NANOSTRUCTURED SURFACE EFFECTS ON POOL BOILING DEVICES

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ABSTRACT
In recent years, the research community has been studying the addition of nanoparticles to working fluids of heat transfer devices. These efforts stem from an expected enhancement on boiling heat transfer with nanofluids. However, the mechanisms involved are not well understood yet. Some authors attribute the decrease of heat transfer coefficient and Critical Heat Flux increase to a nanostructured surface formed by the deposition of nanoparticles. This study presents results about the boiling heat transfer coefficient and critical heat flux of water on smooth and oxidized copper surfaces caused by Alumina nanoparticles deposition. The wettability of copper surfaces with deposited nanoparticles of maghemite are also analyzed and compared with copper surfaces with deposited Alumina nanoparticles.

1. INTRODUTION

Nucleate boiling regime can be considered one of the most effective ways to make viable a great amount of heat exchange in a relatively small area. The limit of the nucleate boiling is characterized by the Critical Heat Flux, CHF, and it occurs when the liquid film under the bubbles evaporates completely, Carey [1]. When this limit of heat flux is attained, for a wall heating system with controlled heat flux, the melting of the heating surface can occurs.

Scientific community has, in the past few years, been concerned to understand the effects of a promising interaction between high thermal conductivity nanoparticles and a base fluid, the nanofluids, first presented by Yang and Maa [2]. This nanoparticles: metals, metal oxides or allotrope of carbons, diluted in base fluid, have for purpose enhance heat transfer properties of the fluid and currently are being employed in different research areas such as: heat transfer, tribology, pharmaceutical, pollution cleaning, medical, among others.

The main question about nanofluid pool boiling heat transfer mechanisms is if it can enhance or reduce the heat transfer coefficient compared with the boiling of the base fluid. Liu et al [3], Wen and Ding [4] and Tu and Dinh [5] studied boiling heat transfer of Cu-H_2O, TiO_2-H_2O and Al_2O_3-H_2O nanofluids, respectively, and showed the enhancement of the heat transfer coefficient. Bang and Chang [6] and Jackson and Bryan [7] studied the nucleate boiling of Al_2O_3-H_2O_3 and Au/H_2O, respectively, and showed the deterioration of the heat transfer. Moreover, Kim et al [8] noticed no big differences between the nucleate boiling heat transfer coefficient for the base fluid alone and with nanoparticles.

On the other hand, authors agree with the idea of a CHF enhancement, despite the existing percentage differences among the results, Golubovic et al. [9], Truong et al. [10], Forrest et al. [11], Taylor and Phelan [12], Kim et al. [13-15], Liu et al. [3], Bang et al. [16] and Vassalo et al. [17].

Both heat transfer coefficient and Critical Heat Flux variations may be attributed, mainly, to surface´s wettability change, caused by nanoparticles deposition. In this case, a new nanostructed surface increases its wettability, which makes rewet process much easier and explain, in parts, high CHF values. Contact angle decrease can also partially explain heat transfer coefficient reduction, since frequency of active sites and bubbles' departure tends to decrease. Golubovic et al. [9] observed an increase of CHF in tests with Al_2O_3 and attributed it to wettability´s change. It is interesting to notice that they obtained similar results without cleaning nanoparticles deposition and using water as work fluid.

Forrest et al. [11]tested surface´s nanostructuring with SiO_2. Hydrophobic, hydrophilic and super hydrophilic surfaces were created and pool boiling tests with water revealed CHF enhancement in all surfaces. They suggested also that it is a mistake not to consider the contact angle effect on the CHF, as it is the case in Zuber´s and Kutateladze´s correlations. By their study, the advancing and receding contact angles must be considered in CHF correlations. Low receding angle may be the reason for CHF increasing even in the hydrophobic surface, which a contradictory result is obtained if only the static contact angle is considered.

Results may also vary according to experimental set-ups, base fluids and nanoparticles. For example, ethanol and acetone, for their low boiling point, should be interesting alternatives instead of water as base fluids, since would make easier to control fluid temperature and achieve CHF without taking the risk of burnout of the test device. However, as shown by Coursey and Kim [18] ethanol is a wetting liquid, with low contact angle, and nanoparticles deposition in this case doesn't seems to increase wettability in order to substantially change the CHF values. So, it might be reasonable to assume that nanoparticles deposition effects decrease as low as base fluid's contact angle is.

For its low price, the facility to handle and obtain, and usually interesting results obtained, AL_2O_3 is the most used nanoparticle in pool boiling tests. For these reasons, AL_2O_3 combined with water is the nanofluid used in this article, which has the purpose to present CHF results and fully understand wettablity's influency over the heat transfer mechanisms. The contact angle of Fe_2O_3 deposition on copper surface was also measured.

2. EXPERIMENTAL FACILITIES

2.1 Experimental Set-up

Experimental set up consists of a 160x150x5mm square acrylic box, surrounding a glass cylinder with 100mm diameter, 150mm height and 10mm thickness, Fig.1. Both cube and cylinder are fixed by two plates of 316 stainless steel with dimensions 200x200x17mm and sealed by rubber gloves. The region between the tube and the acrylic box is filled with water flow which temperature is controlled by a digital cryostat. A coil condenser, located at the upper part of the inside boiling chamber, with controlled temperature water by a second cryostat, serves to condense the vapor and to maintain the pressure inside the boiling chamber.

Inside the boiling chamber, at the bottom, is mounted the test section, Fig. 2. It consists of a copper bloc with 12mm in the upper diameter and is thermal insulated by Teflon and glass wool. Two electrical resistances, cartridge type, with nominal resistance of 83 Ω are able to dissipate up to 500W to the test section.

Surface, fluid and vapor temperatures are measured by using five thermocouples T-type, three in the cooper section; and two inside the tube, one in Teflon surface and other above work fluid.

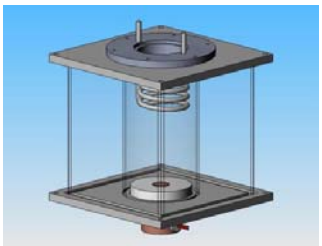

Figure 1 – Transparent boiling chamber with the heater and the cooling units.

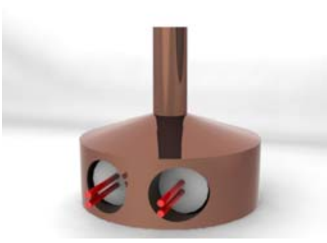

Figure 2 - Heated part without the teflon cover. The top is discerned to the to the bottom of the chamber of Fig. 1.

2.2 Nanofluid preparation

As mentioned above, nucleate boiling of water with 1% weight of alumina nanoparticles (Al_2O_3), Fig. 3, were tested in this study. The comparison tests made were between this nanofluid and distilled water. According to Bang and Chang [6] Al_2O_3-Water forms stable, uniform and continuous suspensions in water, without being charged chemically. Das et. al. [19] analyzed the possibility of using cooper oxide (CuO) nanoparticles, however, despite of their high thermal conductivity these nanoparticles become explosive at 100°C.

Stabilization of nanoparticles and base fluid was obtained by an ultrasonic bath for four hours. Surfactant could have been an alternative way to prevent agglomeration of nanoparticles, but this unknown influence over the boiling properties has become a considerable obstacle.

Nanofluid's properties are calculated using correlations reported by Bang and Chang [6] and Coursey an Kim [18]. Similar values for the density, surface tension, thermal conductivity (máx. variation - 3%) between nanofluid and base fluid were obtained.

Table 1 - Al_2O_3 Properties

Purity	99.5%
Structure	Alpha-hexagonal
Bulk density (Apparent)	0.3–0.5 g/cc
Bulk density (Actual)	3.88 g/cc
Surface Area	10–20 m^2/g
Size	80-100 nm
Morphology	Spherical

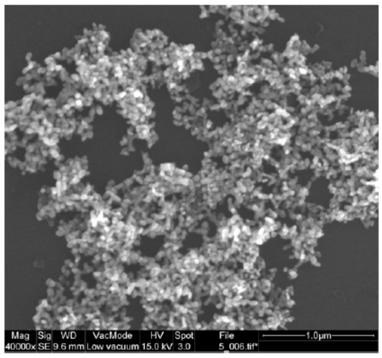

Figure 3 – Tunnel-Electron-Microscopy of nanoparticles of Al_2O_3

3. RESULTS

3.1 Pool boiling experiment

Four partial boiling curves were obtained: two with sub-cooled distilled water at 30 and 80ºC, and two with sub-cooled nanofluid at the same temperatures.

Figure 4 shows that the addition of nanoparticles in water shifts the curves to the right that indicates the decrease of the heat flux coefficient (h). Even the CHF was not attained for theses cases with nanoparticles, it is shown that the trend is the increasing of the CHF. Equivalent result it is shown for distilled atmospheric water at 30^{o}C. Because the limitations of the condenser area of the serpentine it was impossible to overcome the CHF. It is clear, also, an increase of the heat transfer coefficient for water at 30 and 80ºC and the very small difference between the curves for water at 30 and 80^{o}C, as reported by Carey [1].

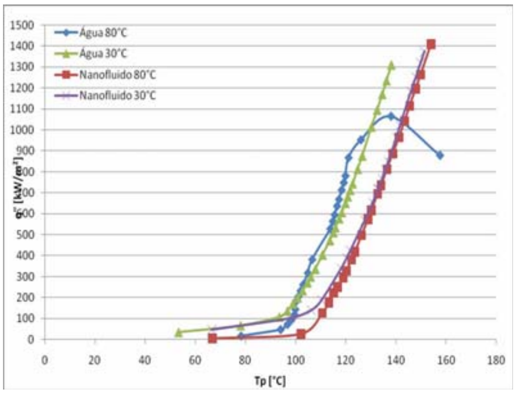

Figure 4 – Partial boiling curves for Al_2O_3.

3.2 Surface characterization

Figure 5 shows the state of the heating surface, with high surface oxidation of copper, after nucleate boiling tests of water with Alumina nanoparticles, obtained in LEPTEN by Coelho et al. [20]. Surface´s roughness measurement, conducted with profilometer Perthometer S8P 4:51 (sensor point diamond with a 60 ° angle and radius of 3 μm) and the results of average roughness (Ra), root mean square roughness (Rq) and the total roughness (Rt), which is basically difference between the highest peak and major depression, are presented in Table 2. As expected by visual analysis, there was an increase in roughness of the heating surface after tests with nanofluid.

(a) (b)

Figure 5 – Images from: a) the heating surface and b) the serpentine condenser, after boiling experiments

The next step was metallography analysis of surface before and after test with nanofluid. Figures 6 and 7 show pictures that confirm the modification of the surface structure of the heating surface after pool boiling with nanofluid, corroborating the idea that deposited nanoparticles can nanostructure the surface.

At last, wettabillity tests had to be done. For this particular analysis, due to difficult in measuring contact angle in small area, four samples of copper plates with 150mm diameter were made. A smooth surface, a rough surface and two more

Table 2- Roughness of test section before and after experiment.

	Before experiment			Avarege
Ra (μm)	0.04	0.10	0.09	0.08
Rt (μm)	0.45	1.06	1.56	1.02
Rq (μm)	0.05	0.20	0.19	0.15
R (μm)	0.33	0.47	0.64	0.48
	After experiment			Avarege
Ra (μm)	0.33	0.36	0.24	0.31
Rt (μm)	2.59	6.41	2.14	3.71
Rq (μm)	0.43	0.57	0.14	0.44
R (μm)	1.91	1.13	1.25	1.43

nanostructured, with alumina alpha (α - Al_2O_3) and maghemite (γ - Fe_2O_3), surfaces. Special manufactured surfaces were prepared in a separate set-up consisting of a boiling vessel in which specimen could be immersed in boiling water. Interesting was the fact that maghemite's nanoparticles, even after cleaning, were still adhered to the surface. Alumina alpha had an opposite behavior. Roughness measurements were also conducted in these samples and the results are presented in Table 3.

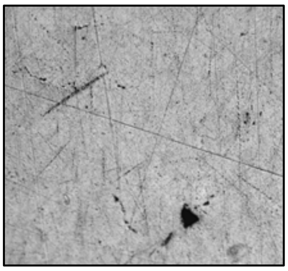

Figure 6 – Metallographic analysis before experiment. View 100x.

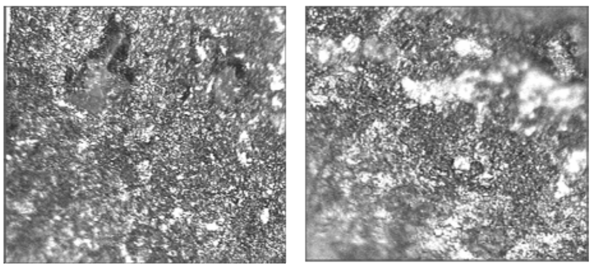

Figure 7 – Metallography analysis after experiment. View 100x onthe left and 200x on the right.

As expected, nanostructured surfaces exhibited hydrophilic behavior, while rough and smooth surfaces values were neutral (near 90º). Roughness, in principle, can increase wettability in hidrophilic surfaces and decrease in hidrofobic. Apparently contact angle's similar values in smooth and rough surfaces were because of smooth surface neutral behavior. After cleaning, alumina's nanostructured surface contact angle increased near smooth and rough surfaces values, while maghemite's surface continued hydrophobic, but with a contact angle increase, as is summarized in Fig. 8.

Table 3 – Roughness of the copper plates smooth, rough and after deposition of nanoparticles.

Roughness (μm)	Clean Surface	Rough Surface	Al_2O_3 deposited surface	Fe_2O_3 deposited surface
Ra	0.04	0.84	3.78	3.90
Rq	0.06	1.05	4.66	6.09
Rt	0.37	5.25	19.54	32.80
Ry	0.37	5.25	19.54	32.80
Rz	0.37	5.25	19.54	32.80

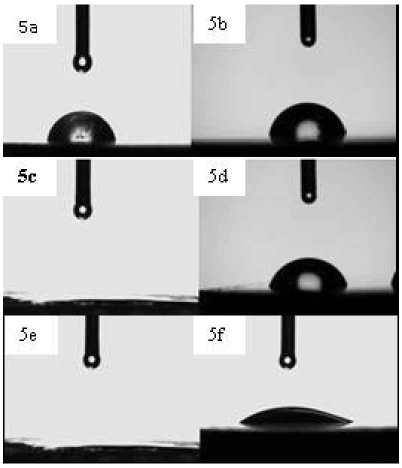

Figure 8: Contact angles for: a) clean surface, b) rough surface, c-) Alumina deposited surface, d-) Alumina deposited surface after excess removal, e-) Maghemite deposited surface, f-) Maghemite deposited surface after excess removal

4. DISCUSSION

Boiling literature is generally deficient in explaining CHF enhancement mechanism using nanofluids. Even after several decades of intense study, simple questions about boiling such as bubble's departure and CHF mechanism haven't a consensual explanation, so, it's hard to understand nanofluid's effect if there are still a lot of doubts about boiling mechanism.

To explain CHF mechanism authors have been usually considering at least one of four famous theories: hydrodynamic instability theory, macrolayer dryout theory, hot/dry spot theory and bubble interaction theory. However, none of these theories considers wettability's effects for CHF, which contradicts test results with nanofluid as working fluid, once there is no properties change that could allow such enhancement of CHF.

Reduction in contact angle and wettability's increase obtained for both alumina and maghemite may suggest changes in nucleate boiling departure mechanism and also in frequency and size of starting radius of bubbles. One good hypothesis is that surface becomes continuously wet in consequence of contact angle changes, making possible to achieve higher values of critical heat flux. Moreover, to explain heat transfer degradation, the argument that density of active nucleation sites is reduced may be used, once formation energy (W *) of active sites consider contact angle values, as expressed below, [21]:

$$W^* = \frac{16\pi\sigma^3}{3(p_v - p_l)^2}\Psi(\theta) = W_H^*\Psi(\theta) \tag{1}$$

with:

$$\Psi(\theta) = (1+\cos\theta)^2 \frac{(2-\cos\theta)}{4}, \quad \Psi(\theta) \le 1 \tag{2}$$

The function Ψ (θ) is equal to the unit when the contact angle of liquid-surface interaction is zero, that means that the liquid wetts completely the surface.

According to Eq. (1), higher wettability demands higher energy to form and activate nucleation sites. Soaked surfaces would hinder formation of nucleation sites, reducing heat transfer by nucleate boiling.

Another interesting observation is the affinity between deposited nanoparticles and heating surface materials. When copper section was completely covered with nanoparticles of alumina or maghemite, contact angle was zero (completely wet). However, when removing excess with sandpaper, alumina deposition almost completely disappeared, while maghemite deposition continued partially adhered. Adhesion between maghemita and copper is better than between alumina and copper.

5. CONCLUSION

The following conclusions can be drawn from this study:

- During the nucleate boiling regime nanoparticles can be deposited on the heater surface.
- Deposition of nanoparticles modifies the surface characteristics on the heating surface, in the case of alumina-copper and maghemita-copper increasing the wettability.
- Changes in surface properties can affect CHF and heat transfer of boiling mechanism.
- Higher wettability induces a CHF enhacement and heat transfer degradation.
- Affinity between the nanoparticles and heating surface materials determine the modification degree of the heat transfer coefficient.

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