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REVIEW OF THE INFLUENCE OF NANOFLUIDS ON THE NUCLEATE POOL BOILING

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Abstract. *This paper mainly focuses on the experimental studies reported in the literature on the pool boiling phenomena using nanofluids as the working fluid. An analysis on contradictory data provided by researchers for the HTC behavior is carried out. Also, the heat transfer mechanisms pointed in the literature as responsible for the heat transfer behaviors are compared. The main cause of the HTC and the CHF modification is the nanoparticle deposition on the heating surface: for CHF cases, the nanoparticles deposition can improve the wettability of the heating surface and, for the HTC cases, the nanoparticles deposition generates a porous layer on the heating surface that leads to a change in the surface roughness and in the number of micro-cavities Therefore, the nanofluid pool boiling heat transfer is strongly affected by the relative size between nanoparticles suspended in the base fluid and the heating surface geometry and, their interactions.*

Keywords: *Nanofluids, nucleate pool boiling, heat transfer coefficient, critical heat flux, heat transfer mechanism*.

1. INTRODUCTION

In the last years, nanofluids have been extensively investigated because of their significant effect on the critical heat flux and pool boiling characteristics, due to nanoscale structures deposited on the heating surface. Researchers generally agree with the idea of a critical heat flux (CHF) enhancement, despite existing differences among the experimental results. The same cannot be said for the heat transfer coefficient (HTC), because the mechanism for HTC enhancement or degradation is not fully understood. Therefore, the main question nowadays regarding nanofluid pool boiling heat transfer mechanisms is whether they increase or decrease the HTC in comparison with base fluid boiling alone.

The enhancement of nucleate boiling using passive techniques has been an interesting challenge for researchers looking for industrial applications, particularly in microelectronics, which combines miniaturization with a volume restriction for the cooling liquid (Souza *et al.*, 2014). The passive heat transfer enhancement can be done by changing flow geometry, boundary conditions or by improving thermophysical properties of the working fluid, for example, increasing its thermal conductivity by adding small solid particles. Nanofluids are colloidal suspensions of nanoparticles, with the diameter in a range from 1 to 100 nm, in a base fluid such as water, light oils, ethylene glycol or a refrigerant. These nanoparticles can be metallic (Cu, Au) or metal oxides (Al2O3, TiO2, ZrO2), carbon (diamond, nanotubes) or another material (Barber *et al*., 2010). According to Gonzalez (2013), these nanofluids are a promising way of enhancing heat transfer due to increasing the base fluid properties, such as thermal conductivity.

In 1995, Choi introduced the term “Nanofluids” reporting a theoretical study of suspended copper nanoparticles in a base fluid. The interaction between the high thermal conductivity of the nanoparticles and the base fluid provided an increase in the thermal conductivity of the mixture (nanofluid) and also increased the critical heat flux (CHF) for pool boiling applications.

Yang and Maa (1984) conducted the first experimental study involving nanofluids boiling, using suspended alumina particles (50 nm, 300 nm and 1000 nm) at low concentrations (0.1 and 0.5 wt.%). They demonstrated that nanoparticles of alumina dispersed in water, with different concentrations, can significantly lower the superheat needed for a given flux, leading to an enhancement in the heat transfer coefficient (HTC).

You *et al*. (2003) observed CHF enhancement of 200% using alumina nanofluid compared to pure water, while no change for the HTC in pool boiling was found. In addition, they noted that there was an optimal concentration (<0.01 g/l) where no more CHF enhancement occurred. However, they could not explain the CHF enhancement and the optimal concentration.

Several studies were published in the beginning of this century in order to determine the effect of nanofluids on the heat transfer coefficient. Some significant the HTC enhancement has been reported (Wen and Ding, 2005; Liu *et al*., 2007; Kedzierski, 2009; Park and Jung, 2007) but in contrast, some studies also reported the HTC deterioration (Das *et al*., 2003; Bang and Chang, 2005; Kim and Kim, 2007). Both the HTC and the CHF behaviors may be attributed, mainly, to changes in the surface wettability caused by the nanoparticle deposition. In this case, the nanolayer formed on the heating surface increases the wettability, which makes the rewetting process much easier and explains, in part, the high CHF values. A decrease in the contact angle can also partially explain a reduction in the HTC, since the frequency of active sites and bubble departure tends to decrease.

This paper mainly focuses on the experimental studies reported in the literature on the pool boiling using nanofluids as the working fluid. An analysis on contradictory results provided by researchers for the heat transfer coefficient (HTC) behavior are carried out, and the mechanisms pointed in the literature as responsible for the heat transfer behaviors are also compared.

2. POOL BOILING USING NANOFLUIDS

2.1 Influence on the HTC

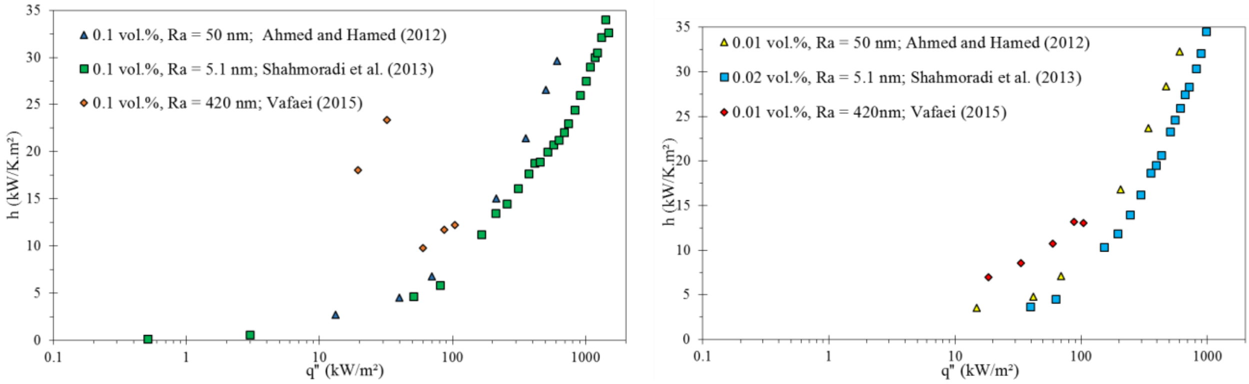
In the last five years, the thermal behavior of alumina nanoparticles dispersed in pure water (Al_2O_3-water) has been extensively used as a nanofluid on pool boiling studies. Kwark *et al*. (2010) used alumina nanoparticles, with particle size of around 139 nm diameter, dispersed into deionized water for studying the effect of low concentrations of nanofluid in nucleate pool boiling. The nanofluid concentration varied from 0.001 g/l to 1 g/l, and stabilized the nanoparticle solution in ultrasonic bath for 2 h. The heating surface consisted of a square copper block of 10 mm × 10 mm and the tests were performed by increasing heat flux until the CHF is reached. No change was reported in the HTC for 0.001 g/l to 0.025 g/l nanofluid concentrations compared to pure water. A decrease in the HTC was observed for nanofluid concentration in a range from 0.01 g/l to 1 g/l.

Ahmed and Hamed (2012) also carried out experiments for nucleate pool boiling using Al_2O_3 - deionized water with three different nanofluid concentration: 0.01, 0.1 and 0.5 vol.%. The alumina nanoparticles (40-50 nm) were added to deionized water and placed in an ultrasonic bath for 5 h. The heating surface consisted of a copper block of 25.4 mm diameter and 71 mm length, with the surface roughness (R_a) equal to 50 nm. The experimental procedure was similar to the Kwark *et al*. (2010), with the heat flux varying from 15 kW/m^2 to 600 kW/m^2 during the experiment, corresponding to the nucleate boiling regime. The results for nanofluid concentration of 0.01 vol.% showed a HTC enhancement of around 35% in comparison to the pure water. In contrast, for 0.1 vol.% nanofluid the HTC value was similar to that for pure water and, for 0.5 vol.% nanofluid the HTC showed a deterioration of around 45%.

Shahmoradi *et al*. (2013) also used alumina water based nanofluid in five concentrations (0.001, 0.002, 0.02, 0.05 and 0.1 vol.%) for studying the nanofluid boiling heat transfer behavior and the effect of surface characteristics on the HTC and the CHF. The alumina nanoparticles with average diameter of 40 nm were dispersed into distilled water and then placed in ultrasonic bath alternating with a mechanical mixer up for 3 h. The heating surface consisted of a copper block of 38 mm diameter with surface roughness (R_a) equal to 5.1 nm measured before each test. According to Shahmoradi *et al*. (2013), the HTC decreased by adding alumina nanoparticles in pure water (for concentrations higher than 0.001 vol.%) and it becomes higher as the nanoparticle concentration increases. For very low nanofluid concentration, such as 0.001 vol.%, changes in the HTC were not significant.

Recently, Vafaei (2015) studied the effect of suspended and deposited nanoparticles on pool boiling heat transfer using as nanofluid solution α-Al_2O_3 – deionized water, with three low concentrations 0.001, 0.01 and 0.1 vol.%. The heating surface consisted of a copper plate of 20mm × 20mm, with average surface roughness of 25 nm (smooth surface) and 420 nm (rough surface), and the nanoparticle sizes varied between 20 –150 nm. The highest heat flux applied was 105 kW/m^2. According to the author, the HTC increased for smooth surface and for 0.001 vol.% nanofluid in comparison to the pure water. On the other hand, the HTC decreased for rough surface and for 0.001 vol.% and 0.01 vol.% nanofluid compared to the pure water. For 0.1 vol.% nanofluid and for rough surface, the HTC increased about 140% compared to pure water for very low heat flux values (< 30 kW/m^2), and for high heat fluxes, the same HTC behavior of pure water was observed.

Figures 1a and 1b show the influence of nanofluid concentration and surface roughness on the HTC, based on experimental data obtained from the literature for Al_2O_3 – deionized water (Ahmed and Hamed, 2012; Shahmoradi *et al*., 2013; Vafaei, 2015). For 0.1 vol.% and 0.01 vol.% nanofluid, the HTC increased as surface roughness increased, for heat fluxes higher than 150 kW/m². For 0.1 vol.% and for heat fluxes less than 100 kW/m² the influence of surface roughness was not observed on the HTC. However, increasing the heat flux the effects of surface roughness are noticeable on the HTC. This behavior could be due to nanolayer formed on the heating surface during nanolfuid pool boiling. For smooth surfaces (R_a = 5.1 nm), the deposited nanolayer increases the thermal resistance while for rough surfaces (R_a = 50 nm), the nanoparticles deposition increases the number of micro-cavities, leading to a HTC enhancement.



(a) (b)

Figure 1 – Influence of nanofluid concentration and surface roughness on the HTC, for Al_2O_3 – water, for (a) 0.1 vol.% nanofluid and for (b) 0.01 vol.% nanofluid.

Sarafraz and Hormozi (2015) carried out experiments using copper oxide nanoparticles and pure water as base fluid to analyze the effect of nanoparticles on the HTC. Nanofluid was prepared in four concentrations: 0.1, 0.2, 0.3 and 0.4 wt.%, with and without surfactant SDS. For surfactant mixture was added 0.1 wt.% of SDS in the nanofluid. The experimental setup and procedure was the same that Sarafraz and Hormozi (2014), with surface roughness of R_a = 340 nm. The HTC for nanofluid without surfactant were significantly lower than that for pure water. The highest decrease in the HTC was 28%, for 0.4 wt.% concentration. In contrast, the nanofluid with 0.1wt.% of surfactant SDS showed the highest HTC (up to 70 % for 0.4 wt.% of SDS).

Nanofluids with other base fluids, such as ethylene glycol, have been studied in this decade. Raveshi *et al*. (2013) used Al_2O_3 nanoparticles dispersed in ethylene glycol as the base fluid. These authors combined ethylene glycol with water (mixture of water and ethylene glycol by equal volume concentration, WEG50). They also added a surfactant, sodium dodecyl benzene sulfonate (SDBS), for improving the solution stability. The nanofluids concentrations were 0.05, 0.1, 0.25, 0.5, 0.75 and 1 vol.% with SDBS. A cooper plate with 40 mm diameter was used as the heating surface and its roughness, measured before each experiment, was R_a = 200 nm. Raveshi *et al*. (2013) reported an enhancement on the HTC for all nanofluids concentrations in comparison to WEG50. The optimum concentration was 0.75 % nanofluid as well as the maximum increment was 64% for low heat fluxes and 45% for high heat fluxes.

Recently, Sarafraz and Hormozi (2014) used Al_2O_3 nanoparticles (average size 45 nm) dispersed in ethylene glycol as base fluid. They performed tests with different nanofluid concentrations of 0.03, 0.05 and 0.08 vol.%. The heating surface used was a 316A stainless steel cylinder with 21 mm diameter and 105 mm length, and roughness (R_a) equal to 54 nm. The authors observed deterioration in the HTC for all nanofluid concentrations as compared to water, and this behavior was more noticeable as the nanofluid concentration increased.

The effect of Al_2O_3 - R141b nanofluid on the HTC was studied by Tang *et al*. (2014). The nanofluid concentrations were equal to 0.001, 0.01 and 0.1 vol.%, with and without the surfactant SDBS. The number of molecules of the SDBS added in the solution was equal to the nanoparticles. A copper block with a rectangular surface of 20 × 20 mm^2, with a surface roughness controlled by #2000 emery paper, was used as heating surface. The authors reported that the presence of nanoparticles improved the pool boiling heat transfer characteristics of R141b at concentrations of 0.01 vol.% and 0.1 vol.% with surfactant SDBS. However, for 0.1 vol.% concentration without the surfactant SDBS occurred a HTC deterioration of around 70% due to the nanoparticles deposition on the heated surface. Figure 2 shows a comparison of the experimental results for the HTC obtained by the authors described above, taking into account different base fluids and nanofluids concentration. This figure reports the best results, for different conditions, found by Sarafraz and Hormozi (2014), Raveshi *et al*. (2013) and Tang *et al*. (2014).

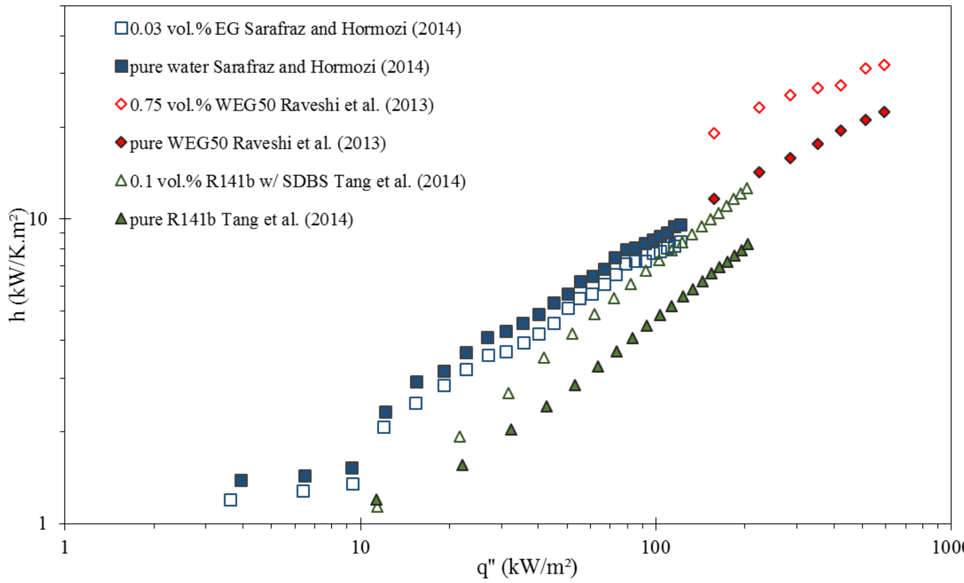


Figure 2 – Comparison of the experimental results for HTC obtained from literature, for different base fluids.

2.2 Influence on the CHF

Kwark *et al*. (2010) also studied the CHF effect in Al_2O_3-water nanofluid. They reported an enhancement in the CHF value as nanofluid concentration increased, reaching a maximum value of 2000 kW/m^2 for 0.025 g/l. As a result, the authors reported the existence of an optimum nanofluid concentration for which both the CHF and the HTC is maximum.

In order to study the effect of nanoparticles on the CHF, Kathiravan *et al*. (2010) used copper nanoparticles (average size of 10 - 20 nm) dispersed in water as base fluid, with and without sodium lauryl sulphate anionic surfactant (SDS). Nanofluid was prepared in 0.25, 0.5 and 1 wt.% concentration, with and without 9 wt.% of SDS. The nanoparticles were weighted and dispersed into distilled water and then placed in an ultrasonic bath for 10 h. The test section consisted of an emery polished square stainless steel surface of 30 × 30 mm^2 and 0.44 mm thickness, with roughness of R_a = 167 nm. The CHF was found to be higher for nanofluid without surfactant SDS when compared to the pure water. For distilled water with 9% SDS and for all nanofluid concentrations with 9% SDS, the CHF was lower than pure water and Cu-water nanofluid.

Kole and Dey (2012) used ZnO nanoparticles (average size of 30 - 40 nm) with ethylene glycol as base fluid, in order to study the pool boiling characteristics and CHF of ZnO-EG nanofluids. The nanofluid was prepared in five concentrations: 0.35, 0.62, 0.93, 1.6 and 2.6 vol.%. The nanoparticles were dispersed into distilled water and then placed in ultrasonic bath for more than 60 hours. The authors used two different heating surfaces: for measuring the HTC, it was used a cooper cylinder with 15 mm diameter and roughness equal to R_a = 90 nm. After the boiling experiment, it was used a constantan wire to measure the CHF. Kole and Dey (2012) reported an increase of 22% in the HTC for 1.6 vol.% nanofluid concentration. However, further increase in ZnO nanoparticles deteriorated the boiling heat transfer. The CHF increased for all nanofluid concentrations, reaching a maximum enhancement of 117% for 2.6% vol.% nanofluid concentration.

Lee *et al*. (2012) studied the effect of magnetite - water nanofluid, with different concentrations of 0.0001, 0.001 and 0.01 vol.% without surfactant, on the CHF. Another two types of nanoparticles (alumina and titanium) were prepared for the pool boiling CHF experiments using the same concentrations of magnetite. The heating surface was a horizontal Ni-Cr wire with 0.4 mm diameter and 100 mm length. The CHF was calculated using the data obtained immediately before the sharp increase of the Ni–Cr wire resistance. According to Lee *et al*. (2012), the CHF increased for all cases, however the CHF for magnetite – water nanofluid showed the highest value among the evaluated nanofluids. The authors emphasized the importance of the surface wettability and the surface tension as parameters responsible for CHF enhancement.

Shahmoradi *et al*. (2013) also determined the CHF in the final phase of experiment that determined the HTC (previous section). The authors determined the CHF when the surface temperature increased rapidly .The authors showed a CHF enhancement by adding nanoparticles into the base fluid. According to them, this enhancement is due to the fact that the precipitation of the suspended nanoparticles on the heating surface form a porous layer, which leads to an increase in the surface wettability. Figure 3 presents the CHF ratio of the nanofluids versus the nanofluid concentration, for the authors described above.

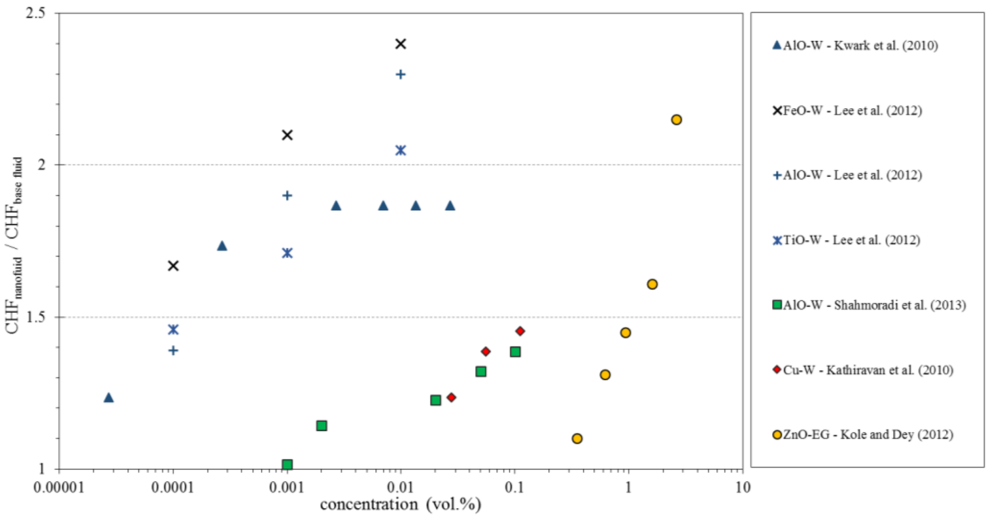


Figure 3 – CHF ratio of the nanofluids versus the nanoparticle concentration (Kwark *et al*., 2010; Shahmoradi *et al*., 2013; Kathiravan *et al*., 2010; Kole and Dey, 2012; Lee *et al*., 2012).

The CHF increases as nanofluid concentration increases. According to the authors, the nanoparticle deposition on the heating surface increases as nanofluid concentration increases, leading to an improvement in the surface wettability. Kwark et al. (2010) reported a critical layer condition, corresponding to the maximum limit of the wetting surface, reflected by a constant CHF value for AlO – water nanofluid. Additional nanoparticle layers increase the coating thickness but do not change the wetting characteristics of the heating surface. Figure 3 shows different CHF values for the same nanofluid concentration (AlO – water). This divergence could be explained by the ratio of heating surface roughness to nanoparticle diameter, since the extreme variation in boiling parameters cannot be explained only by the changes of the thermophysical properties of nanofluid (Shahmoradi *et al*., 2013).

Table 1 shows a summary of the studies cited above. The CHF enhancement was found by all authors, but, as mentioned previously, there some divergences concerning the effect of nanofluids on the HTC.

Table 1 - Literature review of some of existing nanofluid heat transfer experimental studies, in the last five years.

Authors	**Nanofluid characteristic**	**Surface material and roughness**	**CHF effect**	**HTC effect**	**Surface roughness after boiling**
Kwark *et al.* (2010)	Alumina (139 nm) in water	Copper plate	enhancement	Unchanged / deterioration	not reported
Kathiravan *et al*. (2010)	Copper (20 nm) in water with and without surfactant (SDS)	Stainless steel plate R_a = 167 nm	enhancement (without SDS) deterioration (with SDS)	deterioration	decreased
Ahmed and Hamed (2012)	Alumina (40 nm) in water	Copper plate R_a = 50 nm	-	enhancement / deterioration	increased
Lee *et al.* (2012)	Magnetite (25 nm), Alumina (40 - 80 nm) and Titanium (15 nm) in water	Ni-Cr wire	enhancement	-	not reported
Kole and Dey (2012)	Zinc oxide (30 - 40 nm) in ethylene glycol	Copper plate R_a = 90 nm	enhancement	enhancement	increased
Raveshi *et al.* (2013)	Alumina (20 - 30 nm) in water or ethylene glycol with surfactant (SDBS)	Copper plate R_a = 200 nm	-	enhancement	not reported

Authors	Nanofluid characteristic	Surface material and roughness	CHF effect	HTC effect	Surface roughness after boiling
Shahmoradi *et al*. (2013)	Alumina (40 nm) in water	Copper plate R_a = 5.1 nm	enhancement	deterioration	increased
Sarafraz and Hormozi (2014)	Alumina (45 - 50 nm) in ethylene glycol	Stainless steel cylinder R_a = 54 nm	-	deterioration	decreased
Tang *et al*. (2014)	Alumina (20 - 200 nm) in R141b with and without surfactant (SDBS)	Copper plate	-	enhancement (with SDBS) deterioration (without SDBS)	not reported
Vafaei (2015)	Alumina (20 - 150 nm) in water	Copper plate R_a = 25 nm and R_a = 420 nm	-	Enhancement / deterioration / unchanged	increased for R_a = 25 nm decreased for R_a = 420 nm
Sarafraz and Hormozi (2015)	Copper oxide (50 nm) in water with and without surfactant (SDS)	Stainless steel cylinder R_a = 340 nm	-	enhancement (with SDS) deterioration (without SDS)	decreased

3. NANOFLUID POOL BOILING HEAT TRANSFER MECHANISMS

All authors observed that the nanoparticles deposition onto the heating surface during nanofluid pool boiling was the main cause of changes in the HTC and CHF. The coated layer formed by the deposited nanoparticles onto the surface provides a barrier to heat transfer and reduces the bubble creation which may lead to a reduction in the number of micro-cavities and an increase in the thermal resistance of the surface (Sarafraz and Hormozi, 2014; Kwark *et al.*, 2010; Sarafraz and Hormozi, 2015; Kole and Dey; 2012; Kathiravan *et al*., 2010; Ahmed and Hamed, 2012). When the ratio of heating surface roughness on to nanoparticle diameter is much lower than 1 (R_a/d_p << 1), the number of nucleation sites or micro-cavities greatly decreases. Shahmoradi *et al*. (2013) reported that the sedimentation of nanoparticles onto the heating surface, for $R_a/d_p \ll 1$, increase the resistance of nanolayer and, also, an adds thermal resistance due to the blocked vapor inside the gaps between the micro-cavities (Fig. 4), resulting in a HTC deterioration.

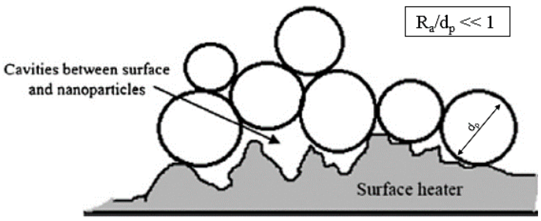


Figure 4 – Mechanism of nanoparticles deposition on heating surface, for $R_a/d_p \ll 1$, according to Shahmoradi *et al*. (2013).

Regarding the HTC enhancement, Raveshi *et al*. (2013), and Kole and Dey (2012) used $R_a/d_p > 1$ and reported that the nanolayer formed on the boiling surface can increase the active nucleation site density, by splitting a single nucleation site into multiple ones**,** leading to the enhancement of the nucleate pool boiling heat transfer (Fig. 5a). In contrast, according to Vafaei (2015), deposited nanoparticles are more effective to enhance the boiling HTC by increasing the roughness of smooth surfaces, i.e., when $R_a/d_p < 1$ (Fig. 5b), and less effective to change the HTC on surfaces with higher roughness ($R_a/d_p >> 1$) (Fig. 5c).

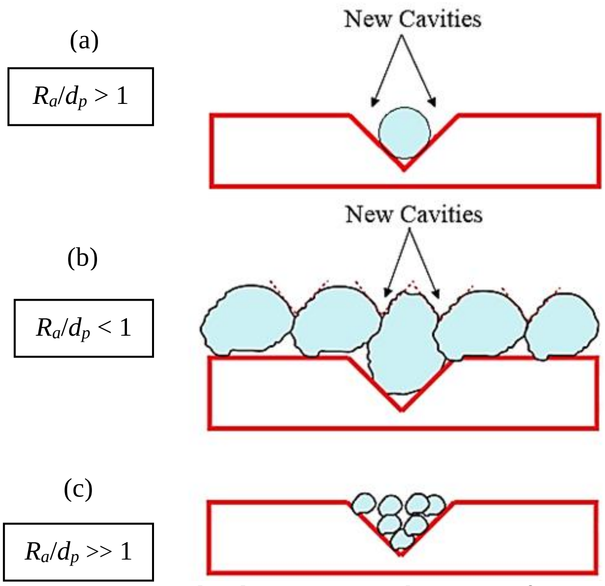


Figure 5 – Nanoparticles deposition onto heating surface (Vafaei, 2015).
a) Nanoparticle diameter is lower than surface roughness. b) Nanoparticle diameter is bigger than surface roughness. c) Nanoparticle diameter is much lower than surface roughness.

Ahmed and Hamed (2012) showed that the interaction between surface roughness and the nanolayer formed by nanoparticles deposition depends on the nanofluids concentration. Nanoparticles deposition occurred at a slower rate for low nanofluids concentration (0.01 vol.%) resulting in an enhancement in the boiling HTC. According to authors, this enhancement is due to the effect of the thermal conductivity of nanofluids being more dominant than the effect of the nanoparticle deposition on the surface.

In order to avoid the nanoparticle deposition and to improve the solution stability, Tang *et al*. (2014) performed boiling experiments with Al2O3 - R141b, at concentrations of 0.001 vol.%, 0.01 vol.% and 0.1 vol.% with and without surfactant SDBS. According to them, the presence of surfactant increased the HTC at higher particle concentrations (0.01 vol.% and 0.1 vol.% concentrations) because the surfactant strongly reduces the nanoparticles deposition.

The observed CHF enhancement was explained by the change in the wettability of the heating surface after nanoparticles deposition during the nucleate boiling. In the other words, that porous layer improves the wettability of the surface considerably, observed by a significant reduction of the static contact angle (Kwark *et al*., 2010; Kathiravan *et al*., 2010; Kole and Dey, 2012; Shahmoradi *et al*., 2013; Lee *et al*., 2012).

4. CONCLUSION

All the studies cited in this paper showed that the use of nanofluids can significantly enhance the pool boiling CHF. However, the literature is still in conflict over whether nanoparticles can enhance or degrade boiling heat transfer, as presented in Tab. 1. The main cause of the HTC and the CHF modification is the nanoparticle deposition on the heating surface. For CHF cases, the nanoparticles deposition can improve the wettability of the heating surface, allowing the liquid located near the surface to rewet the hot spots and to cool the heating surface. This rewetting capability enhances the CHF of the nanofluids. For the HTC cases, the nanoparticles deposition generates a porous layer on the heating surface that leads to a change in the surface roughness and in the number of micro-cavities. The researchers who reported an enhancement in the HTC also reported that surface roughness increased and vice-versa. Therefore, the nanofluid pool boiling heat transfer is strongly affected by the relative size between nanoparticles suspended in the base fluid and the heating surface geometry and, their interactions. A study focusing on these interactions and the bubble growth dynamic in nanofluids is required to fully understand the nanofluid boiling phenomena.

5. ACKNOWLEDGEMENTS

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