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Effect of the droplet size of an emulsion dispersion phase in nucleate boiling and emulsion boiling crisis

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ABSTRACT

This paper presents the results of an experimental investigation of heat transfer in a boiling water/(vacuum oil VO-1C) emulsion at the surface of platinum wire 0.10 mm in diameter and in a pipe with an inner diameter of 16 mm. The influence of the diameter of a disperse phase droplet on the character of heat transfer in nucleate boiling and emulsion boiling crisis has been investigated.

1. Introduction

The boiling of emulsions with a low-boiling disperse phase is accompanied by a number of peculiarities [1–6]. These are high superheating of droplets, wide, as compared with pure liquids, intervals of nucleate boiling, and high values of heat transfer coefficients. The boiling-up of droplets of an emulsion disperse phase is accompanied by a considerable delay of the beginning of boiling, disperse phase droplets prove to be superheated above the temperature of their saturated vapors. The length of the delay of the boiling onset is affected by the emulsion concentration and the size of disperse phase droplets.

The peculiarities of boiling in emulsions have been studied in considerable detail at heat exchange with wire heaters. The present paper investigates the peculiarities of formation, growth and detachment of vapor bubbles at the surface of a wire heater depending on the average diameter of disperse phase droplets. It gives the results of an investigation of heat transfer during the boiling of emulsions at the inner surface of a pipe of type X18H9T stainless steel 16.0 mm in diameter, and in length 330 mm. The paper continues examining heat transfer to emulsions from thin wires and determines the onset of the boiling crisis. The effect of the droplet size on the boiling crisis is revealed.

2. Effect of the diameter of a disperse-phase droplet on heat exchange in nucleate boiling

2.1. Boiling at the surface of a platinum wire

Refs. [1] and [3] present video filming of the process of boiling-up of emulsions. Visualization of the process of boiling of emulsions is hampered by their opacity. The boiling of *n*-pentane/water and FC-72/water emulsions on a horizontal copper wire 0.10 mm in diameter is considered in [3], and [1] examines the boiling of *n*-pentane/water, freon-11/water and water/(VO-1C vacuum oil) emulsions on a vertical and a horizontal platinum wire with a diameter of 0.10 mm. The data for boiling of *n*-pentane/water emulsions on a horizontal wire in [1] and [3] are in complete agreement. Explosive boiling-up of superheated disperse-phase droplets has been revealed in a water/(VO-1C oil) emulsion. In the present work, the process of nucleate boiling of an emulsion at the surface of a platinum wire was investigated with the help of microfilming. The microfilming was carried out with the use of a stereomicroscope with a magnification from 4 to 200 times. Since the emulsion under investigation was opaque, a photoflash was used during the filming. The investigations were conducted on the experimental setup described in [4]. A coarse-grained emulsion with an average diameter of disperse-phase droplets to 20–30 μm was prepared with a propeller mixer, and fine-grained emulsion with an average droplet diameter of 1–2 μm in ultrasound field with a frequency of 22 kHz.

Fig. 1 [7] presents experimental data at convective heat transfer and nucleate boiling of VO-1C oil *1*, a coarse-grained *2*, and a

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Nomenclature

T, T_s and T_0	temperatures of a heat transfer surface, disperse phase saturated vapors and heat-transfer agent (emulsion), °C
G	flow rate, m^3/s
U	voltage, V
I	electric current, A
q	heat flux density, W/m^2
T_w	the temperature of the inner surface of the measuring pipe *14*, °C
T_i	the temperature of the *i*th thermocouple
T_{in}	the average temperature of the heat-transfer agent at the inlet of the measuring pipe *14* (the thermocouple *11*, Fig. 4), °C
T_{out}	the average temperature of the heat-transfer agent at the outlet of the measuring pipe *14* (the thermocouple *18*, Fig. 4), °C
Q	the amount of heat transferred from the inner surface of the measuring pipe *14* to the heat-transfer agent, W
$S = 2\pi rL$	the area of the surface of the measuring pipe *14*, m^2
r	the inner radius of the measuring pipe *14*, m
L	the length of the measuring pipe *14*, m
Greek symbols	
α	heat-transfer coefficient, $W/(m^2\,K)$
$\Delta T = T - T_0$	temperature drop, °C
λ	the thermal conductivity of the pipe material, W/(m K)

fine-grained *3* water/(VO-1C oil) emulsion at the surface of a horizontal platinum wire 53 mm in length and 0.10 mm in diameter. Microfilming has shown that superheated disperse-phase droplets boil up at pre-existing nucleation sites (Fig. 1, points a_f aa_c), situated at the surface of a heater (Fig. 2, photographs a_f and a_c). At the heating surface there form single vapor bubbles, which under the action of convective streams move chaotically over the heating surface. With increasing heating power one can also observe an increase in the number of disperse-phase droplets capable of boiling-up (Fig. 2 photographs b_f and b_c). A great number of vapor bubbles form at the heating surface, but since the emulsion temperature (T_0 = 16 °C) outside the thermal boundary layer is much lower than the temperature of saturated vapors of the disperse phase (T_S = 100 °C) such bubbles do not grow to the critical size, tear off the wire and emerge. Large vapor bubbles remain adherent to the wire surface, and in them near the wire one can observe the evaporation of a liquid (water), the vapor transport to the bubble vertex, the condensation and flowing of the liquid formed over the vapor surface of the bubble to its base, where the water evaporates again. Such an evaporation mechanism leads to an increase in the tear-off (critical) diameter of a vapor bubble and a considerable intensification of the heat transfer from the heating surface. Large vapor bubbles adherent to the heater surface were observed in boiling freon-11/water [1], *n*-pentane/water [1,3], and in boiling FC-72/water [3] emulsions.

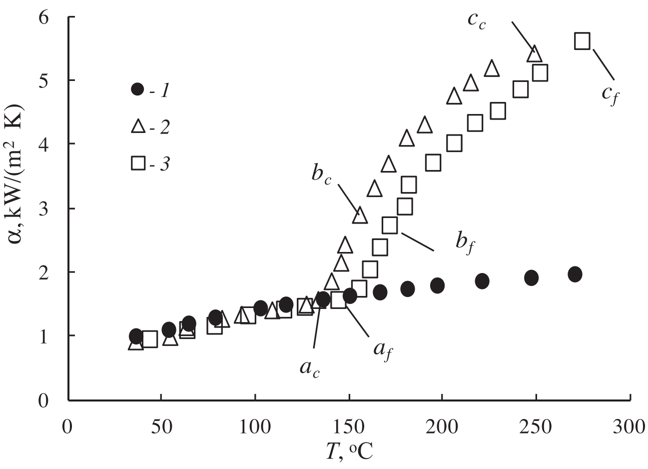

Fig. 1. Dependence of the heat-transfer coefficient α on the heater temperature T at convective heat transfer and nucleate boiling on a horizontal platinum wire. T_0 = 16 °C: 1 – VO-1C oil; 2 – coarse-grained water/(VO-1C oil) emulsion; 3 – fine-grained water/(VO-1C oil) emulsion with concentration C = 1.0 vol.%. The letters designate pictures in Fig. 2.

With a further increase in the heat flow density q [1,3], which is observed with increasing temperature head ΔT, the number of vapor bubbles at the heating surface increases, but their tear-off size decreases. This is connected with the amplification of the emulsion convective streams near vapor bubbles, which contributes to an earlier detachment of vapor bubbles (bubbles with smaller tear-off diameters).

In a water/(VO-1C oil) emulsion one more mechanism is intensified, which contributes to the detachment of vapor bubbles from the wire. This is explosive boiling-up of disperse-phase droplets at the surface and in the wall (thermal) boundary layer of the wire. The explosive boiling-up of superheated disperse-phase droplets may be determined by the arising characteristic sound clicks. Disperse-phase droplets that boil up explosively turbulize the wall layer, which consists of a heated emulsion (Fig. 2, photographs c_f and c_c). A contribution to the heat-transfer intensity is also made by large vapor bubbles, which in separating from the heating surface (Fig. 3) carry along the heated boundary layer of the emulsion, whose place is occupied by a new portion of the emulsion, with new disperse-phase droplets, which have not yet boiled up. These droplets get hot and boil up. Such a character of heat transfer is observed up to the onset of an emulsion-boiling crisis.

In the investigations conducted it has been found that fine-grained emulsions boil up at higher temperatures than coarse-grained ones. During poorly developed boiling, when single disperse-phase droplets boil up at boiling sites located at the heating surface, the volume of the forming vapor in a coarse-grained emulsion is larger than that of a fine-grained emulsion. At intense boiling along with large adherent vapor bubbles one can observe explosive boiling-up of superheated disperse-phase droplets between them. The shock waves [8] that arise during the explosive boiling of every disperse-phase droplet make vapor bubbles that have not reached critical sizes break away from the heating surface.

2.2. Boiling in a pipe

To investigate heat exchange in a pipe, use was made of an experimental setup, whose scheme is given in Fig. 4 [9]. The temperature of the emulsion was maintained with the help of a thermostat *10* with an error +0.05 °C, and it was pumped through a measuring pipe *14* located horizontally with a prescribed flow rate G. In the experiments we also measured the temperature at the inlet and outlet of the measuring pipe *14*, determined the variations in temperature along the measuring pipe with the help of