International Journal of Thermal Sciences 116 (2017) 214–223

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

The experimental study of nanofluids boiling crisis on cylindrical heaters

A.V. Minakov [a, b, c, *], M.I. Pryazhnikov [a, b, c], D.V. Guzei [a, c], G.M. Zeer [a], V. Ya. Rudyak [c]

[a] Siberian Federal University, Krasnoyarsk, Russia
[b] Kutateladze Institute of Thermophysics, SB RAS, Novosibirsk, Russia
[c] Novosibirsk State University of Architecture and Civil Engineering, Russia

ARTICLE INFO

Article history:
Received 22 April 2016
Received in revised form
26 January 2017
Accepted 27 February 2017

Keywords:
Nanofluid
Nanoparticles
Boiling crisis
Critical heat flux (CHF)
Deposition of nanoparticles
Heater surface microstructure

ABSTRACT

The paper deals with the experimental study of nanofluids boiling on cylindrical heater. The studied nanofluids were prepared on the basis of distilled water and nanoparticles of silicon, aluminum and iron oxides as well as diamond. The volume concentration of nanoparticles varied from 0.05 to 1%. The nanoparticles diameter ranged from 10 to 100 nm, the diameter of the heater was varied from 0.1 to 0.3 mm. It is revealed that the use of nanofluids provides a several-fold increase of the critical heat flux. However, critical heat flux in nanofluids depends on the material and size of nanoparticles as well as on the diameter of used cylindrical heater. It is shown that the critical heat flux increases with increasing the nanoparticles size, while it decreases with increasing the heater diameter. It was revealed for the first time that the critical heat flux depends on the boiling process duration.

1. Introduction

Boiling, as one of the most effective and efficient ways of heat transfer, is used in various engineering applications. Therefore, the enhancement of the critical heat flux in boiling has been the subject of numerous studies carried out in the last century [1–4].

An intensive research on the possible use of nanofluids in boiling-related applications has started just recently. Apparently, works [5,6] should be considered as the first investigations of nanofluids boiling heat transfer and crisis. The first work dealt with the boiling of water-based silicon dioxide and aluminum oxide nanofluids on a square heater with a characteristic size of 10 mm. The authors observed a sharp increase in the critical heat flux (CHF) caused by the presence of nanoparticles. At the pressure of about 0.198 bar, the increase in CHF reached more than 200% when using water-based Al_2O_3 nanofluid with nanoparticle concentration of $5 \cdot 10^{-4}$ wt%. It was also noted that the supplement of nanoparticles to water increases the size of bubbles, though reduces the frequency of their detachment. It is unclear, however, how these changes are related to the observed increase in CHF.

In Ref. [6], a nucleate pool boiling was studied on the surface of cylindrical heating element 20 mm in diameter in the water-based alumina nanofluid. Contrary to work [5], it was shown that the presence of nanoparticles degrades the boiling characteristics (heat transfer coefficient), and this deterioration increases with increasing nanoparticle concentration. A similar phenomenon was observed in a later study [7], where smaller heaters with an outer diameter ranged from 4.5 to 6 mm were used. The authors explained the deterioration in heat transfer by the changes of heaters surface characteristics. They claim that during boiling of nanofluids, the surface became smoother due to the deposition of nanoparticles at the nucleation sites. The higher the concentration, the smoother the surface, which in turn leads to a greater reduction of heat transfer coefficient.

This explanation is not consistent with observations [8], concerned with the study of water-based alumina nanofluids boiling on a square surface with the characteristic size of 100 mm at high heat fluxes. It was revealed that after boiling, the surface roughness increased with increasing the nanoparticle concentration.

Vassallo et al. [9] studied boiling of water-based silicon dioxide nanofluid on the horizontal nickel-chromium wire with a diameter of 0.4 mm at atmospheric pressure. Similar to work [5], a two-fold increase in CHF was observed.

* Corresponding author. Siberian Federal University, Krasnoyarsk, Russia.
E-mail address: Aminakov@sfu-kras.ru (A.V. Minakov).

http://dx.doi.org/10.1016/j.ijthermalsci.2017.02.019
1290-0729/

Tu et al. [10] conducted boiling experiments in water-based alumina nanofluid in a relatively large volume with rectangular heating surface of 26 × 40 mm^2 at atmospheric pressure. A significant increase in both heat transfer and CHF was obtained in the nucleate boiling mode. For example, compared to pure water boiling, an increase in heat transfer coefficient by more than 60% was recorded while investigating highly diluted aqueous nanofluids. A significant reduction in the maximum wall temperature of the heater as well as a four-fold increase in the number of active bubble nucleation sites was found in comparison with pure water boiling.

The boiling heat transfer in water-based nanofluid with gold nanoparticles was studied in Ref. [11]. A significant increase in heat transfer coefficient was found during boiling at atmospheric pressure on the heater with the diameter of 100 mm. In particular, the authors managed to increase the heat transfer coefficient of nanofluid containing 0.001 wt % of gold nanoparticles by 21% at the heat flux of 45 kW/m^2. The increase in boiling heat transfer coefficient was also accompanied by the growth of critical heat flux with increasing nanoparticle concentration.

Most researchers observe the deposition of nanoparticles on the heater surface in the course of boiling. Apparently [12], was the first work, where the increase in CHF was explained by the presence of nanoparticles depositions (see also [13]). It was shown that the wettability of heater surface covered by deposited nanoparticles was much higher than that of a pure surface. The key role of nanoparticles deposition on the heater surface in the boiling crisis and the effect of surface wettability on the CHF were also observed in the later works [14–28].

The effect of nanoparticle concentration on CHF has been studied well enough to date. It is revealed that in most cases, increasing concentration of nanoparticles increases CHF, though in some cases there was a decrease in CHF at high concentrations of nanoparticles [15]. In addition, the effect of heater surface area on the CHF was observed in Refs. [17,18]. It is shown in Ref. [18] that increasing the size of the heater slows down the enhancement of CHF in nanofluids. The effect of pressure on CHF was studied in Ref. [19], where it was revealed that the gain in CHF the value due to use of nanofluids instead of pure fluids decreases with the increase of pressure.

The data on the effect of particle size on CHF are rather contradictory. Thus, Moreno et al. [20] claimed that CHF does not depend on the size of alumina nanoparticles within the particle size range from 69 to 346 nm. Similar conclusions were made in Ref. [21]. At the same time, it was found in Ref. [15] that CHF decreases with increasing particle size in nanofluids containing silver particles. On the contrary, in Refs. [22,23] it was shown that CHF increases with increasing particles size.

In many studies, it was observed that the effect of increased CHF was retained even in boiling of pure fluids on the heaters covered by nanoparticles [18,24,25]. Among the recent works, we should note theoretical papers and surveys [26–29], which are dealing with detail consideration of various mechanisms leading to enhancement of CHF in boiling nanofluids. However, the decisive conclusions on these mechanisms have not yet been made.

Thus, despite a large number of experimental data, they are quite contradictory and do not allow comprehending clearly the mechanisms of CHF variations in the boiling process of nanofluids. In order to remove at least some of these contradictions, this paper provides with the systematic experimental study of saturated pool boiling of nanofluids on a cylindrical heater. Our main objective is to understand the dependence of CHF on the nanoparticle size and material, heat diameter, and nanoparticles deposition on its surface.

2. Description of the experimental setup

The scheme of experimental setup is presented in Fig. 1. The studied fluid in amount of 300 ml was placed in a high sealed glass flask (4) with the diameter of 8 cm. A nickel-chromium wire heater with the length $L = 34$ mm and the diameter $d_h = 0.2$ mm was emerged into the flask filled with fluid. The wire was fixed by copper bus leads with the cross section of 10 × 2 mm to supply voltage. The heater was energized by means of GPS-6030D power source. The applied voltage was recorded using a GDM-78261 voltmeter ("V" in Fig. 1). Load amperage in the circuit was measured by the APPA–109N ammeter ("A" in Fig. 1). The flask with the test fluid was sealed, so that the condensate formed in the upper part of the flask dripped back into the flask, maintaining saturation conditions in the working chamber. The fluid temperature in the flask was controlled by means of a chromel-copel thermocouple, which was connected to the TRM-200 temperature meter (5). The tail end of the thermocouple was located at the same level with the nickel-chromium heater at a distance of 2 cm from it.

The flask with the test fluid was placed in a water bath (3) with the constant temperature, which was about 0.5 °C below the boiling point and maintained by means of electric heater (2). Thus, in this paper we investigate the boiling close to saturation conditions. The temperature control in a water bath was conducted using another chromel-copel thermocouple connected to the TRM-200 m. After placing the flask into a water bath, the temperatures in the flask and water bath equalized with time. Then the nickel-chromium heater was energized, and the heat flux density was measured. The programmable current power supply allowed increasing the heater voltage with a fixed predetermined step. Thus, it was possible to control the heat flux growth rate and, thereby, to fix the onset of boiling crisis.

The boiling heat flux density on the heater was determined by the ratio: $q = Q/S = IU/S$, where $S = \Pi dL$ is the lateral surface area of the heater between the current-carrying wires, Q is the heat flux released by the heater, I is the electric current in the heater circuit,

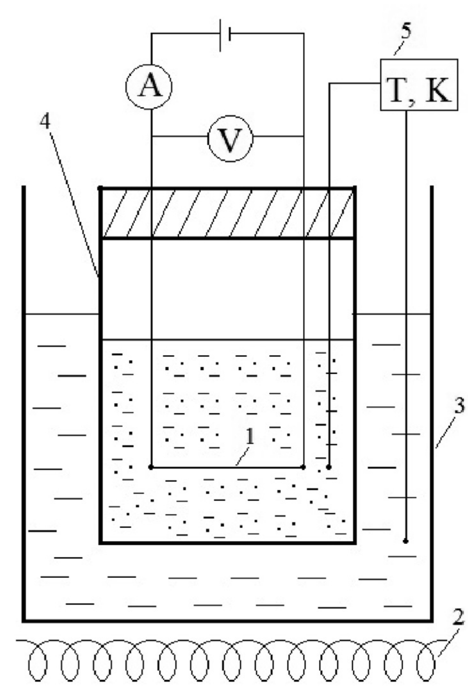

Fig. 1. The scheme of experimental setup.