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Confined and unconfined nucleate boiling of HFE7100 in the presence of nanostructured surfaces

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ABSTRACT

This article presents experimental results for the confined and unconfined nucleate boiling of saturated HFE7100 ($C_4F_9OCH_3$) at atmospheric pressure and using nanostructured copper discs as heating surfaces. The nanostructures studied consisted of nanoparticles of maghemite (Fe_2O_3) on the heating surface, comprised of a copper disc. Different values for the diameter (10 and 80 nm) and roughness (R_a = 0.02 µm and 0.16 µm) were studied. The nanoparticle adhesion on the heating surface plays a more important role in the confined boiling process than the surface roughness. As an original result, it was demonstrated that for a confinement with a gap length of 0.1 mm and heat flux of 40 kW/m^2 the heat transfer coefficient (HTC) increased by 31% and 100% for the cases with the deposition of nanoparticles of 10 nm and 80 nm, respectively. However, without the nanoparticles the HTC decreased by 21% when compared with the reference case, that is, a smooth plate (R_a = 0.02 µm) and unconfined boiling.

1. Introduction

The nucleate boiling regime can be considered one of the most effective ways to obtain a higher heat flux and a relatively small difference between the wall temperature and the saturation temperature of the liquid. In the literature, few of the studies carried out focus on the physics of the boiling phenomenon. Wang and Dhir [1] evaluated the effect of surface wettability on the heat transfer during the water nucleate boiling regime and they drew attention to the following parameters: nucleation site density and the spatial distribution (distance between active nucleation sites and their neighborhood). According to these authors, these parameters are strongly dependent on the type of finishing and/or surface treatment. Rougher surfaces were found to be associated with a higher HTC due to the increased number of nucleation sites, and this result was also reported by other authors (Mikic and Rohsenow [2], Berenson [3], Kang [4]). The heat transfer mechanism may be related to the number of vapor bubbles present on the heating surface, and the general trend is that the HTC decreases as the wettability increases (Dhir [5]).

Surface roughness also has a significant impact on the boiling process. Pool boiling on heating surfaces with different roughness values, at atmospheric pressure using two working fluids with different wetting characteristics, was experimentally studied by Jones et al. [6]. For water, the results showed a slight improvement in the HTC for roughness values higher than $R_a = 1.08\,\mu m$. A different trend was found for FC 77: the heat transfer coefficient continuously increased with the surface roughness, for the same heat flux value. The general trend was correlated using $h = R_a^m$, where m is the roughness exponent. The results indicated a stronger dependence on the surface roughness for FC 77 with $m = 0.2$ compared to $m = 0.1$ for water.

The majority of models relating boiling heat transfer to nucleation site density suggest that the nucleation site density and the wall superheating are correlated by a power law, represented by (Wallis [7]):

$$q'' = (n_a')^x \cdot (T_w - T_{sat})^y \tag{1}$$

where n_a', $(T_w - T_{sat})$, x and y are, respectively, the nucleation sites density, the wall superheating, and the exponents. The value for the exponent x varies between 0.3 and 0.5 while y varies between 1.0 and 1.8, as suggested by classical models (Mehta and Khandekar, [8]).

McHale and Garimella [9] emphasized that most of the published studies on boiling have considered idealized surfaces in their models, that is, they are totally smooth with perfectly conical or reentrant cavities, among other features, while surfaces with more natural structures have not been extensively studied.

Another difficulty highlighted by Dhir [10] and Avedisian [11] is to connect the micro and nanoscales in research on boiling mechanisms.

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Nomenclature

Alphabetic

CHF	critical heat flux
HTC	heat transfer coefficient
SEM	scanning electron microscopy
AFM	atomic force microscopy
h	heat transfer coefficient
h_{lv}	latent heat of vaporization
L	capillary length ($L = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$)
q''	heat flux
R_a	average roughness
s	gap size
T_{sat}	saturation temperature of the fluid
T_w	surface temperature

Greek letters

ρ	density
σ	surface tension
υ	specific volume

Subscripts

l	liquid
v	vapor

Recent studies focused on the effect of nanostructures and nanofluids on the nucleate boiling regime have shown that the behavior of the boiling process is very sensitive to changes in the surface characteristics, especially the number and shape of nucleation sites (Wen [12], Shahmoradi et al. [13]).

The deposition of nanoparticles on the heating surface increases the surface roughness and the wettability, and the critical heat flux (CHF) can be significantly improved. Rainho Neto et al. [14] measured the HTC and the CHF during the nucleate boiling of water in the presence of nanoparticles of alumina, maghemite and carbon nanotubes (CNTs). They showed that the CHF increased by 26–37% for all tests when compared with the reference case for water. The heat transfer coefficients were almost the same with the deposition of CNTs on the copper plate and lower for the other two nanoparticles, when compared with the reference case (copper in water as the base fluid).

Concerning the heat transfer coefficient, most researchers reported no change in the HTC, others observed a deterioration in the heat transfer (Kim and Kim [15], Bang and Chang [16], Kwark et al. [17]) and some authors have reported heat transfer enhancements (Kedzierski [18], White et al. [19], Heitich et al. [20]). Nevertheless, authors generally agree that a CHF enhancement can be achieved, despite of the differences in the percentage reported (from 10% to 400%). Both the heat transfer coefficient and critical heat flux modifications can be attributed, mainly, to changes in the surface wettability due to the nanoparticles deposition.

Mehta and Khandekar [8] suggested that the density of active nucleation sites, n_a', can be affected by two mechanisms: (i) physical adhesion, blocking the active nucleation sites with nanoparticles and also reducing the radius of the cavities present on the heating surface; and (ii) a change in the contact angle/wetting characteristics due to the addition of nanoparticles in the base fluid. According to the authors, nanoparticle deposition could reduce the cavity radius, leading to a decrease in the HTC.

The effect of nanostructured surfaces on heat transfer has been experimentally observed in recent studies by Jun et al. [21], Tang et al. [22] and Lee et al. [23]. According to these authors, nanostructured surfaces have the potential to alter the surface properties, such as, wettability and thermal conductivity.

Narayan et al. [24] carried out experiments to investigate the effects of the nanoparticle concentration, surface roughness and nanoparticle size on pool boiling heat transfer on a vertical tubular heater using water as the base fluid. Different heating surface roughness values (48, 98 and 524 nm) and alumina nanoparticle concentrations (0.5, 1 and 2 wt%) were analyzed. The results showed an enhancement or deterioration in the HTC depending on the combination of nanoparticle concentration, surface roughness and nanoparticle size. 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, to take into account the heating surface characteristics and its interaction with the nanoparticles deposited on it.

Ji et al. [25] studied boiling heat transfer surfaces with uniform and non-uniform porous coatings using acetone as the working fluid, at atmospheric pressure, on different heating surfaces including a plain surface and surfaces with a thick porous coating with uniform particle layer thickness or with 2-D and 3-D porous coatings. In general, the authors observed that the 2-D and 3-D porous coatings significantly enhanced the pool boiling heat transfer and their explanation was based on the effects of the porous structure on liquid suction and the valley channel on vapor escape. According to Ji et al. [25], these effects are dependent on the solid and liquid thermophysical properties, the pore parameters, such as pore size and distribution, and the porous layer thickness.

Kim et al. [26] proposed a novel mechanism for HTC reduction and CHF enhancement using nanofluids (Al_2O_3/water nanofluids). Below a critical concentration (0.001 vol% in this study), the CHF increases while the HTC decreases with increasing nanoparticle concentration. Above the critical concentration, both the CHF and HTC decrease with increasing nanoparticle concentration. According to the authors, this is because below the critical concentration the effective surface area increases and above the critical concentration the film resistance increases, blocking the cavities.

Souza et al. [27] presented experimental results for HFE 7100 nucleate boiling on copper discs, nanostructured with maghemite (10 nm and 80 nm diameters) using the nanofluid evaporation technique. The surface roughness (R_a) was 0.16 μm before the nanoparticle deposition. The authors concluded that the microstructure of the nanostructured surfaces influences the heat transfer process in such a way that the surface defects can be treated as nucleation sites. Also, factors such as the size and quantity of these defects are important.

In several industrial applications where an immersion-cooling system is used it is very common that the space reserved for the vapor-liquid system is small. In these situations, after the formation and growth of vapor bubbles, bubble deformation can occurs and the time for which the vapor bubble remains in the limited space increases. When this occurs, the nucleate boiling process shows a different behavior in relation to the heat transfer (Ishibashi and Nishikawa [28], Katto et al. [29], Passos et al. [30], Cardoso and Passos [31] and Cardoso et al., [32]).

The effect of the gap size on the bubbles can be characterized by a dimensionless parameter known as the Bond number, Bo, defined as the ratio of the gap, s, between the heating surface and the unheated surface, and the capillary length, $L = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$,

$$Bo = \frac{s}{\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}} \tag{2}$$

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. As