

Visual study of propagation of self-sustained evaporation front within the thickness of a thermal liquid layer

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Abstract. In the range of low reduced pressures, the development of self-sustained evaporation front along the heat-releasing surface at non-stationary heat release is an important factor that determines possible transition to film boiling at heat fluxes, significantly lower than the critical heat fluxes at stationary heat release. This paper presents the experimental results on the scale of a leading part of the interface of self-sustained evaporation front at stepped heat release. The scale of the leading part of the interface of the evaporation front is compared with the thermal layer thickness, registered using the shadow method of visualization at high-speed video shooting with up to 25,000 frames per second. Experiments were carried out in Freon R21 under the conditions of free convection at relative pressures of 0.032 - 0.068. It is shown that self-sustained evaporation front spreads along the heated wall within the thickness of a liquid layer, superheated relative to the saturation temperature. Dependence of the front velocity on wall superheating relative to the saturation temperature does not change with significant subcooling to the temperature of liquid saturation in the volume.

1. Introduction

Non-stationary heat release within a local region of the heat exchanger can create a metastable layer of a contacting liquid coolant and lead to formation and propagation of a vapor film. The vapor front propagates along the heat-releasing surface due to transfer of heat accumulated in a thin thermal layer during heating the single-phase liquid. In the case of non-stationary heat release, when the times of evaporation front formation are considerably less than the times of convection development, the thermal layer thickness increases by the root law, accumulating heat from the heat-releasing surface by the mechanism of heat conduction. Several studies demonstrate that the average velocity of evaporation front propagation is constant for the same temperature of the heat-releasing wall in the case of stationary heat release [1], and the front propagates with acceleration at non-stationary heat release and increasing temperature of the heat-releasing wall [2]. It is shown in [3] that the velocity of evaporation front interface pulsates in a vicinity of the average front velocity. The mode of pulsations is low-frequency; it is determined by the heater scale comparable with the scale of the capillary constant. The high-frequency mode is determined by the thickness of the vapor layer of evaporation front. There are some models that describe propagation of undisturbed self-sustained evaporation front [1,4,5], as well as the single attempts to model the dynamics of front propagation dynamics with consideration of small-scale interface perturbations under the conditions of intensive evaporation [6]. Despite a long history of studying such a phenomenon as the self-sustained evaporation front, to date



there is no model that describes the dynamics of front propagation with consideration of all processes occurring at the interface of the evaporation front.

The aim of this work is to obtain new experimental data on the process of evaporation front propagation within the thickness of a thermal layer at non-stationary heat release. It is necessary to develop the model description of this phenomenon.

2. Setup and method description

Experiments were performed in a large volume of liquid Freon R-21 in the range of reduced pressures of 0.032 - 0.068. The detailed description of setup is given in [2]. The tube with the diameter of 3 mm made of steel 12X18H10T was used as a working section. Heat release was organized by the pass of a rectangular current pulse with the amplitude of 420 A and predetermined duration of 10 - 90 ms through the working section. Due to the high thermal inertia of the working section, the wall temperature increased almost linearly with time (the initial exponential region). The wall temperature was determined by dependence of electrical resistance of the working section on temperature, as well as by numerical calculation using the heat conductivity equation. In addition to the wall temperature, the temperature profile in liquid near the heat-releasing wall was determined by numerical calculation at specified duration of heat release and the value of electric current through the heater. The use of the heat conductivity equation in this case is admissible, as the process of front formation and propagation was observed for the short times, significantly less than the time of convection development. Laminar convection was observed in experiments during the times of the order of 300 ms. To visualize the evaporation front within the thickness of the thermal layer illumination in the transmitted light was used. A laser level with the wavelength of 650 μm or LED SMD assemblies was used as a light source. In the case of laser use in the working section of 3-mm diameter, the thermal layer was observed as a shaded area; when using LED lighting, the upper border of the thermal layer was observed as a dark line, and the space of the thermal layer near the heating wall was observed as the clear liquid.

In experiments, there was high-speed recording that allows observation of evaporation front propagation along a length of about 30 mm. According to this video (frequency of 25,000 frames per second), the propagation velocity of evaporation front was determined depending on wall superheating relative to the saturation temperature. There was also macrorecording, which allowed us to consider the structure of the front interface in detail with simultaneous observation of the thermal layer using the shadow techniques. The maximal video resolution obtained in macrorecording is about 10 μm per pixel.

3. Results and discussions

Time dependences of thermal layer thickness from the beginning of heat release, measured by video records and calculated are presented in *Fig. 1*. The thickness of the thermal layer calculated numerically for the cylindrical heater from the condition of 98-% temperature difference between the wall and undisturbed liquid (line 6) and calculated for a flat layer (line 3) by formula (1) coincide satisfactorily with the thicknesses measured in experiments by the shadow method.

$$\delta = 2.4\sqrt{a\tau} \quad (1)$$

Lines 4 and 5 determined though numerical calculation and corresponding to the thickness of a thermal layer, limited by the temperature of saturation in experiments with subcooling, are also shown in *Fig. 1*.

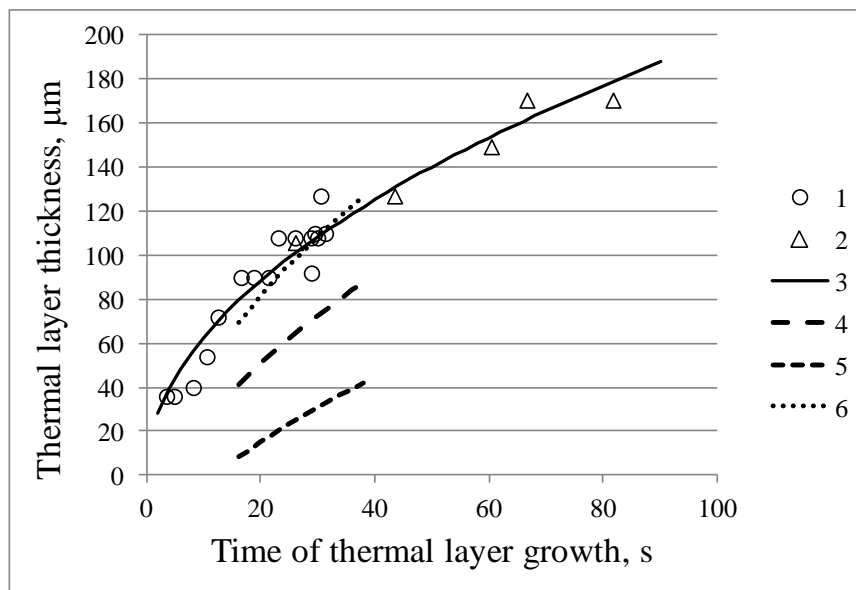


Figure 1. Thermal layer thickness measured in the video frames. 1 –saturated liquid; 2 –subcooled liquid, subcooling $\eta = 24$ K; 3–calculation by formula (1); 4,5,6 – numerical calculation of superheated layer, $\eta = 4.2$ K; 24; 0, respectively.

The fragments of evaporation front propagation in the saturated and subcooling liquids at the same temperature 22.3°C are shown in Figs. 2 – 4.

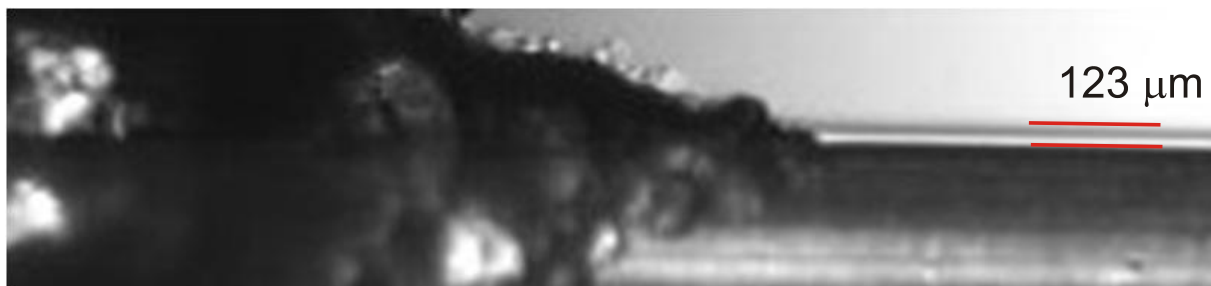


Figure 2. Fragment of evaporation front propagation in saturated liquid. $P = 0.167$ MPa. Thermal layer thickness is $123\ \mu\text{m}$.

In Fig. 2, the thermal layer boundary is observed as a washed-out shaded line at some distance from the cylindrical wall. The vapor front propagated along the heater within the thermal layer thickness due to heat accumulated in the superheated layer. At that, only a part of heat from the thermal layer is spent for evaporation in the leading part of the vapor layer; another part of the superheated layer is pushed off by the propagating front and, then, it is spent for vapor layer thickening. In liquid significantly subcooled to the saturation temperature the front propagates in a thin part of the thermal layer adjacent to the heated wall and superheated relative to the saturation temperature under the given pressure (Fig. 3).

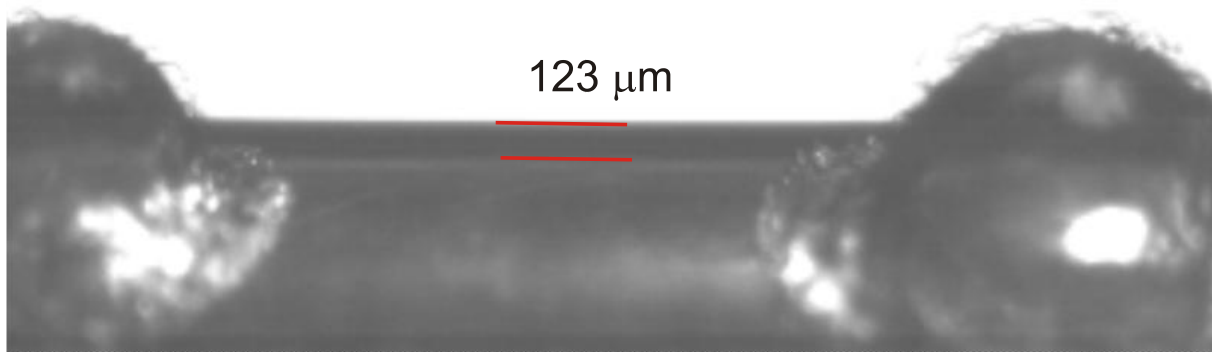


Figure 3. Fragment of evaporation front propagation in subcooled liquid. The thermal layer thickness to the saturation temperature is $38\ \mu\text{m}$, total thermal layer thickness is $123\ \mu\text{m}$. $\Delta T_s = 46\ \text{K}$; $T_s = 46\ \text{K}$; subcooling $\eta = 24\ \text{K}$; $P = 0.353\ \text{MPa}$.

It can be seen in *Fig. 3* that the thermal layer thickness in the frontal part on the upper generatrix of the working section is about a third part of the thermal layer thickness observed as a dark shaded area with the thickness of about $120\ \mu\text{m}$. The calculated value of the layer adjacent to the wall and having a temperature above the saturation temperature under the conditions of our experiment is $38\ \mu\text{m}$. As we can see, the thickness of the frontal part of the vapor layer thickness correlates with the thickness of the liquid layer superheated relative to the saturation temperature. The fragment of evaporation front propagation under the similar conditions, but at a lower subcooling value ($\eta = 4.2\ \text{K}$) is shown in *Fig. 4*. The thickness of the thermal layer with the temperature higher than the saturation temperature in this experiment is $84\ \mu\text{m}$. As it can be seen in the video frame, the thickness of the frontal part of the vapor layer is about 0.5 - 0.7 of the total thickness of the thermal layer, observed as a shaded area with the calculated thickness of $123\ \mu\text{m}$. Also on the scene observed pushing off the remaining part of the thermal layer from the heated is also observed in this frame.

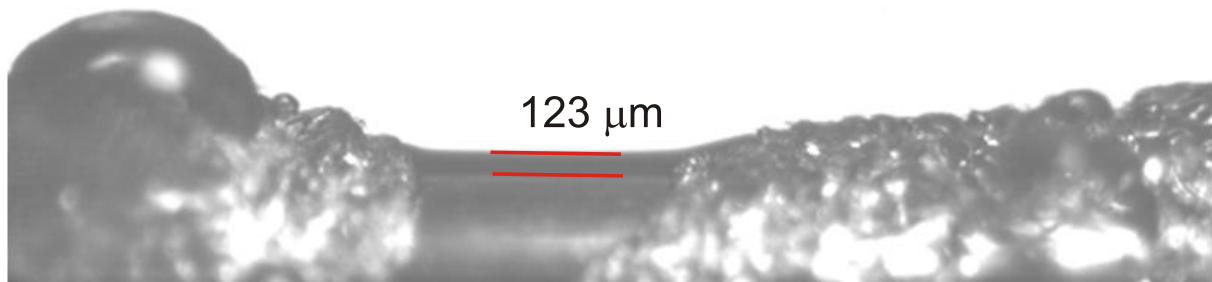


Figure 4. Fragment of evaporation front propagation in subcooled liquid. The thermal layer thickness to the saturation temperature is $84\ \mu\text{m}$, total thermal layer thickness is $123\ \mu\text{m}$. $\Delta T_s = 65.7\ \text{K}$; $T_s = 26.5\ \text{K}$; подогрев $\eta = 4.2\ \text{K}$; $P = 0.19\ \text{MPa}$.

Dependence of propagation velocity of a self-sustained evaporation on wall superheating relative to the saturation temperature is shown in *Fig. 5*. Data are shown for liquid subcooled to the saturation temperature in a varying degree at three different pressures. As it can be seen from the diagram, the front velocity is virtually independent of the value of liquid subcooling, and it is determined by the superheating degree of near-wall liquid layer with respect to the saturation temperature.

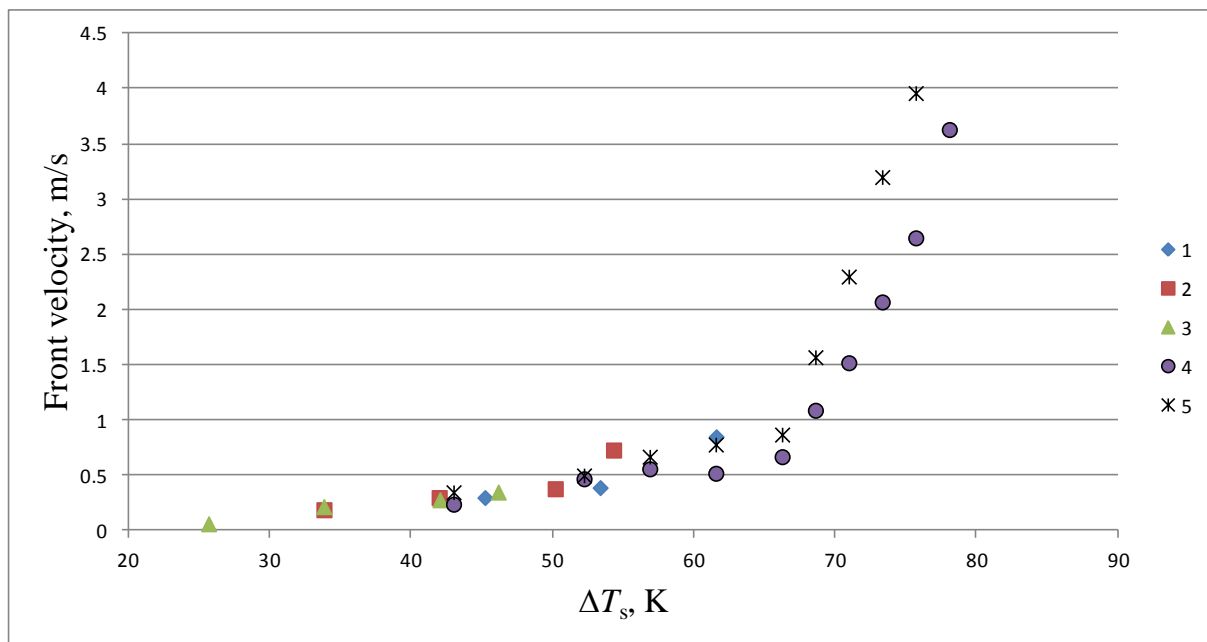


Figure 5. Propagation velocity of self-sustained evaporation front vs. wall superheating relative to the saturation temperature. 1 – $\eta = 4.2$ K; $P = 0.19$ MPa; 2 – $\eta = 15.6$ K; $P = 0.272$ MPa; 3 – $\eta = 24$ K; $P = 0.353$ MPa; 4 – $\eta = 0$ K; $P = 0.167$ MPa; 5 – $\eta = 0$ K; $P = 0.353$ MPa.

4. Conclusions

The experiments on propagation of self-sustained evaporation front along the cylindrical heat-releasing surface with simultaneous visualization of the thermal layer have been carried out. The results of measuring the thermal layer thickness according to the video agree satisfactorily with the calculated value of the layer. The experiments showed that the self-sustained evaporation front propagates along the heated wall within the thickness of the liquid layer superheated relative to the saturation temperature. Dependence of the front velocity on the saturation temperature does not change at significant subcooling to the temperature of liquid saturation in the volume.

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