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An experimental study of vapor bubbles dynamics at water and ethanol pool boiling at low and high heat fluxes

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ABSTRACT

In this paper the results of experimental study of vapor bubbles dynamics at pool boiling of various liquids in a wide range of heat fluxes up to $q/q_{CHF} \sim 0.9$ are presented. The experiments were performed at boiling of saturated water and ethanol at atmospheric pressure with the use of high-speed experimental techniques including video macro-visualization and IR thermography from the bottom side of a transparent heated sample. As a result, new data on the growth rate of vapor bubbles and dry spots in their base, evolution of the liquid microlayer region and unsteady temperature field of a thin film heater surface were obtained, and analysis of patterns of process at low heat fluxes was carried out. The usage of high-speed experimental techniques also allowed in this study to investigate the evolution of vapor bubbles with formation of vapor patterns and large agglomerates, to study dry spots dynamics, to estimate void fraction close to heating surface at fully developed nucleate boiling regime up to the critical heat flux depending on liquid properties. Obtained experimental information can be further used to construct more accurate physical models for the theoretical description of microcharacteristics, heat transfer and boiling trigger mechanisms at nucleate boiling of liquids with different physical properties.

1. Introduction

Since first papers of Moore and Mesler [1], Labuntsov [2] and Cooper and Lloyd [3], in which authors have proposed the hypothesis of rapidly evaporating thin liquid film at the base of a vapor bubble to explain the sharp decrease in the local temperature at the moment of vapor bubble appearance, the phenomena of the microlayer and influence of it evaporation dynamics on heat transfer at nucleate boiling are widely discussed in the literature [4–6]. At the same time, the detailed picture, based on the experimental data on the microlayer dynamics, its characteristics, including thickness, evaporation rate, etc., has not been available to date. The complexity of such studies is related to the fact that the characteristic thickness of microlayer is several microns and the process of its formation and development does not exceed few milliseconds.

Nowadays, high-speed video recording from the side of the heater is common and already classical technique of nucleate boiling visualization. This type of recording allows to study the evolution of vapor bubbles shape, to measure their departure diameters and nucleation frequencies. So nowadays there are a lot of works devoted to experimental investigation of the vapor bubbles dynamics at pool boiling of various liquids on surfaces with different orientation, geometry and roughness, at various pressures and subcooling degree [7–9]. However video recording from the side of a heater has a number of shortcomings. Among them are the impossibility of observing the sizes of microlayer evaporation region and dry spot, formed at the bubble growth stage in a nucleation site, the impossibility of microlayer thickness determination. Moreover, activation of significant number of nucleation sites, even at relatively low heat fluxes, makes it difficult to identify individual vapor bubbles. This significantly increases the measurement error and complicates analysis of the nucleation dynamics at boiling in a wide range of heat fluxes.

The development of modern experimental techniques in the last two decades makes it possible to obtain fundamentally new information on local and integral characteristics of boiling, including heat transfer coefficient and critical heat flux. Nowadays one of the most popular noninvasive methods to measure the nonstationary temperature field of the heating surface is high-speed infrared (IR) thermography. First, who have used this method for boiling process investigation, were Theofanous et al. [10,11]. In these and subsequent papers [12–15], it was shown, that the usage

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Nomenclature

A	area
C_{sf}	constant for surface fluid term
D	diameter
g	gravity constant
h	distance
h_{av}	cooling depth
h_{fg}	latent heat of vaporization
I	current
Ja	Jacob number
k	thermal conductivity
q	heat flux density
R	radius
R_a	surface roughness
T	temperature
t	time
u	velocity
V	voltage
ΔT	wall superheat

Greek symbols

α	thermal diffusivity
γ, β	empirical constants
δ	thickness
ρ	density
σ	surface tension

Subscripts

a	ascent rate
CHF	critical heat flux
dep	departure
ds	dry spot
ev	evaporation
g	bubble growth
l	liquid
ml	microlayer
o	outer
sat	saturation
v	vapor
w	wall; bubble waiting

of high-speed IR thermography allows to measure bubble nucleation temperature, nucleation site density and frequency, etc. In [16,17] with the use of this method the evolution of temperature field under single bubble was obtained, on the basis of which the features of the local heat transfer in regions of microlayer and dry spot were studied. Also researchers have actively used laser interferometry technique to study the geometry and dynamics of the liquid microlayer at boiling of various liquids [4,18–21]. The laser interferometry technique allows not only to determine the sizes of microlayer and dry spots regions, but also to measure microlayer thickness evolution at the bubble growth stage. Therefore, development and further usage of modern experimental techniques allows to obtain fundamentally new information on the multiscale characteristics of nucleate boiling. However, literature analysis shows that existing experimental data on local boiling characteristics, especially those taking place in the region of triple contact line, are insufficient for theoretical description of the microlayer characteristics, its evolution and evaporation rate at boiling of liquids with various physical properties under different conditions, including pressure change.

In addition to the partially nucleate boiling regime, the nucleation dynamics and evolution of two-phase layer close to heating wall at developed nucleate boiling up to crisis phenomena development (CHF) also has a great interest and importance. Such interest is related both with incomplete understanding of basic heat transfer mechanisms at boiling in the region of high heat fluxes, and with the necessity to determine the main reasons of boiling crisis phenomena development, including modeling safe operation of nuclear reactors [23]. Many researchers have attempted to theoretically describe trigger mechanisms of CHF on the basis of the evolution of liquid-vapor system at developed nucleate boiling. Such approaches can be attributed to the already classic Kutateladze-Zuber hydrodynamic instability model and number of its modifications, as well as subsequent semi-empirical models, which are described in detail in recent reviews [24–26]. At the same time, existing experimental observations do not yet provide a clear picture and understanding of the characteristics and evolution of the two-phase system close to a heating surface at pool boiling of liquids with various properties in the region of high heat fluxes.

In one of the first papers [27], devoted to an experimental study of vapor bubbles dynamics at developed nucleate boiling, author observed formation of large-scale vapor agglomerates (or "vapor mushrooms"), which were anchored to a heating surface by numerous columnar stems of vapor. However, due to the appearance of a large number of vapor bubbles at high heat fluxes, performed photographic study from the side of a flat heater did not allow author to firmly reiterate this assumption, which was later noted in [11]. Kirby and Westwater [28] and later Van Ouwerkerk [29] with the use of transparent conductive heaters visualized nucleate boiling at various pressures directly from bottom side of the heaters, which made it possible to study in detail the formation and growth of dry spots under single vapor bubbles up to CHF point. As a result, the existence of a thin liquid layer close to a heating wall, which was later called the liquid "macrolayer", was proposed. In these papers, the hypothesis of the onset of boiling crisis phenomena development as a result of the irreversible dry spots formation and their subsequent lateral growth along a heating surface was also formulated.

Based on the described experimental observations, Katto and Yokoya [30] and further Haramura and Katto [31] proposed a modified hydrodynamic instability model of boiling crisis, which is widely known in the literature as the "macrolayer dryout model". This model assumes that at developed nucleate boiling, the vapor-liquid system represents stationary columnar stems of vapor, distributed in a thin near-wall liquid macrolayer. The onset of crisis developments corresponds to the moment of complete macrolayer evaporation under massive vapor conglomerate. The hypothesis of liquid rich layer existence close to the heating wall was confirmed by number of researchers [32–36] during experimental investigations on void fraction distribution close to a heating surface at boiling of water, isopropanol and FC-72. Nevertheless, authors of [34] also pointed out that the existence of stationary vapor stems in the liquid macrolayer is rather unlikely.

Chu et al. [37] demonstrated the structure of large vapor agglomerates, as well as the behavior of dry spots formed under them. The experiments were carried out at saturated water boiling on the surface of narrow transparent heater (2.7 mm wide). With the use of synchronized total reflection technique and video recording from the side of the heater authors observed formation of large-scale coagulated dry patch under vapor agglomerates. Authors pointed out, that this fact also directly contradicts macrolayer dryout model.