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NUCLEATE BOILING OF HFE7100 ON NANOSTRUCTURED SURFACES

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Abstract. *The aim of this study was to analyze the effect of nanostructured surfaces on the nucleate boiling of HFE7100, at saturation temperature and atmospheric pressure. The nanostructure investigated consisted of nanoparticles of maghemite, deposited on a copper disc substrate with two different roughness values. The results obtained with the nanostructure were compared with experimental results for the smooth and rough substrates. An increase in the heat transfer coefficient was observed for the substrate with maghemite deposition and for all gap sizes tested.*

Keywords*: Confined Nucleate Boiling, Nanostructures, Maghemite, Heat Transfer Coefficient.*

1. NOMENCLATURE

Alphabetic

CHF	Critical heat flux	
SEM	Scanning electron microscopy	
h	Heat transfer coefficient	[kW/m²K]
h_{lv}	Latent heat of vaporization	[kJ/kg]
q”	Heat flux	[kW/m²]
R	Electrical resistance	[Ω]
R_a	Average roughness	[µm]
T_{sat}	Saturation temperature of the fluid	[°C]
T_w	Surface temperature	[°C]
V	Volume	[m³]
I	Electrical current	[A]
A	Heated surface area	[m²]
e	Nominal deposited layer thickness	[m]
m	Mass	[kg]

Greek Letters

θ	Apparent contact angle	[°]
ρ	Density	[kg/m³]
σ	Surface tension	[N/m]
υ	Specific volume	[m³/kg]

Subscripts

a	Advancing
r	Receding
l	Liquid
v	Vapor

2. INTRODUCTION

Recent interest in boiling on nanostructured surfaces has mainly been derived from research on boiling using nanofluids. Nanofluids are fluids containing suspended nanoparticles (< 100nm). The boiling of nanofluids has become an attractive subject over the past decade. A number of researchers have observed the deposition of nanoparticles on the heating surface. This deposition has the effect of increasing the surface roughness and wettability and the critical heat flux can also be significantly improved. However, controversial results have been reported for the heat transfer coefficient. Most researchers reported no change in the heat transfer; others observed a deterioration in the *h* value (Kim and Kim, 2007; Bang and Chang, 2005) and some reported heat transfer enhancements (Kedzierski, 2009; Park and Jung, 2007). Nevertheless, authors generally agree that a CHF enhancement can be achieved, despite the differences in the percentage reported (from 10% to 400%).

Both heat transfer coefficient and critical heat flux modifications may be attributed, mainly, to changes in the surface wettability due to the deposition of nanoparticles. The behavior of the boiling process is very sensitive to changes in the surface characteristics, especially the number and shape of nucleate sites.

Wen (2011) studied the influence of nanoparticles on the boiling process focusing on the modification of: i) the heating surface through particle deposition; and ii) the bubble dynamics through particles suspended in the liquid. According to the author, both roles are co-existent in a typical boiling system through the influence of the active nucleation sites, bubble departure volume and departure frequency, as well as modifications to other properties.

Wen and Ding (2005) carried out pool boiling experiments using stable aqueous-based nanofluids containing alumina nanoparticles. The results showed that alumina nanofluids can significantly enhance boiling heat transfer. This effect increases with increasing particle concentration and reaches 40% enhancement in the heat transfer coefficient at a concentration of 1.25 wt%.

Narayan et al. (2007) carried out experiments to investigate the effect of concentration, surface roughness and particle size on pool boiling heat transfer on a vertical tubular heater. Experiments with different heating surface roughness characteristics and alumina nanoparticle concentrations were conducted. The results revealed an enhancement or deterioration in *h* depending on the combination of concentration, surface roughness and particle size applied. The authors introduced a surface interaction parameter (SIP), which is defined as the ratio between the surface roughness R_a and the particle size d_p.

Using a series of boiling tests with water and a water-based nanofluid, White et al. (2010) studied the physical mechanisms associated with nanofluid boiling. By comparing the performance of the water and the nanofluid boiling on the same horizontal heating surface, they separated the effect of suspended particles from that of surface roughness.

Enhancement in the heat transfer coefficient was attributed to particles settling on the heating surface which increases the number of nucleation sites and enhances the thermal properties of the nanofluid. Results reported in the literature indicate that the rate and uniformity of particle deposition are dependent on the nanofluid concentration. In one study, particle deposition occurred at a lower rate in the case of a low nanofluid concentration (0.01 vol.%), resulting in an enhancement in *h* (Ahmed and Hamed, 2012).

Heitich et al. (2012) performed experiments on the nucleate boiling of water, as the working fluid, on Constantan nanostructured surfaces of molybdenum and maghemite. The nanostructured surfaces showed an increase in the CHF, especially for the case with maghemite deposition and the rough substrate samples showed an enhancement in the heat transfer coefficient. The authors concluded that surfaces with hydrophobic behavior positively influence the heat transfer coefficient.

The boiling heat transfer mechanism can also be modified by the confinement of the system using, for example, an unheated surface assembled close to the heated one. The characteristic most commonly observed in the results of previous studies is that the heat transfer coefficient increases when the distance between the heated and unheated surfaces decreases (the confinement increases) for moderate heat fluxes (Passos et al., 2005). For relatively high heat fluxes, this enhancement effect disappears and the heat transfer coefficient decreases with increasing confinement and the dryout heat flux (DHF) limit can be attained early as shown by Kim *et al*. (2005).

The effect of the confinement on the bubbles can be characterized by a dimensionless parameter known as the Bond number, *Bo*, defined as the ratio of the characteristic length to the confined space, *s*, and the capillary length, *L*. The latter is proportional to the detachment diameter of the vapor bubble in a pool and defined as (Carey, 1992):

$$L = \sqrt{\frac{\sigma}{(\rho_l - \rho_v)}} \tag{1}$$

where σ, g, ρ_l and ρ_v represent the surface tension, the acceleration due to gravity, the liquid density and the vapor density, respectively. Thus, the Bond number $Bo = s/L$. In general, when $Bo<1$ the effect of the confinement is important and the bubbles trend to be coalesced and deformed, while for $Bo>1$, the bubbles become isolated (Ishibashi and Nishikawa, 1969).

Surface roughness has long been known to have a significant impact on the boiling process. Corty and Foust (1969) studied copper and nickel surfaces prepared with different levels of polishing. The authors found that the surface roughness not only affected the superheating required for the onset of nucleate boiling, but also the slope of the boiling curve. Rougher surfaces resulted in lower superheating for the same heat flux value, due to the presence of larger unflooded cavities on the rougher surfaces.

Results from the polished surfaces indicated that roughness only improved the boiling performance up to a certain point. The best heat transfer performance was obtained for R_a = 1μm and other surface roughness values yielded no additional benefit (Luke, 2003).

Pool boiling on heating surfaces with different roughness, at atmospheric pressure and with two fluids with differing wetting characteristics, was experimentally explored by Jones et al. (2009). For water, the results showed a little improvement in the heat transfer coefficient for roughness above R_a = 1.08μm, except for a very rough surface, which led to a significant increase in the heat transfer coefficient. The working fluid FC-77 showed a different trend with the heat transfer coefficient continuously increasing with the surface roughness, for the same heat flux value. The general trend of increasing heat transfer coefficient with surface roughness was correlated using $h = R_a^{\ m}$, where R_a is a measure of the surface roughness and *m* is the roughness exponent. The results indicated a stronger dependence on surface roughness for FC-77 with *m* = 0.2 compared with *m* = 0.1 for water.

The objective of this study was to analyze the nucleate boiling of HFE7100 under saturated temperature and atmospheric pressure conditions, for different gap sizes (*s* = 0.1 and 13mm), on three types of heating surface, one of which was nanostructured by maghemite nanoparticles deposition via an evaporation process. The main aim was to investigate the influence of different parameters, such as gap size, roughness and nanostructure surface, on the boiling phenomenon and to observe how these parameters act together.

3. EXPERIMENTAL APPARATUS

The test section consists of a copper disc of 12mm diameter and 1mm thickness, with three type-E thermocouples of 0.15mm diameter set in the disc close to its center. The copper disc is heated by a 6.4Ω electrical resistance skin heater, fixed with Araldite® epoxy resin on the bottom side of the disc, and is fixed to a piece of PVC beveled to an angle of 45° with an outside diameter of 20mm. This ensemble is mounted inside a boiling vessel, consisting of a glass tube with a 90mm inside diameter and 180mm height. The boiling vessel is mounted inside a second vessel, 170x170x186mm, as shown in Fig.1, whose lateral walls are transparent plexy-glass plates, allowing the lateral visualization of the boiling space.

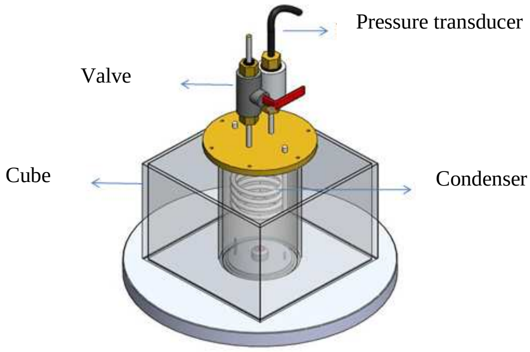


Figure 1. Boiling Chamber.

The test condition temperature of the working fluid is imposed by a forced flow of water in the space created between the glass tube of the boiling chamber and the plexy-glass wall of the external chamber. The water temperature is controlled by a cryostat. Inside the boiling chamber, in the upper part, there is a serpentine condenser cooled by water whose temperature is controlled by a second cryostat. The boiling chamber is equipped with a pressure transducer and valves. Two type-E thermocouples located in the liquid and in the vapor allow the monitoring of the test condition temperature, which is controlled by cold water flowing inside the serpentine.

The thin gap between the periphery of the copper disc and the PVC support is filled with Araldite® epoxy resin but this is not sufficient to avoid the presence of natural parasite sites at the periphery of the copper disc. Moreover, the polishing treatment of the copper surface, after the boiling tests, can contribute to creating new parasite nucleation sites. This can adversely affect the quality of the experimental results.

The experiments were performed using HFE7100 as the working fluid under saturated conditions at p = 1bar (T_{sat} = 61°C). The capillary length is close to L = 1.11mm. The surface of the copper disc, which is in contact with the working fluid, was polished using emery paper #600 or #1200, corresponding to a roughness, R_a, of 0.16µm and 0.09µm, respectively.

The confining element, Fig. 2, consists of a transparent acrylic piece fixed to an aluminum support and this, in turn, is fitted to the test section. This conical unheated plate is placed parallel to the heating surface (45° cone angle and 12mm diameter at the bottom). The gap sizes of 0.1 and 13mm were analyzed in this study.

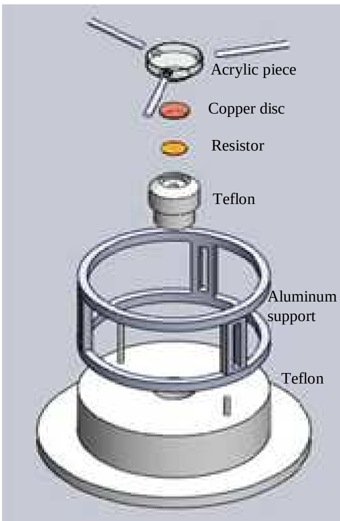


Figure 2. View of test section assembly.

The DC power supply, HP6030A, is connected to the skin heater and controlled by a PC using LABVIEW. The acquisition and preliminary treatment of the data are carried out with an HP34970A system. The heating of the copper disc is controlled by increasing the heat flux.

3.1 Test Section Preparation

In this study three types of heating surface were analyzed: smooth surface, rough surface and a surface with maghemite deposition (nanostructured). The nanostructures were produced by maghemite nanoparticle deposition via an evaporation process. Prior to the deposition process, the copper disc was polished using emery paper #600, corresponding to a roughness, R_a, of 0.16µm and cleaned with acetone.

Maghemite (γ - Fe_2O_3) nanoparticles with an average diameter of 10nm were used. They were synthesized following Massart's method (Massart, 1982) through the precipitation of Fe^{2+} and Fe^{3+} salts in alkaline medium and dispersed in water.

The deposition of maghemite on the heating surface was carried out by evaporation with a nanoparticle suspension, consisting of water and maghemite nanoparticles. The process involves applying a layer of this solution with a syringe onto the copper disc. The surface is connected to a power source, which allows surface heating and consequent evaporation of the liquid, leaving only the deposited nanoparticles.

3.2 Experimental Procedures

The same experimental procedure was applied in each case in order to ensure the repeatability of the results. A vacuum was created inside the boiling chamber prior to filling it with the working fluid. During the experiment the temperature of the working fluid and the atmospheric pressure conditions were controlled by a forced flow of water in the space created between the glass tube of the boiling chamber and the plexy-glass wall of the external chamber.

Before each test run the working fluid was heated to very close to the saturation temperature in order to degas it. No evidence of significant amounts of gas dissolved in the working liquid was detected on the boiling curves. Once the test conditions had stabilized, the heat flux was imposed in the range of 5 to 70kW/m².

The experimental procedure was programmed in LABVIEW and each test had 180s duration for each heat flux applied. Only the temperature data for the last 90s of the test interval were acquired, at a rate of 3 points/s. In this study the heating mode involved increasing the heat flux until the dryout heat flux was reached. Due to the technical limitations of the heating system, only the dryout heat flux for the confined case was obtained.

The temperature uncertainty was ±0.8ºC. The experimental uncertainty for the heat flux varied from 5.6% to 1.7% for all surfaces tested. The experimental uncertainty for the heat transfer coefficients varied from 11% to 2%, for the smooth substrate, 5.6% to 1.7% for the rough substrate and 10% to 2% for the nanostructured surface.

3.3 Characterization of Samples

Prior to each test the samples were characterized using the following techniques:

i. Scanning electron microscopy (SEM) to obtain structural and chemical information. This procedure was performed using a Phillips XL30 scanning electron microscope.

ii. The parameter R_a was determined using a Surftest SS measuring system (model 401), with the same scanning area for all samples.

iv. The wettability test involved measuring the apparent static (θ), advancing (θ_a) and receding (θ_r) contact angles. The device used was an OCA 20 goniometer (DataPhysics Instruments). The measured contact angles for the nanostructure surfaces presented in this study are, in fact, apparent contact angles because of the presence of the porous layer.

The characterization measurements were carried out at the Materials Laboratory - LabMat, at the Federal University of Santa Catarina - Brazil.

Table 1 shows the different types of surfaces tested during the nucleate boiling of HFE7100.

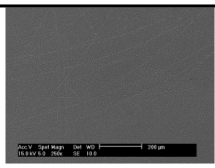
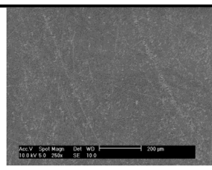
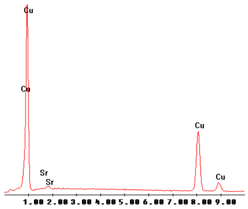
Table 1. Description of the heating surfaces tested in this study.

Smooth Substrate	Copper disc (#1200) without deposition. Standard smooth surface. R_a = 0.09µm
Rough Substrate	Copper disc (#600) without deposition. Higher roughness due to sanding process. R_a = 0.16µm
Maghemite Nanostructure	Copper disc polished with #600 emery paper and maghemite deposition by nanofluid evaporation process (volumetric concentration equal to 0.29g/l and pH = 2). R_a = 0.18µm

3.3.1. Smooth and Rough Substrates

Table 2 shows the characterization of the smooth and rough substrates. The copper disc that was polished using emery paper #1200 is considered as a smooth surface compared to the other samples. The roughness (R_a) was 0.09µm and the images obtained by SEM revealed a smooth surface with few topographic irregularities. The rough substrate surfaces presented roughness (R_a) of 0.16µm and SEM images revealed an increase in the topographic irregularities. The chemical analysis revealed the composition concerning the Cu.

Table 2. Results for the smooth and rough substrate characterization.

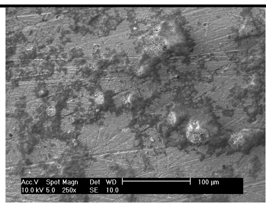
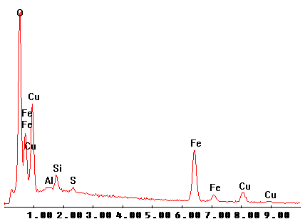
Characterization Techniques	Smooth Substrate	Rough Substrate
R_a	0.09µm	0.16µm
SEM	 250x	 250x
SEM		

3.3.2. Maghemite Nanostructure Surfaces

Table 3 shows the results for maghemite nanostructures characterization by SEM where the microstructural aspects with different grain sizes and heterogeneous distribution can be observed.

The chemical analysis showed the presence of Fe and O in the composition. In this study, the maghemite deposition was performed only on the copper disc polished with emery paper #600. The roughness was obtained by rugosimeter and the value was 0.18µm.

Table 3. Results for the maghemite nanostructure substrate characterization.

Characterization Techniques	Maghemite Nanostruture
R_a	0.18µm
SEM	 250x
SEM	

A method based on the weight of samples with and without deposition was carried out in order to define the deposited layer on the rough substrate. In the case of the nanostructure the true weight was considered as the difference between the weight of the samples with and without deposition. Based on these values and the corresponding volumes of the samples, as well as the density (ρ) of each material obtained from the literature, it was possible to calculate the nominal thickness of the deposited layer, according to Eqs. (2) and (3):

$$\rho = \frac{m}{V} \tag{2}$$

$$V = A.e \tag{3}$$

where A is the heated surface area (in contact with the working fluid) and e is the nominal of the deposited layer thickness.

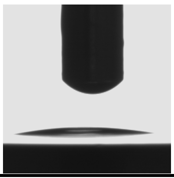
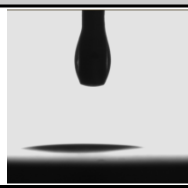
The nominal thickness of the maghemite nanostructure layer deposited on the heating surface polished with #600 emery paper was 0.001mm. The advantage of thinner maghemite deposition is the ability to minimize the thermal resistance normally added by the nanoparticle layer.

3.3.3. Contact Angle Measurements

The surface characteristics of the samples were analyzed by the wettability test using the working fluid HFE7100. Table 4 shows the results for the smooth, rough and nanostructured substrates. It was observed that the copper, which was the material used as the substrate, presented complete wettability and contact angle hysteresis was not observed. The surface with maghemite deposition showed a completely wetting behavior.

This behavior is expected because the working fluid has a low surface tension (about 0.013N/m), i.e., it is a well-wetting fluid.

Table 4. Wettability test results for the smooth, rough and maghemite nanostructure substrates.

Contact Angles	Smooth Substrate	Rough Substrate	Maghemite Nanostructure
Static			

4. RESULTS

Figure 3 shows the effect of the gap size on the heat transfer coefficient, as a function of heat flux, for the smooth substrate, at saturation temperature, using HFE7100, for s = 0.1 and 13mm. For these values of s, the Bond number is equal to 0.09 and 12.89, respectively.

For s = 0.1mm and heat fluxes higher than 30kW/m^2 the wall temperature increased, and thus the possibility of starting the dryout heat flux earlier than in the case of s = 13mm was considered. Due to this very thin gap, the bubbles are deformed and the frequency of bubble detachment is not sufficient to cool the heating surface, characterizing a decrease in the heat transfer coefficient.

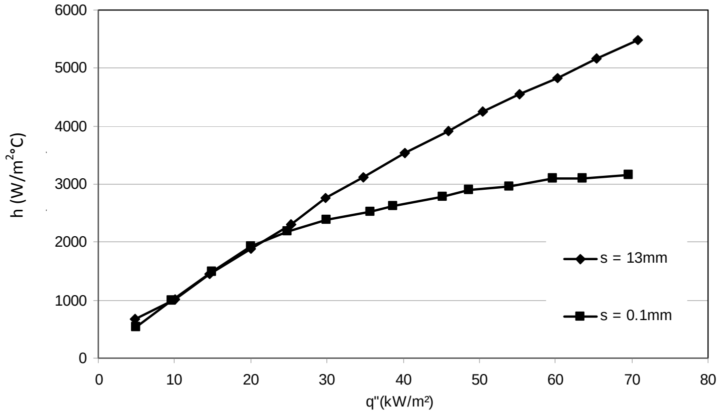


Figure 3. Heat transfer coefficient as a function of the heat flux for the smooth substrate, using HFE7100, for s = 0.1 and 13mm.

Figure 4 shows the effect of the gap size on the *h* value as a function of *q"* for a rough substrate, at saturation temperature, using HFE7100, for *s* = 0.1 and 13mm.

For the cases with a very high degree of confinement, the enhanced boiling for heat fluxes lower than 45kW/m^2 is a consequence of an increase in the number of active nucleation sites, due to an increase in the surface roughness.

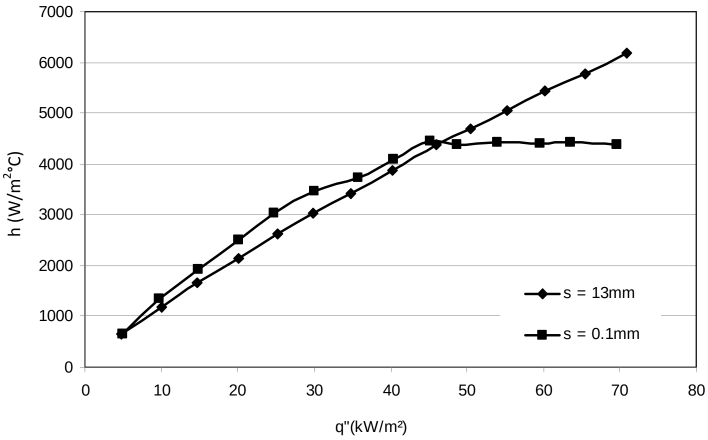


Figure 4. Heat transfer coefficient as a function of heat flux for the rough substrate, using HFE7100, for s = 0.1 and 13mm.

The decrease in the heat transfer coefficient for heat flux higher than 45kW/m^2 and for *s* = 0.1mm is caused by the effect of the confining element, which increases the residence time of the bubbles on the heating surface and inhibits the cooling effect caused by the liquid front after the departure of a bubble. According to Cardoso et al. (2011), the dryout mechanism is dependent on the conditions imposed by the geometric characteristics of the heating surface and its support. Thus, the ratio between the diameters of the support and of the test section can influence the dryout heat flux.

Figure 5 shows the effect of the gap size on the boiling curve for the maghemite nanostructure substrate, at saturation temperature, using HFE7100, for *s* = 0.1 and 13mm.

Compared to the other surfaces tested in this study, this case presented a higher heat transfer coefficient for the confined case and for low heat fluxes. Das et al. (2008) observed that when the average particle size is of the order of the surface roughness, the number of nucleation sites is greatly decreased. It was also found that when the average particle size is smaller than the heater surface roughness value the number of nucleation sites is greatly increased.

According to Narayan et al. (2007), when the surface particle interaction parameter (SIP) is much greater than one, the enhancement is higher. This is because the smaller particles are sitting in nucleation sites and multiplying them by splitting a single nucleation site into multiple ones.

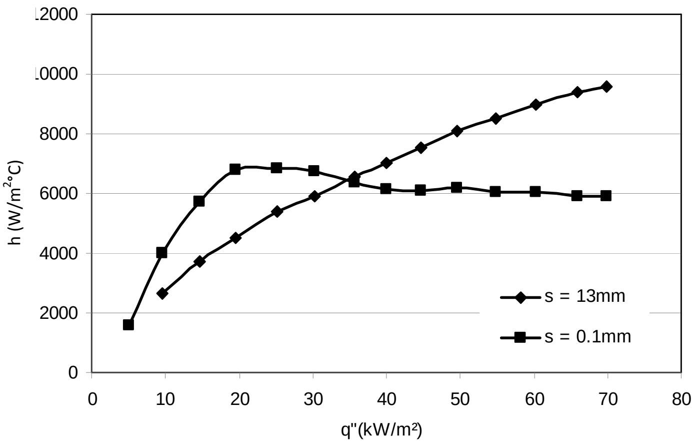


Figure 5. Heat transfer coefficient as a function of the heat flux for maghemite nanostructure substrate, using HFE7100, for s = 0.1 and 13mm.

Figure 6 shows the results for the nucleate boiling on the smooth substrate, rough substrate and maghemite nanostructures, for the unconfined case. The nanoparticle deposition causes an increase in the heat transfer coefficient.

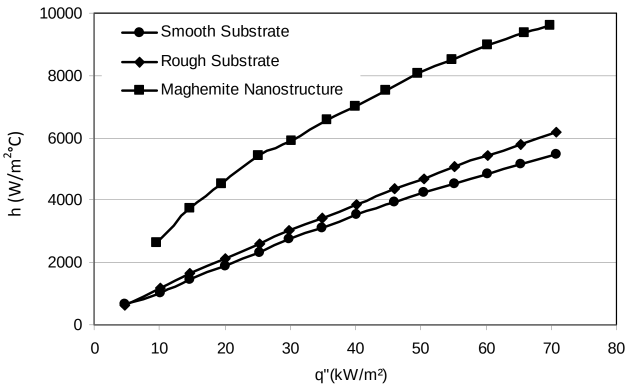


Figure 6. Heat transfer coefficient as a function of heat flux for smooth, rough and maghemite nanostructure substrates, for the unconfined case.

In the case of the nanostructure a decrease in the size of the vapor bubbles and an increase in the bubble release was observed for the same heat flux. As a result, the conditions required for the CHF are delayed and the values for the heat transfer coefficient are significantly higher for the nanostructured surface compared to the smooth substrate.

Figure 7 shows the results for the nucleate boiling on the smooth substrate, rough substrate and maghemite nanostructures, for the confined case. As in the unconfined case, the surface with maghemite deposition showed better results for the heat transfer coefficient compared to the smooth and rough substrates.

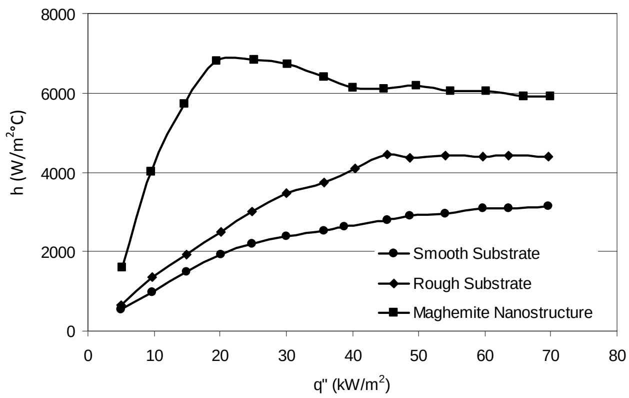


Figure 7. Heat transfer coefficient as a function of heat flux for smooth, rough and maghemite nanostructure substrates, for the confined case.

The presence of the nanoparticles on the substrate surface introduces a substantial change in the roughness, with numerous valleys between the deposited particles and this interferes with the capacity to trap vapor bubbles. From the SEM images (Table 3) it was possible to observe that in the maghemite deposition a microstructure layer was created.

According to Carey (1982), surfaces with smaller cavities require a higher superheating to start the nucleation, but when it starts the superheating required to keep the vapor bubbles is smaller. This could explain the increase in the heat transfer coefficient obtained with the nanostructure application.

In summary, it is suggested that the microstructural nanostructure surface influences the heat transfer process in such a way that its surface defects can be treated as nucleation sites, and factors such as their size and quantity are important factors.

5. CONCLUSIONS

This study presents experimental results for nucleate boiling on copper discs as heating surfaces, nanostructured with maghemite by the nanofluid evaporation technique. The experiment was performed at the saturation temperature and atmospheric pressure of HFE7100, used as the working fluid.

The following conclusions can be drawn from this study:

i. Nanoparticle deposition modifies the heating surface characteristics;

ii. The maghemite nanostructure substrate showed an enhancement in the heat transfer coefficient of around 87% compared to the other samples;

iii. As a general trend the heat transfer coefficient increases when the confinement increases, corresponding to a gap size decrease;

iv. Surface defects can influence the heat transfer mechanisms and the critical heat flux. The nanostructures have a greater number of these defects due to the small nanoparticle size;

v. The heating surfaces tested in this study showed a completely wetting behavior. Due to the lower surface tension, the working fluid was nearly perfectly wetting on all heating surfaces, hindering the measurement of the contact angle;

vi. The maghemite nanostructure substrate, compared to smooth and rough substrates, showed an increase in the heat transfer coefficient, for confined and unconfined cases. The presence of the nanoparticles on the heating surface introduces a substantial change in the roughness, with numerous valleys between the deposited particles and this interferes with the capacity to trap vapor bubbles.

6. ACKNOWLEDGEMENTS

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