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Boiling of emulsions with a low-boiling disperse phase. High-speed filming

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ABSTRACT

High-speed filming has been used to investigate the process of nucleate boiling of emulsions with a low-boiling disperse phase on a platinum wire 0.10 mm in diameter. Investigations have been conducted on an emulsion with which a disperse phase and a dispersion medium participate in boiling, and on an emulsion with which only a disperse phase boils. Vaporization at the boiling of an n-pentane/water and an n-pentane/glycerine emulsion at the surface of a wire has been studied. The boiling of disperse phase droplets in a thermal boundary layer by the mechanisms of heterogeneous and homogeneous nucleation has been shown. A model of avalanche-like boiling of superheated disperse phase droplets in a thermal boundary layer has been checked.

1. Introduction

To understand the mechanism of boiling of emulsions with a low-boiling disperse phase, it is necessary to visualize the process of nucleate boiling with the use of high-speed filming. Emulsions with a low-boiling disperse phase consist of a low-boiling disperse phase and a high-boiling dispersion medium. The regime of convective heat transfer of such emulsions differs little from the similar regime of a dispersion medium. Nucleate boiling has a number of peculiarities, namely, high superheatings of disperse-phase droplets, wide, as compared with pure liquids, intervals of nucleate boiling, high values of the coefficient of heat transfer from the heater to the emulsion. The boiling peculiarities enumerated manifest themselves in boiling on thin wire heaters [1–4], at a flat surface [5,6] and in a pipe [7].

Visualization of the boiling of emulsions with the use of high-speed filming (up to 5000 frames per second) is presented in Ref. [8]. The filming was realized through the eyepiece of a microscope. Investigations were conducted on the following emulsions: water/silicone oil KF-54 with a disperse-phase concentration $C = 10$ vol.% and water/n-undecane with $C = 20$ vol.%. The heater was a nickel wire 0.20 mm in diameter and 15 mm in length immersed in a thin emulsion layer (the layer thickness was 1 mm and less). The results of the work [8] have shown that the boiling of the emulsions under study was observed both at the surface of the heater and at a certain distance from it.

Visualization of the boiling of emulsions with the use of a conventional video camera (30 frames per second) is presented in Refs. [3,9,10]. The boiling of n-pentane/water and FC-72/water emulsions on a horizontal copper wire 0.10 mm in diameter is examined in Refs. [3,9,10] consider the boiling of n-pentane/water, freon-11/water and water/vacuum oil VO-1C emulsions on a vertical and a horizontal platinum wire 0.10 mm in diameter. The use of a conventional video camera does not give a complete understanding of fast boiling processes, but, nevertheless, the results of such investigations have shown the similarity of the processes of nucleate boiling with the boiling of pure liquids at underheatings to the saturation temperature, when at the heating surface there are “sitting” large vapor bubbles, and a collapse of small vapor bubbles is observed. A model of boiling of pure liquids has been used in. Ref. [11] to obtain calculated relations that give an adequate description of experimental data at boiling of emulsions with a low-boiling disperse phase.

References [12,13], on the basis of experimental data, suggest a model of activation (avalanche-like) boiling of superheated disperse-phase droplets in a thermal boundary layer. To check the model of avalanche-like boiling suggested, visualization of the process of nucleate boiling of emulsions was carried out with the use of high-speed filming, and the results are given in the present paper.

2. Experimental setup

The main difficulties in visualizing the boiling of emulsions are connected with their opacity. Owing to this, experiments in Ref. [8] were conducted in a thin emulsion layer. The scheme of an exper-

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Nomenclature

C	volume concentration of the emulsion disperse phase, m^3/m^3
n	refraction index, dimensionless
p_{cap}	capillary pressure, MPa
R	disperse phase droplet radius, m
q	heat flux density, W/m^2
T_w, T_s, T_o and T_{lim}	temperatures of a heat-transfer surface, saturated vapors, heat-transfer agent (emulsion) and limiting superheating, °C

Greek symbols

α	heat-transfer coefficient, $W/(m^2 K)$
$\Delta T_p = T_w - T_s$	superheating temperature, °C
σ_e, σ_m and σ_{ph}	interfacial tension, surface tension of the dispersion medium and disperse phase, N/m
τ	time, s

imental setup for the visualization of boiling is presented in Fig. 1. A platinum wire 1 with a diameter of 0.10 mm and a length of 25 mm was used as a heater. The observation of the wire surface was realized with the help of a digital stereomicroscope “Altami CM II” 2 with a 4–200 fold magnification. A high-speed camera “Fasvideo-250” 3 (up to 5000 frames per second) was connected to the microscope 2 with the help of an adapter. With the help of the camera 3, images were passed from the wire surface to a computer 4 for further processing. The filming was realized in transmitted light from a light-emitting-diode lamp 5 with a power of 14 W. The platinum wire was set in a horizontal position and heated with the help of a direct-current source 6. The temperature of the emulsion was determined by a thermocouple 7 located at a distance of 10 mm from the wire. Experiments were conducted at room temperature and atmospheric pressure. The procedure of data collection and calculation of the heat transfer coefficient is described in detail in Ref. [4].

The liquids of which the emulsions consisted were not deaerated because when the emulsions were obtained they were not insulated from atmospheric air. The deaeration of an emulsion by means of boiling is impossible owing to the presence of a low-boiling disperse phase in it. The emulsions were prepared by a mechanical agitation with a propeller mixer. Such an agitation yielded a polydisperse emulsion with a minimum diameter of disperse-phase droplets of 5–10 μm, and a maximum one of 100–120 μm. The main fraction of disperse-phase droplets had diameters from 50 to 80 μm. The emulsions obtained were located in a flat-parallel beaker 8 with sides measuring 30 × 50 mm and a height of 120 mm. The filming was carried out with a frequency of 1030 frames per second, and the frames of high-speed filming did not undergo any additional processing with the use of any graphic programs.

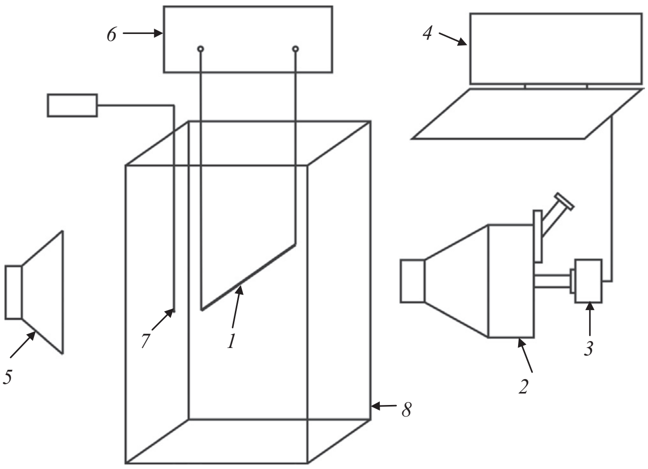

Fig. 1. Schematic diagram of the experimental setup: (1) platinum wire; (2) stereomicroscope; (3) high-speed camera; (4) computer; (5) light-emitting-diode lamp; (6) direct current source; (7) thermocouple; (8) flat-parallel beaker.

3. Results of observations

3.1. Boiling of water and an n-pentane/water emulsion

Fig. 2 presents experimental data on heat transfer at convective heat transfer and nucleate boiling of water 1 and an n-pentane/water emulsion 2 with a concentration of 4.0 vol.%. The n-pentane/water emulsion boils up at temperatures of the wire surface T_w below that of the normal boiling T_s of water. At temperatures T_w higher than the temperature T_s of water, at the wire surface one can observe the joint boiling of n-pentane and water. An emission of microbubbles of a gas dissolved in water is observed in experiments with the boiling of distilled water. Such a phenomenon is observed during the boiling of highly underheated water with different degrees of deaeration [14,15]. The effect of the degree of water deaeration on the intensity of the emission of air bubbles is investigated in Ref. [15]. Observations [15] have shown that with deaeration of water by boiling with evacuation and deaeration with boiling in atmospheric conditions it is impossible to eliminate completely the appearance of air bubbles. In our experiments the emission of microbubbles of a dissolved gas is observed at heat flux densities $q = 1.79$ MW/m^2 (Fig. 3(a_w)). When small vapor bubbles collapse, there arise jets of microbubbles directed into the parcel of liquid at different angles, which, without condensing, rise slowly to the free water surface. The emission of microbubbles ends when a small vapor bubble ceases to collapse and remains at the wire surface. With an increase in the heat flux density, which is observed during the subsequent superheating of the heating surface, a further activation of new boiling sites takes place, the number of small

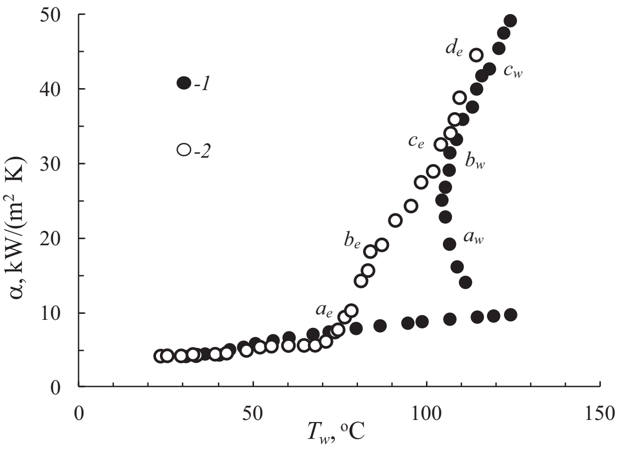

Fig. 2. Dependence of the heat-transfer coefficient α on the heater temperature T_w at convective heat transfer and nucleate boiling on a horizontal platinum wire: (1) water, $T_o = 20.1$ °C; (2) n-pentane/water emulsion, $T_o = 22.1$ °C, $C = 4.0$ vol.%. Letters designate images in Figs. 3–6.