MEASUREMENT OF WAVE CHARACTERISTICS OF A NON-ISOTHERMAL LIQUID FILM BY THE CAPACITANCE METHOD

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Wave characteristics of the water film flow over a vertical plate with a heater of 150×150 mm were measured by the capacitance method. The influence of heat flux density on the wave flow of a liquid film forms rivulets and a thin film between them. In the interjet area wave amplitude and thickness pulsation frequency decrease. Three-dimensional waves propagate along the jet crests. Wave amplitude is determined by a change in liquid film thickness under the action of thermocapillary forces. Relative amplitude is almost independent of the heat flux.

INTRODUCTION

To understand the mechanism of heat transfer and crisis phenomena at heat release to a film, it is important to investigate development dynamics of 3D deformations and formation of jet flows in a non-isothermal liquid film.

The effect of thermocapillary forces on distribution of 2D waves over the water film falling along a vertical tube of the 24 mm diameter was studied in [1]. The tube length was 1.5 m. As in many other experiments, waves on a film falling over the tubes of small diameter kept two-dimensionality at moderate Reynolds numbers, and no regular vertical inhomogeneities were registered.

The effect of thermocapillary forces on 2D waves was theoretically studied in [1−2]. In [2], long-wave approximation of Benney type [3] at Re ~ 1, Bi = 0 and linear distribution of the substrate temperature were used. It was shown that at substrate heating, thermocapillary forces provide an increase in amplitude of 2D waves.

In [4], which studied heat transfer to a water film falling over an outer side of the tube with 31.5 mm diameter and heated region of the 0.2-m length, it was noted that with a decrease in the flow rate two or three vertical bulges with a thin film between them were formed on the liquid surface.

Formation of regular structures in the form of 3D bodies in initially smooth liquid film flowing over a surface with a small heater (6.5×13 mm) was found out in [5, 6]. In experiments significant temperature gradients (up to 10−15 K/mm) on the liquid surface were obtained. Formation of structures at film heating on different small heaters was studied in [7]. Film thickness before and after structure formation was measured by modified schlieren method in [8] and fiber optic method in [9].

Thermocapillary wave mechanism of jet formation was revealed and studied in [10, 11]. In this case vertical jets were formed at non-uniformity of the film on the crests of 2D waves at their decomposition into 3D waves or on the developed synchronous 3D waves. With an increase in the heat flux density, the liquid film between jets became smooth and wave propagated over the jet surface.
In [12], liquid film thickness was measured between the jets, where it becomes even, by a fiber-optic probe of the reflection type mounted from the free surface of the film. It was found out that with an increase in the heat flux, the film between jets becomes thinner and by breakdown it makes up 50–60 % of Nusselt thickness. The wave flow remains up to breakdown, but wave amplitude decreases by the factor of 3–4. It is shown that data on average thickness, residual layer thickness, and wave amplitude correlate well with data presented in [13] for an isothermal film.

Periodic splashes of a signal caused by light focusing by the film surface between capillary waves with negative curvature were observed in the area of large wave precursors. The signal character indicates that the fiber-optic probe can be used for smooth and slightly wave liquid films. However, to reconstruct correctly the profile of a wave film, it is necessary to get additional information or use independent measurements made by a different method.

The capacitance method is widely used for measurements of thickness and wave characteristics of the falling liquid films [14–16]. Particularly, it is used for investigation of the flow of liquid nitrogen films [14]. Operation principle of the capacitance method is described in detail in [17].

In the current work, the capacitance method is used for the study of wave characteristics of a water film at formation of jets on the vertical heater of 150×150 mm for Re = 22 at various track lengths of the film from a nozzle to the upper edge of heater (Xn = 120 and 200 mm).

1. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The setup was a closed circulation circuit including reservoir with a pump, working section, filter, rotameters, pipelines, and stop valves. The working liquid was supplied by the pump into the film-former consisting of an accumulator chamber, distributing device, and nozzle with a calibrated flat slot. The liquid falling down the plate was accumulated in a receiver and under the action of gravity it was returned into the system. The detailed description of experimental setup and measurement procedures is presented in [18]. The temperatures of flowing liquid, heating element, surface of the carrying plate, and vapor-air mixture near the heater were measured by 29 thermocouples. To change the distance from the film coming from the slot nozzle to the heater, special film-former (1) travelling in vertical direction was constructed (Fig. 1). Thermal stabilization of the film temperature in the area of its formation was obtained using a flat metal heat exchanger (2) with a system of channels, where the working liquid was pumped. At the flow of water films in the range of studied Re numbers, condition q = const was satisfied on the heater surface.

In experiments, the equipment and software with original calibration of the capacitance method described in [17] developed at the Institute of Thermophysics SB RAS were used. Four capacitance probes located as on a chess-board were applied. At film heating and jet formation, two probes were located between the jets and another pair of probes was in the zone of jet crest motion or in its vicinity. The probes were mounted at distances X1 = 132 mm and X2 = 144 mm from the upper edge of the heater. The distance between them was 12 mm, that significantly exceeded the size of the probe itself. It is shown in [19] that electric fields were localized in the measurement area of the probe and did not effect characteristics of the adjacent probe. The error of the method depends on liquid film thickness and distance from the film surface to the probe. For this type of the probes, the accuracy of film thickness measurement at Re = 22 was 2 % [19].
2. EXPERIMENTAL RESULTS

At Re = 22, $X_n = 120$ mm, 2D waves propagated on the upper part of the heater. At $X_n = 200$ mm, the wave pattern on the film surface was more complex. A large almost 3D wave with small capillary waves in front of it is shown in Fig. 2, a. At an increase in the heat flux at the heater bottom 3D waves on the film surface transformed into jets (Fig. 2, b). With a rise of the heat flux density, the distance between jet crests decreases [11].

Dependency of average dimensionless film thickness measured by the capacitance probe $h_{av}/h_0$ on heat flux density $q$ is shown in Fig. 3 ($h_0 = l/(3 \text{Re})^{1/3}$) is film thickness

Fig. 2. The flow of water films, $\text{Re} = 22, X_n = 200$ mm. $q = 0$ (a), $0.92$ W/cm$^2$ (b).
calculated by Nusselt dependency, which corresponds to film thickness at wave-free flow, \( l_n = (\nu^2 / g)^{1/3} \) is a constant of viscous-gravitation interaction, \( \nu \) is coefficient of kinematic viscosity of water, \( g \) is acceleration of gravity, \( \text{Re} = \nu \Gamma \), \( \Gamma \) is specific volumetric flow rate of liquid. It is obvious on the diagram that in the interjet area the liquid film thickness doubles at an increase in the heat flux density from 0.5 W/cm\(^2\) to 0.9 W/cm\(^2\), and this correlates with data obtained by the fiber-optic method \[12\]. In a vicinity of the jet, film thickness also reduces, but more gradually. An increase in film thickness is registered on the jet crest.

Dimensionless amplitude of large waves \( h_{\text{max}} / h_0 \) (Fig. 4), decreases in the interjet area with a rise of the heat flux, and increases on the jet crest. Difference of wave amplitudes without heating is caused by different values of \( X_n \).

At relatively high heat flux density, liquid film thickness between the jets decreases with a rise of distance from the heater edge \( X_t \). The profile of local film thickness in the interjet area is shown in Fig. 5 at heat flux density \( q = 0.86 \) W/cm\(^2\) at two measurement points, where the first probe (in the figure its readings correspond to 1) is installed at distance \( X_t = 132 \) mm, and the second probe (readings of 2) is installed 12 mm downstream. Data \( h_{av1} \) and \( h_{av2} \) shown in the diagram correspond to average film thickness for the whole measurement region at the first and second points. According to

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**Fig. 3.** Dependency of dimensionless average thickness of a water film on heat flux density at \( \text{Re} = 22 \).

**Fig. 4.** The effect of heat flux density on amplitude of large waves.
the figure, at this heat flux density, the liquid film after 12 mm (the distance between measurement points) changes significantly: wave amplitude decreases, and amplitude of large waves decreases non-uniformly. Some waves disappear, and this can be considered as a decrease in their frequency. If at $q = 0$, wave frequency is in the range of 11–13 Hz, at $q = 0.86 \text{ W/cm}^2$, $X_t = 132 \text{ mm}$, it makes up approximately 5 Hz.

At jet crests, wave amplitude at a change in $q$ and $X_t$ stays constant and makes up 12–13 Hz (Fig. 6). Data are shown for the same values of $X_t$ as in Fig. 5. With an increase in $q$, average film thickness in the jet increases, however, the conclusion about a similar effect of $X_t$ cannot be made because a change in film thickness is within a range of experimental accuracy.

Therefore, an increase in the heat flux evens the wave liquid film between the jets, reduces thickness amplitude and wave pulsation frequency. Three-dimensional waves propagate along jet crests without a change in frequency. With a rise of the heat flux, film thickness and wave amplitude increase.

It is clear from Figs. 3, 4 that wave amplitude increases at the jet crest and reduces in the interjet area with an increase in the heat flux in the same way as liquid film thickness does. In Fig. 7 experimental data are shown as dependency of relative amplitude $A$ on $q$. Relative amplitude $A = (h_{\text{max}} - h_{\text{min}})/h_{\text{av}}$ is a ratio of maximal and minimal film thickness to average thickness in the measurement range. Solid lines average experimental data. It is obvious that $A$ does not depend on the heat flux both in the interjet area and jet.

There are two mechanisms of thermocapillary force effect on propagation of the wave liquid film. When the liquid film with 2D waves moves over a heated surface with
a positive temperature gradient along the flow, heating growth should lead to an increase in
wave amplitude because in this case thermocapillary forces are directed from the
wave valley to its top [1, 2]. On the other hand, 2D waves are unstable and decay into
3D ones [20]. Appearing non-uniformity of film thickness and temperature provides
formation of a temperature gradient on the film surface across the liquid flow. In the
lower part of the heater, thermocapillary forces are directed across the film flow [10],
and this provides jet formation.

A growth of relative wave amplitude due to the effect of thermocapillary forces
predicted for 2D waves was not determined. Perhaps, in this case a change in film
thickness under the action of thermocapillary forces at jet formation is the determining
one. Wave amplitude adjusts to this change in accordance with a change in film
thickness (local Reynolds number).

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