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Nucleate boiling in bidistillate droplets

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Dynamics of nucleate boiling in droplets of bidistillate on different wall surfaces was studied experimentally. These experiments were carried out on the rough copper and on the polished surface with plasma spraying of a golden film. The surface state was investigated by an electron microscope and 3D image processing software. Characteristic microroughness responsible for minimal superheating at nucleate boiling was determined. Heat transfer on the polished surface was significantly worse than on the rough wall. Thermal measurements were performed by means of a multiple increase in thermal imaging. When boiling on the polished surface, the self-organized ordered structures are formed there.

1. Introduction

Boiling is widely used in devices with high density of energy. Nucleate boiling is applied for microelectronics cooling, space techniques, and cryobiology. A high heat flux is achieved due to evaporation of a liquid microlayer near the basis of a growing bubble [1]. Bubble separation and uplift cause liquid convection, which intensifies heat and mass transfer [2]. High-turbulent microconvective flow with a thin thermal layer is formed near the wall. Large-scale macroconvective transfer is observed along the whole height of the channel. Recently the applied interest to droplet boiling increased significantly; this boiling is generated both artificially for improvement of heat transfer efficiency and as a result of film and jet break-down. At a loss of stability a liquid film is divided into many jets and droplets of different sizes. Usually the theoretical models do not take into account film stability and as a result calculation of heat transfer can lead to significant errors.

Initial studies dealt with determination of the averaged heat transfer characteristics: heat flux and heat transfer coefficient. Last decades many works that emphasize the dynamics of the behavior of individual bubbles have been published. However, the mechanistic models cause significant difficulties. The problem is not only a large number of degrees of freedom, but, first of all, the nonlinear nature of the interaction. Even bubble separation and uplift from one of the holes (without heat transfer, i.e., this is absolutely hydrodynamic factor) lead to the chaotic behavior of the whole system because of the nonlinear interaction between the wall, bubbles, and liquid [3]. The correct description of hydrodynamics requires consideration of the nonlinear interaction between the bubbles: transfer of perturbation from each bubble to liquid and from liquid to all bubbles. At that the motion of bubble surface has the oscillating character. Without doubt, if we add a thermal aspect to hydrodynamics, the scenario of bubble system behavior will become more complex. Nucleation site interaction relates both to liquid and bubble hydrodynamics and a solid wall of the heater [4]. Generation, development and separation of bubbles lead to a change in the wall temperature. Temperature pulsations on the wall switch on and off new sites of nucleation. This nucleation site interaction also causes the chaotic behavior and complicates the use of mechanistic models. Interaction of only two close bubbles on the wall will lead to chaos. The density of nucleation site distribution and boiling intensity depend on surface roughness [5–7]; thermal–physical properties of the heating wall [5–7,9,10]; fractal roughness [8]; the strong effect of the heater wall thickness also plays an important role [7,11]. Therefore, we have a complex multiparametric problem of nucleate boiling. At nucleate boiling liquid evaporates both from the liquid–vapor interface and bubble surface as well as from the near-wall microlayer of bubble base. The process of small droplets evaporation (with the diameter of up to 3 mm) without nucleate boiling and with the fixed contact line of a droplet is the most well studied now [12–19].

The experimental studies of the current paper relate to boiling of droplets of bidistillate in a wide range of wall superheat and at a large size of droplets. Geometrical characteristics of bubbles were measured at significantly nonstationary and non-uniform boiling. This boiling differs significantly from pool nucleate boiling.

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Nomenclature

a	thermal diffusivity ($m^2\ s^{-1}$)
D	droplet diameter (m)
k	specific heat of evaporation ($J\ kg^{-1}$)
l; x; h	coordinate (m)
m	the mass of droplet (kg)
N	the number of vapor bubbles (–)
p	pressure (Nm^{-2})
r_{cr}	the critical radius micropore (m)
r; d	bubble radius; bubble diameter (m)
S	distance between bubbles (m)
S_n	the area of bubble base surface (m^2)
S_d	the area of droplet base surface (m^2)
S_s	the area of droplet interfacial surface (liquid–gas) (m^2)
t	time (s)
t_1	total time of droplet evaporation (s)
T	temperature (°C)
ΔT_w	wall superheat (°C)
V	the droplet volume (m^3)

Greek symbols

α	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
β_1	the function of the contact angle
β	micropore angle (°)
θ	the contact angle (°)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension (Nm^{-1})

Subscripts

a	the average value
cr	critical
d	droplet
l	liquid
m	the maximum value before the bubble collapse
n	bubble
s	droplet surface
v	vapor
w	wall
0	initial value ($t = 0$)
i	current value

2. Experimental setup

Synchronization of thermal imaging and high-speed digital filming allowed us to measure local characteristics for small droplets of liquid. Thermal images were measured by means of six-fold magnification using a high-accuracy measurement cell. The thermal field of droplet surface (T_s) was measured by the thermal imager (NEC-San Instruments). The wall temperature (T_w) was kept constant and it was determined by the readings of graduated thermocouple, located under the heated surface. The thermocouples were located at the distance of 0.5 mm from the wall surface. Four thermocouples were mounted at some distance from the center and one thermocouple was in the center of the cylinder. The wall temperature was kept constant automatically with the accuracy of ±0.5 °C. The batch of liquid was in the cylinder center. At droplet evaporation the wall temperature under the droplet decreased by 2 ÷ 4 °C depending on superheat. The central thermocouple did not participate in automatic regulation; it measured the temperature only under the droplet. In every experiment the dosed batches of bidistillate were put on the heated surface by means of high-precision micro dispensers. Before the experiment bidistillate was degassed thoroughly by means of boiling, to reduce the amount of dissolved gas. For the sessile droplets the process of batch separation from the dosing device occurred without droplet fall, i.e., the dosing device was near the surface and it was located normally to the wall. The separated liquid volume had a short simultaneous contact with dosing device and wall surfaces. Time of separation was about 1 s, and then the dosing device was removed. This method of droplet separation excluded the droplet impact on the wall and its splitting. The moment of dosing device separation from the droplet surface corresponds to zero value of measurement time $t = 0$.

To work with water droplets the working section was made of copper with metal spraying. The cylinder diameter was 84 mm and the height was 55 mm (Fig. 1). While studying nucleate boiling, the type of material, wall thickness, physical–chemical and geometrical properties of the heated surface are of a particular importance. Therefore, to exclude the additional factors effecting bubbles generation, the working section was made of the material with high heat conductivity (copper cylinder with low oxygen content), and the sizes of this section exceeded the diameter of liquid droplets significantly. The cylinder surface was polished, and then a micron layer of chromium (to give the coating strength) and a golden film were deposited by means of plasma spraying. Polishing reduced significantly the roughness. Golden spraying excludes material aging completely (a change of properties with time). Moreover, exclusion of oxide film formation allowed us to keep high heat-conductive properties of section surface.

A magnified image of the cylinder surface roughness obtained via an electron microscope is shown in Fig. 2. The rms roughness of mirrored gold-plated surface was of the order of 50 ÷ 70 nm. Before every experiment the surface was thoroughly cleaned from dust. To exclude contamination of walls, the working section was put into the closed chamber at the constant ambient air temperature of 23 °C. Before the experiment air humidity in the chamber was decreased by means of a sorbent. All experiments were carried out at the atmospheric air pressure of 1 bar. Since the process of bubble nucleation in the droplet had an occasional character, every experiment was multiply repeated. The average characteristics were determined by 4 ÷ 5 experiments under the same controlled conditions.

Fig. 1. The working section with mirrored gold-plated surface.