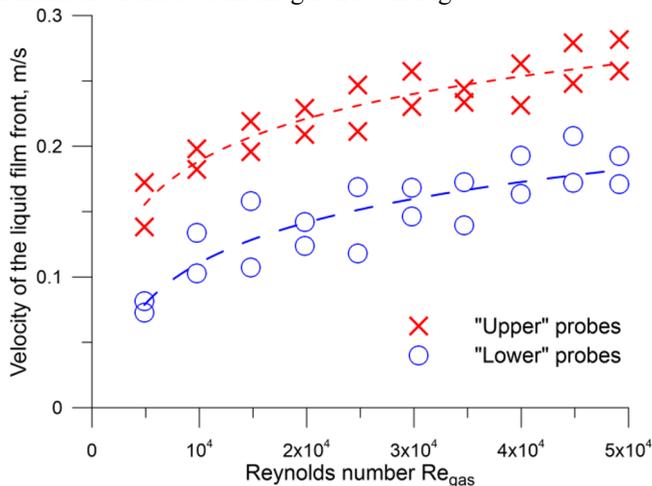
It can be seen that for all three probes, the liquid film thickness data correlates with the Reynolds number of the co-current gas flow. At moving towards the nozzle exit cross-section, as noted above, the liquid film becomes thicker, even despite the increase in the cross-sectional area of the nozzle. Moreover, with a decrease in the Reynolds number  $Re_{gas}$ , the increase in film thickness on the “lower” probe (near the nozzle exit) occurs faster than on the “upper” probes, which indicates the increasing role of the process of boiling of the liquid film inside the nozzle. The dependence of the measured wave velocity on the Reynolds number of the co-current gas flow is shown in Fig. 4.



**Fig. 4.** Dependence of the butanol waves velocity on the Reynolds number  $Re_{gas}$ .  $Re_{liq} = 5.3$  ( $G_{liq} = 0.6$  g/s)

When flowing inside the nozzle, on the one hand, the velocity of the co-current gas flow increases, and on the other hand, its density decreases, which lead to a decrease in the dynamic pressure of the co-current gas flow from the critical section to the nozzle exit. From Fig. 4 it can be seen that the wave velocities on the film surface increase with increasing Reynolds number of the co-current gas flow, and at a fixed value of the Reynolds number, as it approaches the nozzle exit, the film slows down. Although the speed from the critical section to the exit of the nozzle with  $M = 3.75$  increases by 1.8 times and reaches 560 m/s, the dynamic pressure due to a drop in density by 18 times decreases by approximately 5.6 times.

Dependences of the leading edge velocities and waves on the surface of the butanol film on the Reynolds number of the co-current gas flow in Fig. 5.



**Fig. 5.** Dependence of the butanol film front on the Reynolds number  $Re_{gas}$ .  $Re_{liq} = 5.3$  ( $G_{liq} = 0.6$  g/s)

It can be seen that the velocity of the liquid film leading edge towards the nozzle exit decreases, similar to the wave velocity (Fig. 4). In this case, as the Reynolds number of the co-current gas flow increases, the velocity of the liquid film also increases. At the same time, it is clear that the velocity of the leading edge of the film is approximately 2 times

lower than the velocity of waves on its surface. This can be easily explained if we accept the linear nature of the change in velocity across the thickness of the liquid film.

## 4 Conclusion

The experiments carried out made it possible to obtain new data on the influence of gas flow parameters on the characteristics of the near-wall film of butanol under motion with a co-current gas flow inside a supersonic nozzle. It is established that the effect of the gas flow on the wall film significantly affects its flow. It is shown that the process of liquid film boiling leads to a significant increase in the thickness of the film inside the nozzle. The data obtained can be used for the development and optimization of various technological processes associated with the interaction of liquids and gases, as well as the development and verification of numerical models of two-phase flows in various thermally stressed devices requiring film cooling.

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