Experimental investigation of surfactants adding effect on the value of the critical heat flux during pool boiling of nanofluids

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Abstract. The influence of different surfactants on the pool boiling of water and water-based nanofluid was experimentally investigated. The concentrations of xanthan gum and polyacrylamide, which were used as surfactants, were varied from 10 mg/l to 200 mg/l. The concentration of silicon dioxide nanoparticles of 25 nm diameter was equal to 0.1 vol. %. The dependences of the value of the critical heat flux on the concentrations of the surfactants were obtained as a result of the experiments. It was shown, that both xanthan gum and polyacrylamide increase the critical heat flux. The increase in critical heat flux value for water with polyacrylamide relative to the clear water was 61%, and for water with xanthan gum was 32%. The increase in critical heat flux values for nanofluids with polyacrylamide and with xanthan gum relative to the nanofluids without surfactants were 36% and 13%, respectively, and relative to clear water were 263% and 200%, respectively.

1. Introduction

In various engineering applications boiling is used as one of the most effective and efficient ways of heat transfer. Therefore, the enhancement of the boiling critical heat flux was the subject of numerous studies [1-4]. An intensive research of the possible use of nanofluids in boiling-related applications has started just recently. Apparently, first investigations of nanofluids boiling heat transfer and crisis were carried out in [5, 6]. The boiling of water-based silicon dioxide and aluminum oxide nanofluids on a square heater with a characteristic size of 10 mm was investigated in the first research work. The authors observed a sharp increase in the critical heat flux (CHF) caused by the presence of nanoparticles. The increase in CHF reached more than 200% for water-based Al₂O₃ nanofluid with nanoparticle concentration of 5·10⁻⁴ wt.% at the pressure of about 0.198 Bar relative to the clear water. It was also noted that the nanoparticles increase the size of bubbles, though reduce the frequency of their detachment. It is unclear, however, how these changes are related to the observed increase in CHF. A nucleate pool boiling of the water-based aluminium oxide nanofluid on the surface of cylindrical heating element of 20 mm in diameter was studied in [6]. Contrary to [5], it was shown that the presence of nanoparticles degrades the boiling characteristics (heat transfer coefficient), and this deterioration increases with increasing nanoparticles 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 characteristics of heater surfaces. It was stated that during boiling of nanofluids, the surface became smoother due to the deposition of nanoparticles at the nucleation sites. As the concentration increases, the surface becomes

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[The rest of the text continues as per the given context.]
smoother, which in turn leads to a greater reduction of heat transfer coefficient. This explanation is not consistent with observations of [8], concerning 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.

Most researchers observed the deposition of nanoparticles on the heater surface in the course of boiling. Apparently, the increase in CHF was first explained by the presence of nanoparticles depositions in [9] (see also [10]). 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 [11–18]. The effect of nanoparticle concentration on CHF has been studied well enough to date. It is revealed that in most cases, the growing concentration of nanoparticles increases CHF, though in some cases there was a decrease in CHF at high concentrations of nanoparticles [12]. In addition, the effect of heater surface area on the CHF was observed in [13, 14]. It was shown in [14] that increasing the size of the heater slowed down the enhancement of CHF in nanofluids. The data on the particle size effect on CHF are rather contradictory. Thus, it was shown in [15] 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 [16]. At the same time, it was found in [12] that CHF decreases with increasing particle size in nanofluids containing silver particles. On the contrary, in [17, 18] it was shown that CHF increases with increasing particles size. It was observed in many studies that the effect of increased CHF was retained even in boiling of pure fluids on the heaters covered by nanoparticles [14, 19, 20].

Different methods are used to obtain constant thermophysical properties of nanofluids. One way to increase their colloidal stability is applying the surfactants. However, the effect of the presence of surfactant on the value of CHF during boiling of both nanofluids and base clear fluids has not been practically investigated. It was mentioned only in few research works [21, 22] that deal with such phenomena.

Thus, the effect of adding high-molecular polymers, such as xanthan gum and polyacrylamide, as surfactants on the values of critical heat flux during pool boiling of distilled water and water-based nanofluids with silicon dioxide nanoparticles is experimentally investigated in this research work. The main objective is to understand the dependence of CHF on the used surfactants and their concentrations.

2. Experimental apparatus and procedures
The experimental investigation of pool boiling was carried out on a facility, described in detail in [17,23,24]. The studied fluid was placed in a high sealed glass flask with the diameter of 8 cm. A nickel-chromium wire heater was emerged into the flask filled with fluid. The wire was fixed by copper bus leads to supply voltage. 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 flask with the test fluid was placed in a water bath with constant temperature. Thus, boiling close to saturation conditions was investigated in this paper. 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 to fix the onset of boiling crisis.

The boiling heat flux density on the heater was determined as: \( q = \frac{Q}{S} = \frac{IU}{S} \), 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, and \( U \) is the voltage drop in the heater. Heat generated at the lead wires was negligible. The surface temperature of the heater was determined by the dependence of the heater resistance on temperature. Total errors in determining the heat flux density and the surface temperature were about 2% and 3%, respectively.
The nanofluids were prepared based on distilled water and nanoparticles of silicon dioxide. The volume concentration of nanoparticles with mean diameter of 25 nm was equal to 0.1 vol. %. For preparation of nanofluids we used the standard two-step process. After adding the necessary quantity of nanopowder to water, the obtained nanofluid was first thoroughly mixed mechanically. After that, it was placed in an ultrasonic disperser for half an hour to destruct the particles conglomerates. The nanopowder was received from “Plazmoterm” company. The xanthan gum and polyacrylamide were used as surfactants, and their concentrations were varied from 10 mg/l to 200 mg/l.

3. Results and discussion
The dependences of critical heat flux during boiling of distilled water and nanofluid on the concentrations of xanthan gum and polyacrylamide were obtained as a result of conducted experiments. It was found that the presence of surfactants increased the CHF in both cases. In particular, the critical heat flux value of water with polyacrylamide showed a 1.61 times increase relative to clear water, at the same time the value of critical heat flux of water with xanthan gum showed a 1.32 times increase. It may be seen in figure 1a, showing the dependences of relative critical heat flux on the concentration of different surfactants in the water solutions. The increase in critical heat flux values of nanofluids with polyacrylamide and with xanthan gum relative to the nanofluids without surfactants were 36% and 13%, respectively. It can be seen in figure 1b with the same dependences as in figure 1a, but for nanofluids. Moreover, as one can see in figures 1a, 1b, those dependences are non-linear in nature: as the surfactants’ concentration increases, the relative critical heat fluxes increase too, until the concentration reaches the value of about 50 mg/l, and after that the relative critical fluxes slightly decrease. On the other hand, if taking into account the enhancement of the critical heat flux of nanofluids compared to the base fluid (distilled water in our case), the relative critical heat fluxes reach significantly high values. It was found that the CHF values of nanofluids with polyacrylamide and with xanthan gum show 3.7 times and 3 times increase relative to clear water.

Besides, the difference in occurring processes due to the presence of surfactants can be visually observed in the experiments. Specifically, the vapour bubbles in the distilled water are much larger than in the water-surfactant solutions. That leads to the fact that the heat flux densities, at which the boiling crisis occurs, are some higher for water-surfactant solutions. This is clearly seen in figure 2 with experimental photos of distilled water (upper pictures) and water-polyacrylamide solution (lower pictures) boiling process. The concentration of the surfactant was equal to 200 mg/l. The heat flux densities were of about 0.8 MW/m$^2$ (figures 2a, 2d), 1.2 MW/m$^2$ (figures 2b, 2e) and 1.6 MW/m$^2$.

![Figure 1. Dependences of the values of critical heat flux on the concentration of different surfactants: in water solutions (a) relative to the values of critical heat flux for clear water; in nanofluid solutions relative to the values of critical heat flux for nanofluid without surfactants (b) and to the values of critical heat flux for clear water (c).](image-url)
Figure 2. Experimental photos of distilled water at heat flux densities of about 0.8 MW/m² (a), 1.2 MW/m² (b) and 1.6 MW/m² (c), and photos of water-polyacrylamide solution at heat flux densities of about 0.8 MW/m² (d), 1.2 MW/m² (e) and 1.6 MW/m² (f).

(figures 2c, 2f). As one can see, the boiling crisis already occurs for distilled water at 1.2 MW/m², and for water-polyacrylamide solution only at 1.6 MW/m². As discussed in many works, the presence of surfactants decreases the contact angle of wetting [25-27], so the vapour bubbles become much smaller and, consequently, the area of contact between the heater surface and the bubbles reduces. The phenomenon leads to the fact that the value of heat flux density, at which the vapour film forms from vapour bubbles near the heater surface, is much higher in such solutions relative to the clear water. This behaviour (increase of critical heat flux with decreasing contact angle) corresponds to the Kandlikar equation [28].

Most of the mentioned research works observed the deposition of nanoparticles on the heater surface in the course of boiling. Such phenomenon is considered in the experiments, conducted in this work. To prove it, the microphoto of the heater surface was taken. Figure 3 shows the heater surface after boiling of SiO₂-water nanofluid without surfactants.

As can be seen the nanoparticles have deposited on the heater, forming the capillary-porous-like coating on its surface. The influence of capillary-porous coatings on the heat transfer and crisis phenomena at pool boiling of fluids was experimentally investigated in [29, 30]. It was shown, that such structure modification of heater surface significantly enhanced the heat transfer at water pool boiling due to a significant increase in the nucleation site density. The enhancement of the critical heat flux value at nanofluid boiling can be explained in the same way. The presence of surfactant is found

Figure 3. Microphoto on the heater surface after boiling in SiO₂-water nanofluid.
to significantly change the form and structure of the heater surfaces with deposited nanoparticles after boiling of water and SiO$_2$-water nanofluid with both xanthan gum and polyacrylamide surfactants. The most interesting result is that in most cases (except nanofluid + polyacrylamide case) the heater surface was smoother at the highest concentration of both surfactants. That fact can explain the decrease in values of critical heat fluxes, shown in figures 1a, 1b. On the other hand, for “nanofluid + 200 mg/l of polyacrylamide” case the heater surface was rougher, then for lower concentrations. But, at the same time, the deposited nanoparticles covered the heater and doubled its diameter that caused a slight decrease in the value of the critical heat flux. So, it is hypothesized that at pool boiling of nanofluid with surfactant there are two mechanisms that enhance the CHT value: decrease the contact angle of wetting and increase the nucleation site density. But, in addition, further experimental investigations of the influence of the contact angle of wetting and nucleation site density are necessary to be conducted to confirm that hypothesis. Such investigations will be carried out in future.

4. Conclusions
The experimental investigations of the influence of different surfactants on the pool boiling of water and water-based SiO$_2$-nanofluid were carried out. The concentration of silicon dioxide nanoparticles of 25 nm diameter was equal to 0.1 vol. %. The xanthan gum and polyacrylamide were used as surfactants. Their concentrations were varied from 10 mg/l to 200 mg/l. The dependences of the value of the critical heat flux on the concentrations of the surfactants were obtained as a result of the experiments. It has been found that the critical heat flux value for water with polyacrylamide increases 1.61 times relative to clear water, and for water with xanthan gum it increases 1.32 times. The critical heat flux values for nanofluid with polyacrylamide and with xanthan gum increases relative to the nanofluids without surfactants 1.36 times and 1.13 times, respectively. The same values, but relative to clear water were 3.7 times and 3 times higher. It is shown the influence of the material of surfactants on the values of critical heat fluxes, namely, the polyacrylamide, shows higher enhancement in both distilled water and nanofluid. Moreover, significant changes in the form and structure of the heater surfaces have been found.

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