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Autostabilization of propagation velocity of a self-sustaining evaporation front

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A self-sustaining evaporation front propagates along the heat-transfer surface within the thickness of the metastable thermal layer due to the heat stored in this layer. Under conditions of quasi-stationary heat release at a constant wall temperature, the front propagates at a constant velocity. With stepwise heat release, when the temperature of the heat-transfer wall increases with time, the researchers observed an increase in the velocity of evaporation frontpropagation. The dynamics of propagation of the evaporation front with a significant temperature gradient along a surface has not been previously studied. This paper presents the results of an experimental study of the dynamics of propagation of a self-sustaining evaporation front over a flat wedge-shaped surface with stepwise heat release. The dynamics of heating of the wedge-shaped surface and the temperature profile of the adjacent thermal layer, where a self-sustaining evaporation front propagates, were calculated. The measured spatial velocity of front propagation was compared with the calculated rate of heat-transfer wall heating. The experiments were carried out at pool boiling of freon *R*21 at ambient temperature. The working section in the form of an isosceles trapezoid with bases of 12 and 24 mm and height of 50 mm was made of stainless steel 0.2 mm thick. The experiments were carried out at a pressure of 0.18 MPa. The experiments showed that under the conditions of a significant temperature gradient of the heater surface, at the first stage the velocity of front propagation increases and at the second stage it correlates with the heating rate of the heat-transfer surface; thus, the velocity of evaporation front propagation is stabilized.

Keywords: pool boiling, self-sustaining evaporation front, evaporation rate, hydrodynamic stability

INTRODUCTION

At pool boiling, the heat transfer coefficient increases with increasing heat flux density; therefore, the heat exchanger works most efficiently at high heat flux densities. However, the energy intensity of devices is limited by the heat transfer crisis of the first kind [1, 2]. Therefore, significantly less intense regimes are chosen for safe operation of heat exchangers. Nevertheless, the development of crisis phenomena at thermal loads much smaller than the magnitude of heat transfer crisis of the first kind is possible with substantially unsteady regimes of device operation [3]. Unsteady heat release into a single-phase liquid leads to formation of an overheated thermal layer with high metastability near the heat-transfer surface. The vapor bubble formed under such conditions starts growing; the interface of the growing vapor bubble loses stability, and starts propagating along the heat-transfer surface. A self-sustaining evaporation front propagates along the heat-transfer surface within the thickness of a metastable thermal layer due to the heat accumulated in this layer [4, 5]. Under conditions of quasi-stationary heat release at a constant wall temperature, the front propagates at a constant velocity [6–8]. With stepwise heat release, when the temperature of the heat-transfer wall increases with time, the researchers observed an increase in the propagation velocity of the evaporation front [9, 10].

The dynamics of evaporation front propagation over a surface with a significant temperature gradient along the heat-transfer surface has not been previously studied. This paper presents the experimental results on the dynamics of propagation of a self-sustaining evaporation front over a flat wedge-shaped surface with stepwise heat release.

EXPERIMENTAL

The experiments were carried out under the conditions of a large volume at an experimental setup described in [10]. A stainless steel cylindrical vessel with a diameter of 240 mm and depth of 225 mm is equipped with four windows designed to take the videos of the process and illuminate the research object. The working section is made of 0.2 mm thick stainless steel in the shape of an isosceles trapezoid. The bases of the trapezoid are 12 and 24 mm; the height is 50 mm. The video was shot with a high-speed Phantom video camera at a speed of 25,000 frames per second. To achieve stepwise heat release, a DC source Gorn-K 12/600 was used. The electric current density was linearly varied along the length of the trapezoidal working section, and the density of volumetric heat release in the plate was changed with the current density. As a result, a substantial temperature gradient was formed along the working section and in the thermal layer

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adjacent to the heat-transfer surface. A self-sustaining evaporation front propagated under the conditions of that gradient.

RESULTS AND DISCUSSION

The experiments were carried out using freon *R*21 at a pressure of 0.18 MPa, which corresponded to the ambient temperature of 24°C. The magnitude of current passing through the wedge-shaped working section was 420 A. The current was supplied in the form of a rectangular pulse of controlled duration. The maximum pulse duration was 32 ms. Over such a period of time, free convection does not have time to develop and formation of the temperature field in the working section and thermal layer of the adjacent liquid is determined by the laws of heat conduction. A numerical calculation of the temperature field for these conditions was performed using the equations of unsteady heat conduction. The diagram for calculating the temperature field of the working section is shown in Fig. 1.

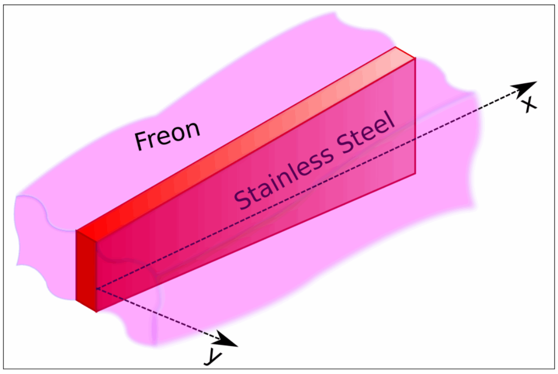

Fig. 1. Scheme for calculating the temperature field of the working section.

The diagram of distribution of heat-transfer surface overheating relative to the temperature of liquid saturation along the working section is shown in Fig. 2 at various points of time from the beginning of the stepwise heat release. This calculation was made for the condition of phase transition absence. In reality, at overheating by 30-40 K, single vaporization sites are activated on the heat-transfer surface; they start growing, and the interface loses stability under the conditions of high metastability of the surrounding thermal layer, and the evaporation front starts propagating. Nevertheless, before the front, the single-phase thermal layer and the heat-transfer wall have the temperatures corresponding to those calculated by the equations of unsteady heat conduction.

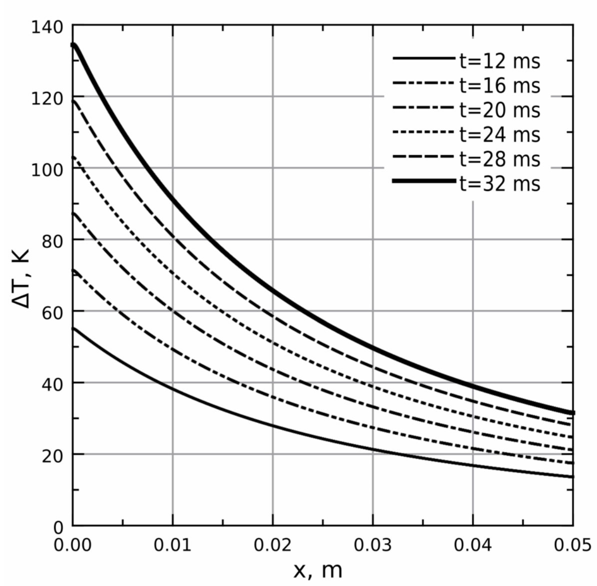

Fig. 2. Overheating of the heat-transfer surface relative to the temperature of liquid saturation. The saturation temperature is 24°C.

The video fragments of evaporation front propagation at various points of time from the beginning of heat release are shown in Fig. 3.

As it can be seen in the video frames, at 10 ms from the beginning of heat release there is a single vaporization site in a narrow part of the working section. At 15 ms, the vaporization sites and initial formation of the evaporation front are observed at several sites of the narrow edge. At 20 ms, the formed self-sustaining evaporation front spreads subsequently in a single line along the working section.

The diagram of a change in the coordinate of the leading point of evaporation front is shown in Fig. 4 depending on time from the moment of heat release beginning. The diagram also shows the lines of change in the coordinates of the calculated isotherms of the heat-transfer surface. As it can be seen in the diagram, the coordinate of the interface on the time interval of 10 - 15 ms from heat release beginning stays most unchanged. In the video, we see the growth of a bubble. For the next 5–6 ms, interface propagation with an increasing velocity is observed. Moreover, in the process of moving, the leading point of the front at each step is in the region of a higher temperature, which leads to acceleration of the leading point. At a time interval of 22-32 ms, an almost linear change in the coordinate of the leading point of the evaporation front is observed with time, which indicates moving at a constant velocity.

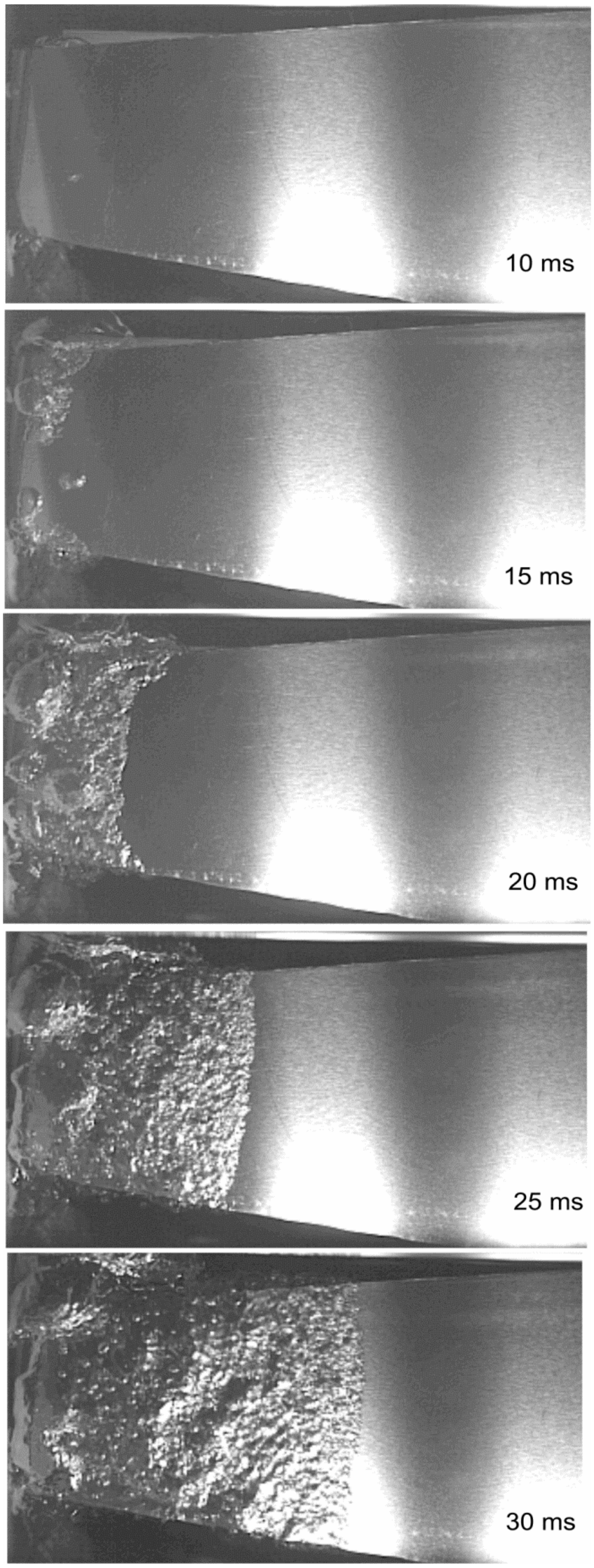

Fig. 3. Fragments of a video of evaporation front propagation. The time from the beginning of heat release is shown in the frames.

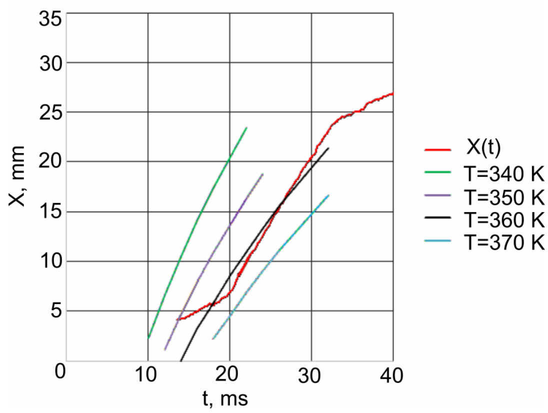

Fig. 4. Changes in the coordinates of the leading point of the evaporation front and calculated isotherms of the heat-transfer surface depending on the time from the moment of heat release beginning.

The diagram shows that the leading point of the front moves almost simultaneously with the isotherm (T = 360 K) corresponding to a temperature head of 63 K. Advancing the isotherm by the leading point leads to the contact of the interface with the region of less metastability, which leads to a slowdown of the front. Thus, autostabilization of propagation velocity of the self-sustaining evaporation front occurs. At a time interval of 22 - 32 ms, the leading point of the front moves to a distance of 12.9 mm, which corresponds to a velocity of 1.29 m/s. Therefore, at a temperature head of 63 K, the velocity of evaporation front propagation is 1.29 m/s.

CONCLUSIONS

The experimental studies showed that a self-sustaining evaporation front forms in the region of maximum overheating of the heat-transfer surface at a temperature head of 40-50 K with respect to the saturation temperature. The evaporation front formed in the region of maximum overheating propagates with acceleration in the direction of the temperature gradient along the heat-transfer surface until an equilibrium state is reached between the velocity of spatial displacement and the rate of metastable layer heating. Further front propagation occurs at a constant average velocity caused by the velocity of the corresponding isotherm of the heat-transfer surface.

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