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## **EFFECT OF POOL BOILING USING $Al_2O_3$ -WATER AND $Fe_2O_3$ -WATER NANOFUIDS ON HEAT TRANSFER**

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**Abstract:** Several studies on pool boiling with addition of nanofluids have been carried out in recent years. Due to their unusual behavior in different situations, authors sometimes present conflicting results. However, critical heat flux (CHF) enhancement is always observed. This article consists of an analysis of pool boiling with  $\alpha-Al_2O_3$ -water and  $Fe_2O_3$ -water and the effects on heat transfer properties. The experimental setup consists of an environment with controlled temperature, atmospheric pressure and a horizontal copper heated surface as the test section. Results showed a decrease in the heat transfer coefficient followed by an increase in the CHF. Nanoparticle deposition on the test section surface seems to be the reason for this behavior, since wettability changes on the surface were observed.

**Keywords:** *Pool Boiling, Nanofluid, Critical Heat Flux.*

### **1. INTRODUCTION**

The nucleate boiling regime can be considered one of the most effective ways to obtain a great amount of heat exchange in a relatively small area. The limit of nucleate boiling is characterized by the critical heat flux (CHF), and occurs when the liquid film under the bubbles evaporates completely, Carey (1992). When this limit of heat flux is reached, for a wall heating system with controlled heat flux, the heated surface can suddenly melt.

The scientific community has, in the past few years, been concerned with understanding the effects of the promising interaction between high thermal conductivity nanoparticles and a base fluid, the nanofluids, first presented by Choi (1995). These nanoparticles of metals, metal oxides or allotropes of carbons, diluted in base fluid, are used to enhance the heat transfer properties of a fluid and are currently being employed in different research areas, such as heat transfer, tribology, pharmaceutical, pollution remediation, and medical, among others.

Authors generally agree with the idea of a CHF enhancement, despite the existing percentage differences among the results. The same cannot be said for the heat transfer coefficient (HTC). Therefore, the main question nowadays regarding nanofluid pool boiling heat transfer mechanisms is whether these increase or decrease the HTC in comparison with base fluid boiling alone. Liu et al. (2007), Wen and Ding (2005), and Tu and Dinh (2004) studied boiling heat transfer of Cu-H<sub>2</sub>O, TiO<sub>2</sub>-H<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O nanofluids, respectively, and noted an increase in the heat transfer coefficient. Bang and Chang (2004), and Jackson and Bryan (2007) studied the nucleate boiling of Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O and Au/H<sub>2</sub>O, and showed a reduction in the heat transfer. Moreover, Kim et al. (2004, 2006 and 2007) noted no significant differences between the nucleate boiling heat transfer coefficients for the base fluid alone and with nanoparticles.

Both the HTC and the CHF may be attributed, mainly, to changes in the surface wettability caused by nanoparticle deposition. In this case, a new nanostructured 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. Golubovic et al. (2009) observed an increase in the CHF in tests with Al<sub>2</sub>O<sub>3</sub> and attributed it to a change in the wettability. It is interesting to note that they obtained similar results without removing the deposited nanoparticles and using water as the working fluid.

Forrest et al. (2009) tested surface nanostructuring with SiO<sub>2</sub>. Hydrophobic, hydrophilic and super hydrophilic surfaces were created and pool boiling tests with water revealed CHF enhancement on all surfaces. They also suggested that the effect of the contact angle on the CHF needs to be considered, which was not the case in the correlations

obtained by Zuber and Kutateladze. According to their study, the advancing and receding contact angles should be considered in CHF correlations. Low receding angle may be the reason for a CHF increase, even on a hydrophobic surface, that had high static contact angle but low receding angle.

Results may also vary according to experimental set-ups, base fluids and nanoparticles. For example, ethanol and acetone, due to their low boiling point, are potential alternatives to water as base fluids, since they would facilitate control of the fluid temperature and achieve the CHF without a risk of burnout of the test device. However, as shown by Coursey and Kim (2008) ethanol is a wetting liquid, with a low contact angle, and nanoparticle deposition in this case does not seem to increase the wettability and thus a substantially change in the CHF values is not achieved. Therefore, it might be reasonable to assume that the effect of nanoparticle deposition decreases with low base fluid contact angles.

In this study, an analysis of the nucleate boiling heat transfer for subcooled water on a clean copper surface and with nanoparticles of alumina and maghemite deposited on the copper surface was carried out. The influence of these nanoparticles on the wettability of the surface is considered.

## 2. EXPERIMENTAL SET UP

### 2.1 Nanofluid preparation

Distilled water combined with 1% weight of  $\text{Al}_2\text{O}_3$  and distilled water with  $\text{Fe}_2\text{O}_3$  in a concentration of around 1.5% weight are the nanofluids used in this article, which aims to presents CHF results and fully understand the influence of wettability on the heat transfer properties. Tests were performed to compare this nanofluid with distilled water. According to Bang and Chang (2005)  $\text{Al}_2\text{O}_3$  forms stable, uniform and continuous suspensions in water, without being charged chemically. Das et al. (2003) analyzed the possibility of using copper oxide (CuO) nanoparticles, however, despite their high thermal conductivity these nanoparticles become explosive at  $100^\circ\text{C}$ .

Stabilization of nanoparticles and the base fluid was obtained by immersion in an ultrasonic bath for 4 hours. The use of a surfactant is an alternative way to prevent agglomeration of nanoparticles, but this has an unknown influence on the boiling properties.



Figure 1: a-)  $\text{Fe}_2\text{O}_3$ -Water, b-)  $\text{Al}_2\text{O}_3$  - Water

### 2.2 Experiment Set up

The experimental set up consists of a  $200 \times 150 \times 5$  mm square acrylic cube, surrounding a glass cylinder with 83 mm diameter, 150 mm height and 5 mm thickness. The glass cylinder is fixed by two plates of 316 stainless steel, one in the upper part with 150 mm internal diameter and 11 mm thickness and the other in lower part with 330 mm internal diameter and 21.6 mm thickness, sealed with rubber stopper. The square cubes are fixed only by a lower plate. The region between the tube and the acrylic cube is flooded with water controlled by a digital cryostat in order to control the working fluid temperature. A coil condenser, outside the boiling chamber, is used to maintain constant pressure and temperature inside the tube.

Inside the glass tube there is the test section, made of copper with 12 mm upper diameter and insulated by Teflon and glass wool to guarantee proportional distribution of temperature. Two electric resistors, cartridge type, with nominal resistance of  $83 \Omega$  and able to dissipate up to 500 W are responsible for the test section heating.

The surface, fluid and vapor temperatures are measured through 4 T-type thermocouples in the copper section; and two thermistors, one on the teflon surface and other above the working fluid.



Figure 2 – Transparent boiling chamber and, in detail, the heating section without Teflon cover

### 3. RESULTS

#### 3.1 Pool Boiling - $\text{Al}_2\text{O}_3$

Initially, two boiling curves were obtained: one with sub-cooled distilled water at 80°C, and the other with the sub-cooled alumina-water nanofluid at the same temperature.

The nanofluid boiling curve in Fig. (3) shows a decrease in the HTC in comparison with distilled water. On the other hand, the CHF was first reached in the test with distilled water. Higher heat fluxes were not possible to obtain because of limitations related to maintaining a constant sub-cooled temperature.

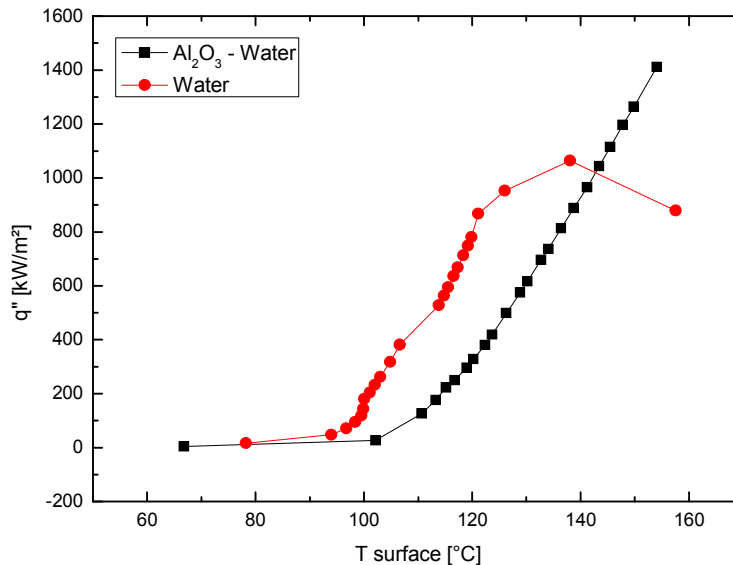


Figure 3 – Boiling Curve for  $\text{Al}_2\text{O}_3$ .

#### 3.2 Surface characterization

The idea of nanoparticle deposition in pool boiling with nanofluids, changing the wettability and, consequently, the boiling mechanism is already widespread. Deposition of the nano-layer above the heated surface may reduce the contact angle, facilitating the rewetting process and delaying site activation, as occurred in the alumina test. High surface oxidation and nanoparticle deposition, after nucleate boiling tests using alumina-water, obtained at the LEPTEN laboratory by Coelho et al. (2009), can be seen in Fig. (4).

Surface roughness measurements, conducted with a Perthometer S8P 4:51 profilometer (sensor point diamond with a 60 ° angle and radius of 3 μm) included: average roughness (Ra), root mean square roughness (Rq) and total roughness (Rt), which is basically the difference between the highest peak and lowest trough. As expect by visual analysis, there was an increase in the roughness of the heating surface after the tests with the nanofluid.

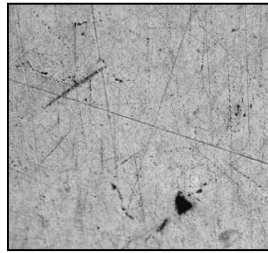
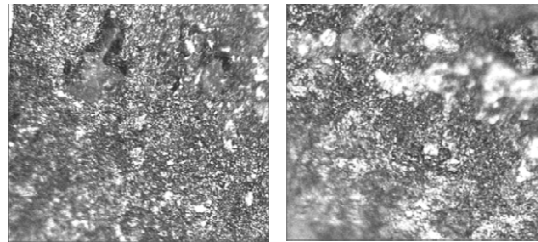


Figure 4 – Images of the boiling chamber after the experiment

**Table 1- Roughness of the test section before and after experiment.**

<i>Before experiment</i>				<i>Average</i>
Ra ( $\mu\text{m}$ )	0.040	0.102	0.094	0.079
Rt ( $\mu\text{m}$ )	0.450	1.058	1.560	1.023
Rq ( $\mu\text{m}$ )	0.051	0.198	0.187	0.145
R ( $\mu\text{m}$ )	0.330	0.470	0.640	0.480
<i>After experiment</i>				<i>Average</i>
Ra ( $\mu\text{m}$ )	0.329	0.361	0.236	0.309
Rt ( $\mu\text{m}$ )	2.590	6.410	2.140	3.713
Rq ( $\mu\text{m}$ )	0.434	0.576	0.139	0.443
<b>R (<math>\mu\text{m}</math>)</b>	1.910	1.130	1.250	1.430

The next step was the metallographic analysis of the surface before and after the tests with the nanofluid. Figures (5) and (6) confirm the modification of the surface structure after pool boiling with the nanofluid, verifying that deposition of nanoparticles can change the nanostructure of the surface.

**Figure 5 – Metallographic analysis before the experiment: magnification 100x.****Figure 6 – Metallographic analysis after experiment: magnification 100x (left) and 200x (right).**

Finally, the wettability tests were performed. For this particular analysis, due to the difficulties associated with measuring the contact angle in a small area, four samples of copper plates with 150mm diameter were tested: one with a smooth surface, one with a rough surface and two which were nanostructured, with alpha alumina ( $\alpha$  -  $\text{Al}_2\text{O}_3$ ) and maghemite ( $\gamma$  -  $\text{Fe}_2\text{O}_3$ ) surfaces. Special manufactured surfaces were prepared in a separate set-up consisting of a vessel in which the specimen could be immersed in boiling water. Interestingly, the maghemite nanoparticles, even after cleaning, were still adhered to the surface. Alpha alumina showed the opposite behavior. Roughness measurements were also conducted on these samples and the results are given in Table (2).

As expected, nanostructured surfaces exhibited hydrophilic behavior, while values for rough and smooth surfaces were neutral (near  $90^\circ$ ). Roughness, in principle, can increase the wettability of hydrophilic surfaces and decrease the hydrophobicity.

Similar values were obtained for the apparent contact angle of the smooth and rough surfaces because of the neutral behavior of the smooth surface. After cleaning, the contact angle of the alumina nanostructured surface increased to a value close to the smooth and rough surface values, while the maghemite surface continued to be hydrophobic, but with an increase in the contact angle, as summarized in Fig. (7).

Table 2 – Roughness of the smooth and rough copper plates after deposition of nanoparticles.

<i>Roughness (<math>\mu\text{m}</math>)</i>	<i>Clean Surface</i>	<i>Rough Surface</i>	<i>Al<sub>2</sub>O<sub>3</sub> on surface</i>	<i>Fe<sub>2</sub>O<sub>3</sub> on surface</i>
<b>Ra</b>	0.04	0.84	3.78	3.90
<b>Rq</b>	0.06	1.05	4.66	6.09
<b>Rt</b>	0.37	5.25	19.54	32.80
<b>Ry</b>	0.37	5.25	19.54	32.80
<b>Rz</b>	0.37	5.25	19.54	32.80

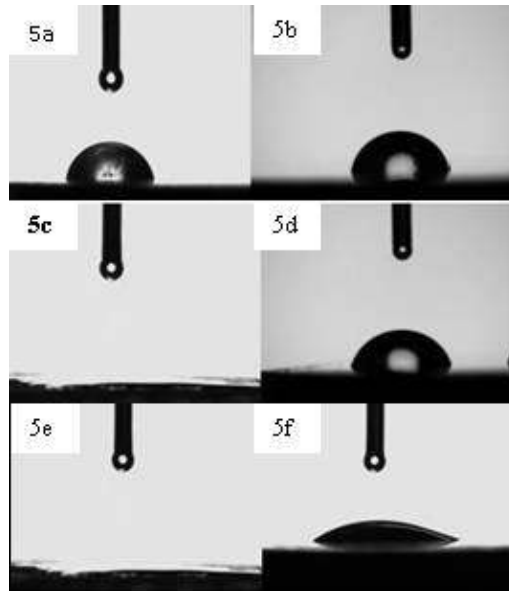


Figure 7: Contact angles for: a) Smooth surface, b) Rough Surface, c) Alumina-deposited surface, d) Alumina-deposited surface after excess removal, e) Maghemite-deposited surface, and f) Maghemite-deposited surface after excess removal.

### 3.3 Pool Boiling - Fe<sub>2</sub>O<sub>3</sub>

In order to verify the influence of the deposited nanoparticles on the pool boiling results, further tests were conducted. The objective was to ascertain whether the observed increase in the CHF and decrease in the HTC may be attributed to the nanofluid properties or to the nanolayer created by the Fe<sub>2</sub>O<sub>3</sub> deposited.

Firstly, a water-Fe<sub>2</sub>O<sub>3</sub> nanofluid nucleate boiling test was carried out. Because of its dark color, making it difficult to visualize the boiling, and the fact that the liquid became viscous directly above the heated surface at high temperatures, the test was conducted only up to 1000Kw/m<sup>2</sup> and the data were discarded. However, after removal of the nanofluid, the nanoparticle deposition became clear and was similar to the deposition observed in Fig. (7).

Two more tests were performed using water as the working fluid: one without cleaning the deposited surface, and another after excess removal. Theoretically, water should completely wet the surface in the former case, as in Figure 7.e, and behave hydrophobically in the latter case, Fig. (7). Figure (8) shows nucleate boiling curves similar to that for alumina-water presented in Fig.(3). Compared to distilled water, Fig. (3), both cases start nucleate boiling at higher temperatures and do not reach the critical heat flux, as in the case of alumina-water.

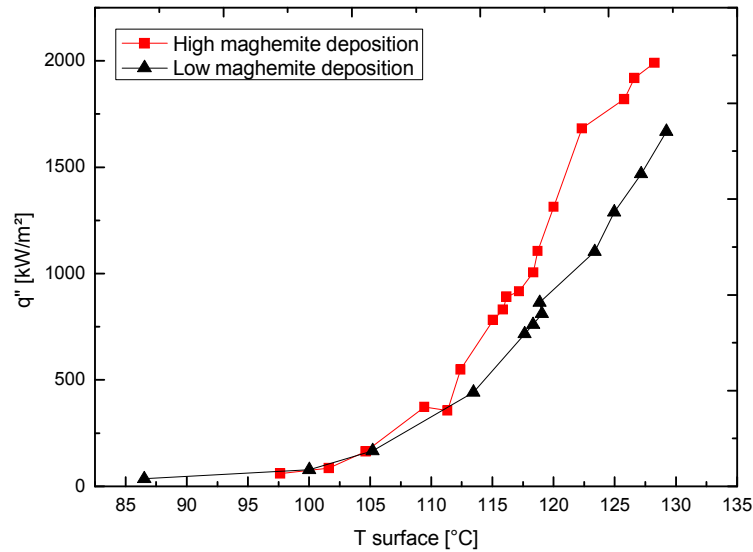


Figure 8 – Boiling Curve for Fe<sub>2</sub>O<sub>3</sub>.

#### 4. DISCUSSION

The literature related to boiling is generally deficient in explaining CHF enhancement mechanisms using nanofluids. Even after several decades of intense study, simple questions related to boiling, such as bubble departure and the CHF mechanism, have not received consensual explanations, which inhibits the understanding of the effect of a nanofluid in this context.

To explain the CHF mechanism, what first comes to mind is the hydrodynamic instability theory proposed by Zuber et al. (1959) which considers Helmholtz and Taylor's instabilities as the causes for the occurrence of critical heat flux. Although it provides a good physical explanation, it fails in not predicting the effect of wettability on the boiling mechanism.

Haramura and Katto (1983) postulated that the thickness of a liquid macrolayer covering the surface between the vapor bubbles is linked to the CHF mechanism through what is called the macrolayer dryout theory. According to these authors the macrolayer is dependent on the contact angles and critical heat flux takes place when it fully evaporates.

In the hot/dry spot theory, Unal et al. (1993) proposes that the CHF is reached when rewetting is no longer able to occur at nucleation sites, due to high temperatures at the wall and a poor rewetting process. Therefore, wettability is considered in this theory, since it is associated with the rewetting capacity.

The effects of the dynamic contact angle were predicted by Kandikar's CHF model (2001), and may explain some interesting results reported by Forrest et al. (2009), related to a higher CHF for hydrophobic surfaces with low receding angles.

On analyzing the alumina-water and Fe<sub>2</sub>O<sub>3</sub> deposition results, it is reasonable to state that the nanostructured surface after nanoparticle deposition had increased wettability and changed nucleate boiling mechanism, which induce an increase in the CHF and decrease in heat transfer. Considering the hot/dry spot and macrolayer dryout theories, it can be considered that a surface becomes continuously wet as a consequence of changes in the contact angle, allowing higher critical heat flux values to be reached. Moreover, to explain the decrease in heat transfer, the argument that the density of active nucleation sites is reduced may be used, since the formation energy ( $W^*$ ) of active sites considers the contact angle values, as expressed below:

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

where:

$$\psi(\theta) = (1 + \cos \theta)^2 (2 - \cos \theta) / 4 \rightarrow \psi(\theta) \leq 1 \quad (2)$$

The function  $\Psi(\theta)$  is unitary when the contact angle of a liquid-surface interaction is zero, or rather, when there is a perfectly liquid water surface.

According to equation (1), higher wettability requires higher energy to form and active nucleation sites. Soaked surfaces would hinder formation of nucleation sites, requiring more energy to initiate nucleate boiling.

Another interesting observation is the affinity between the deposited nanoparticles and the test section. When the copper section was completely covered with nanoparticles of alumina or maghemite, the contact angle was zero (completely wet). However, after removing the excess with sandpaper, the alumina deposited almost completely disappeared, while the maghemite deposited continued to be partially adhered. Therefore, it may be said that there is an affinity between the nanoparticles and the work surface, which influences the surface characteristics and possibly the boiling mechanism.

## 5. CONCLUSIONS

The following conclusions can be drawn from this study:

- During nucleate boiling nanoparticles can be deposited on the heated surface.
- Deposition of nanoparticles modifies the surface characteristics of the work surface, in the case of alumina-copper and maghemite-copper increasing the wettability.
- Changes in the surface properties can affect the CHF and heat transfer of the boiling mechanism.
- Higher wettability induces an increase in the CHF and more energy is required to activate nucleate boiling sites.
- The affinity between the materials of the nanoparticles and work surface determine the degree of wettability modification.

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