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 is used boiling, 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 Al_2O_3 nanofluid with nanoparticle concentration of $5 \cdot 10^{-4}$ wt.% at the pressure of about 0.198 Bar relative to the clear water. It was also noted that the nanoparticles 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. 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 heaters surface characteristics. They claim 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 smoother, 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.

Most researchers observe 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, increasing 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 is shown in [14] that increasing the size of the heater slows down the enhancement of CHF in nanofluids. The data of 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 to obtain constant thermophysical properties of nanofluids are used. One way to increase their colloidal stability is applying the surfactants. However, the effect of presence of the surfactant on the value of CHF during boiling both nanofluids and base clear fluids was almost not investigated. It can be mentioned only couple researches [21, 22], that deal with such phenomena.

Thus, experimental investigation of the effect of adding high-molecular polymers, such 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 was carried out in this research work. The main objective is to understand the dependence of CHF on the using surfactants and their concentrations.

2. Experimental apparatus and procedures

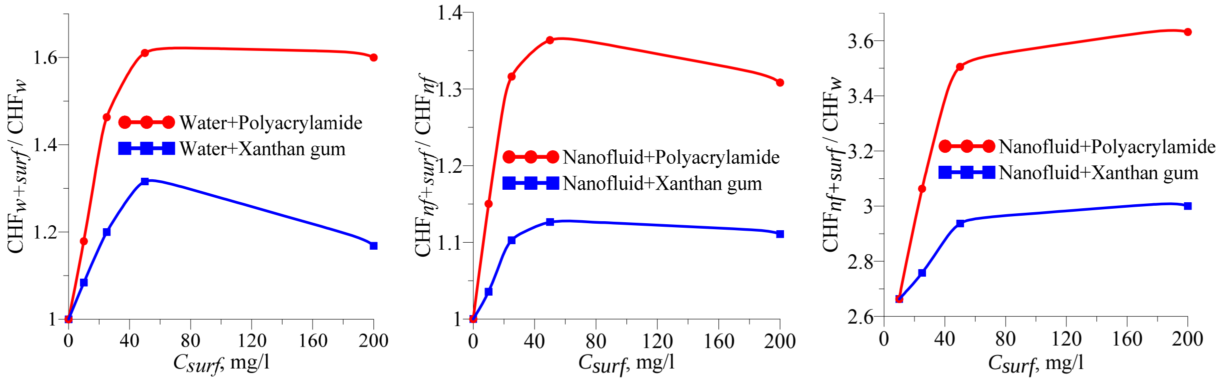
The experimental investigation of pool boiling was carried out on a facility, which was described in detail in [17,23,24]. The studied fluid was placed in a high sealed glass flask with the diameter of 8 cm. A nickel-chromium wire heater was emerged into the flask filled with fluid. The wire was fixed 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 the constant temperature. Thus, the boiling close to saturation conditions was investigate 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: $q = Q/S = IU/S$, 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, 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 the 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, their were concentrations were varied from 10 mg/l to 200 mg/l.

3. Results and discussion

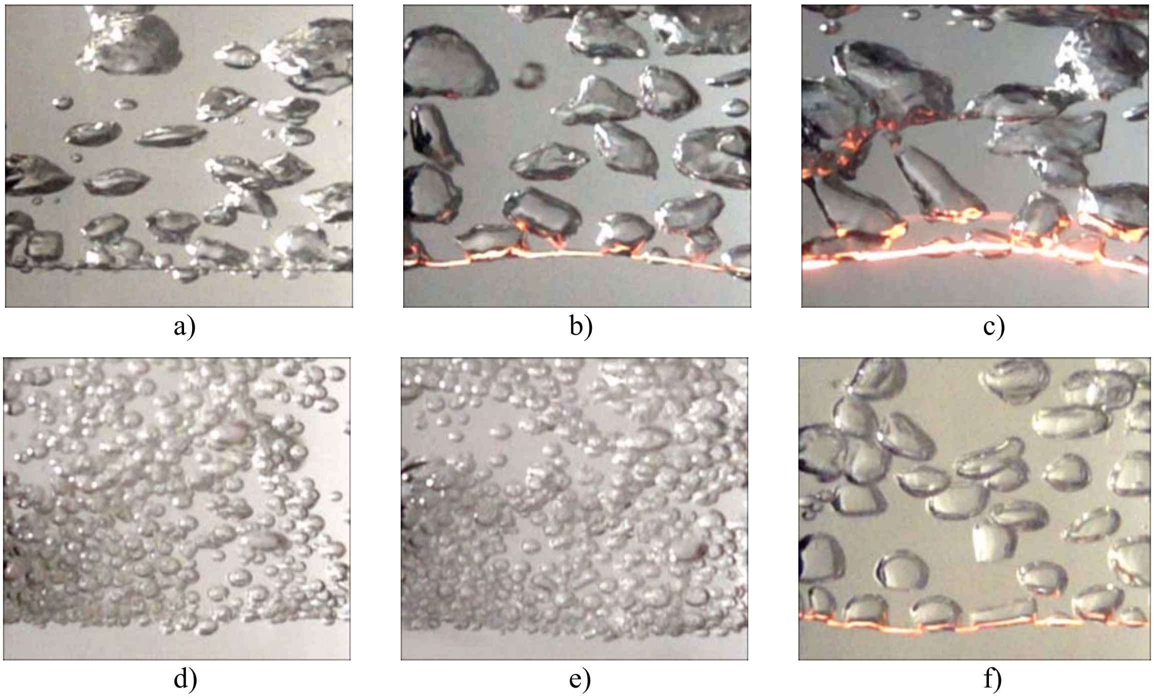
The dependences of critical heat flux during boiling distilled water and nanofluid on the concentrations of xanthan gum and polyacrylamide were obtained as a result of conducted experiments. It was found that presence of the surfactants increased the CHF in both cases. In particular, the critical heat flux value of water with polyacrylamide shown 1.61 times increase relative to the clear water, at the same time the value of critical heat flux of water with xanthan gum shown 1.32 times increase. It can be seen in Fig. 1a, which represented the dependences of relative critical heat flux on the concentration of the 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 Fig. 1b, which represented the same dependencies as in Fig. 1a, but for nanofluids. Moreover, as one can see in Figs. 1a,1b, those dependencies 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 value of the critical heat flux of nanofluids compare 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 shown 3.7 times and 3 times increase relative to the clear water, respectively. It can be seen in Fig. 1c. Those dependencies are non-linear in nature too.



a) b) c)

Figure 1. The dependences of the values of critical heat flux on the concentration of the different surfactants: in the 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)

Besides, the difference in occurring processes due to the presence of surfactants can be visually observed in the experiments. Specifically, the vapor bubbles in the distilled water are much bigger then in the water-surfactant solutions, as well the heat flux densities, at which the boiling crisis occurs, for water-surfactant solutions are some higher. This is clearly seen in Fig. 2, where represented the 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 (Figs. 2a,2d), 1.2 MW/m^2 (Figs. 2b,2e) and 1.6 MW/m^2 (Figs. 2c,2f). As one can see, the boiling crisis already occurs for distilled water at 1.2 MW/m^2, and for water-polyacrylamide solution only at 1.6 MW/m^2. 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. That phenomenon leads to the fact that the value of heat flux density, at which the vapour film forms from vapour babbles near the heater surface, is much higher in such solutions relative to the clear water. Such behaviour according to Kandlikar equation [28], that shown increase in critical heat flux with a decrease in contact angle.


a) b) c)

d) e) f)

Figure 2. The experimental photos of distilled water at the heat flux densities of about 0.8 MW/m^2 (a), 1.2 MW/m^2 (b) and 1.6 MW/m^2 (c), and photos of water-polyacrylamide solution at the heat flux densities of about 0.8 MW/m^2 (d), 1.2 MW/m^2 (e) and 1.6 MW/m^2 (f)

As mentioned above in most research works was observed the deposition of nanoparticles on the heater surface in the course of boiling. Such phenomenon will has to take place in the experiments, conducted in this work. To proof that statement the microphoto of the heater surface were taken. In Fig. 3 is shown the heater surface after course of boiling of SiO_2-water nanofluid without surfactants.

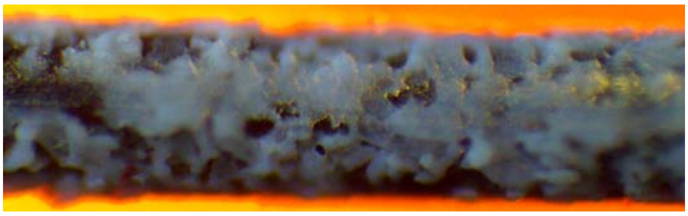


Figure 3. The microphoto on the heater surface after boiling in SiO_2-water nanofluid

As can be seen, the nanoparticles significantly 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 in that works, 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. It was found, that the presence of surfactant significantly changes form and structure of the heater surfaces with deposited nanoparticles after course of 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 highest concentration of both surfactants. That fact can explain the decrease in the values of the critical heat fluxes, shown in Figs. 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 slight decrease in the value of the critical heat flux for that case. So, it has been hypothesized that at pool boiling of nanofluid with surfactant there are two mechanisms that enhanced the CHT value: decrease in the contact angle of wetting and increase in the nucleation site density. But, in addition, the 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 was found that the critical heat flux value for water with polyacrylamide increased for 1.61 times relative to the clear water, and for water with xanthan gum that value increased for 1.32 times. The critical heat flux values for nanoflud with polyacrylamide and with xanthan gum increased relative to the nanofluids without surfactants for 1.36 times and 1.13 times, respectively. The same values, but relative to the clear water were 3.7 times and 3 times higher, respectively. Also it was shown the influence of the material of the surfactants on the values of the critical heat fluxes, namely, the polyacrylamide shown higher enhance of that values in both distilled water and nanofluid. Moreover, it was found significant changes in form and structure of the heater surfaces.

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