Visualisation of subcooled pool boiling in nanofluids

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\begin{abstract}
High-performance cooling is of vital importance for the cutting-edge technology of today, from micro-electronic devices to nuclear reactors. Boiling heat transfer is expected to play a critical role for the safe and efficient operation of components exposed to high heat flux in future nuclear fusion reactors. Recent advances in nanotechnology have allowed the development of a new category of coolants, termed nanofluids, which exhibit superior thermophysical characteristics over traditional heat transfer fluids. Qualitative experimental results of Al\textsubscript{2}O\textsubscript{3}-H\textsubscript{2}O nanofluids under subcooled pool boiling conditions are reported and compared to deionised water that served as a benchmark in the current work. A visual evaluation of the impact of nanoparticles on bubble dynamics and nucleation site activity at the heated surface of a bare NiCr wire is performed with the use of a Guppy F-080 FireWire camera. It was observed that the presence of nanoparticles significantly modifies the nucleation site density, bubble size at departure and frequency of bubble generation from the surface of the heating wire. Intense nanoparticle deposition on the heating wire surface was identified as a key mechanism for the observed differences via scanning electron microscopy. The deposited nanolayer reported to alter the surface texture of the wire. The outcome of this work is a step forward towards the evaluation of the applicability of nanofluids in cooling applications via boiling heat transfer.
\end{abstract}

1. Introduction

High Heat fluxes are expected in the current generation of experimental fusion reactors and future fusion power plants. The large heat loads must be conveyed away from the reactor and towards the power generation infrastructure in a fast, efficient and reliable way, to ensure a safe and financially viable operation of the fusion power plant. High heat flux components, such as the divertor, are expected to receive extreme heat loads, hence advanced cooling techniques must be employed to ensure operational reliability and longevity.

Subcooled water cooling at intermediate pressures \cite{1,2} is the chosen method of heat management for the divertor of the International Thermonuclear Experimental Reactor (ITER), since subcooled boiling heat transfer is able to accommodate very high heat fluxes \cite{3}. However, water is reported to have both advantages and disadvantages as a coolant in conceptual designs of future fusion power plants. Its main drawback arises from phase change limitations (i.e. critical heat flux, CHF) \cite{4}. The CHF represents the limit of the safe operating condition of a component or system employing boiling heat transfer under constant heat flux \cite{5}.

Therefore, there is a need to employ new, innovative coolants with enhanced thermophysical properties than conventional heat transfer fluids, including water. Nanofluids, as initially coined and proposed in the early 1990s by Stephen U.S. Choi \cite{6}, have the potential to be used in demanding heat transfer applications, by replacing traditional coolants. Nanofluids are comprised of a conventional heat transfer fluid, known as the base fluid, and usually highly conductive nanoparticles with typical sizes of the order of 1–100 nm, in concentrations that do not exceed 10 vol.%. It has been well reported that a small concentration of nanoparticles can provide a promising improvement in the heat transport properties of the base fluid \cite{7,8}.

Most investigations around nanofluids have focused on thermal conductivity measurements, where a notable enhancement has been noticed. More recently though, a methodical step towards the study of nanofluids under the more complex nucleate boiling and CHF modes has been observed. Nucleate boiling is the most effective pool boiling regime with extensive applicability in thermal management, while the CHF is a key design and safety parameter of a heat exchanger \cite{9}.

Similarly to the findings for convection heat transfer in nanofluids \cite{10–13}, results for boiling have also been contradictory. Pool boiling systems are widely employed for the simplicity and cost efficiency they offer. The addition of nanoparticles to such systems has been found to both increase and decrease heat transfer, while the CHF is notably enhanced \cite{9,14–16}. For instance, it has been reported that the

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addition of a small quantity of aluminum oxide nanoparticles to water increases the CHF by 200% [17], while for silica-water nanofluids the CHF can be found up to three times higher than that of water [18].

According to a comprehensive review for nanofluids under pool boiling [19], the condition of the heating surface, following the deposition of nanoparticles, is mainly responsible for the varying results in boiling studies. Consequently, most of the studies have been focused on the underlying mechanisms behind the increase of the CHF, which is of critical importance for cooling applications and systems. The purpose of the present work was to visually evaluate the impact of nanoparticles on bubble dynamics and nucleation site activity, primarily at the heating surface, under subcooled pool boiling conditions.

2. Methodology

2.1. Experimental apparatus

The experimental apparatus involves a custom-made pool boiling cell with unobstructed optical access and fast responding control and instrumentation systems to facilitate repeatable and stable operation for accurate and precise measurements. Fig. 1(a) shows a sketch of the pool boiling cell and its main components. The focus of the optical study is a bare heating wire A that is submerged in a small (0.125 L) cubic glass container B, which contains the testing fluid. The heating wire is made of 80/20 nickel chrome (NiCr) alloy and is connected to two vertically placed insulated test lead wires C, which are housed in a custom-made three-dimensional (3D) printed part D, as depicted in detail in Fig. 1(b). The cubic glass container B is placed inside a rectangular-shaped container G. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire.

A purpose-made electrical device controlled the power input to the water bath, while a DC power supply unit (IPS1810H, ISO-TECH) controlled the power to the heating wire. The electrical device incorporates two proportional–integral–derivative (PID) temperature controllers (7605371, RS), one for each K-type thermocouple, that are placed inside the pool boiling cell. Since the pool boiling cell is not insulated, the heat losses from the container are expected to be considerably high. The first PID controller, through an improved auto-tuning algorithm, continuously turns on and off the operation of the heating element, to maintain the temperature of water in the bath constant (± 0.5 °C). Simultaneously, the second PID controller monitors the temperature of the testing fluid in the cubic glass.

The visualisation studies a FireWire camera (Guppy F-080 B/C, Allied Vision Technologies) is used with maximum acquisition frame rate of 56 Hz, depending on the area of interest and exposure time. A Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire. For improved visualisation experiments with high clarity images, a Nikon AF Nikkor 50 mm f/1.8D lens is mounted in front of the camera to focus on the NiCr wire.

2.2. Experimental procedure

The operating conditions for the pool boiling experiments were constant temperature (± 0.5 °C) of the water bath $T_{\text{bath}} = 97$ °C and constant heat flux at the heating wire, ranging from $q^* = 241.81$ kW/m$^2$ to 313.46 kW/m$^2$ (the fractional uncertainty on the heat flux was on average 10%). During the experiments, the topside of the container was open to the air and the pressure of the system was atmospheric. According to the experimental procedure of this study, the NiCr wire was submerged in the small cubic glass container that contained ∼ 60 ml of testing fluid, while the glass container was surrounded by ∼ 1000 ml of deionised (DI) water contained in the water bath. Subsequently, the DC power supply was turned on to provide electric current $I$ to the wire. Once the temperature of the testing fluid $T_{\text{fluid}}$ was stabilised (steady state conditions), 1000 images of the flow field close to the heating wire were recorded with a frequency of $f = 15.2$ Hz. For the next experiment, the electric current was increased by 0.5 A and the system was left to reach steady state conditions before capturing the next set of images. The same procedure was repeated for all the experiments.

The nanofluid experiments were performed after the completion of the water experiments, using the same heating wire. Specifically, freshly prepared [20,21] dense nanofluids were poured into the cubic glass container and stirred well with DI water to ensure good dispersion, while an equal amount of DI water had been previously removed with a syringe needle. Due to mass losses from the top of the boiling cell, a small amount of degassed DI water was poured into the bath (≤ 100 ml) and into the cubic glass (≤ 5 ml) at the end of each experiment. Assuming that all the nanoparticles remain in the suspension (none are carried away by the vapour), the nanoparticle volume fraction is slightly modified during an experiment. In case of vapourised nanofluids, the nanoparticle volume fraction is marginally decreased, as the experimental procedure progresses. Nevertheless, this behaviour is not expected to notably affect the results or conclusions drawn, as also reported in [18].

3. Results and discussion

Fig. 2 displays sequential images (dt1, dt2, dt3) of bubble formation in DI water and dilute Al$_2$O$_3$-H$_2$O nanofluid, $\varphi_s = 0.0012$ vol.%, during subcooled pool boiling, under three different operating conditions. Starting with DI water at $q^* = 241.81$ kW/m$^2$ (a), there are many active nucleation sites along both the horizontal and vertical parts of the wire that result in intense boiling activity. As the heat flux increases, the boiling activity becomes more intense and considerable bubble coalescence is observed. For the maximum heat flux, $q^* = 313.46$ kW/m$^2$ (c), the bubble activity and nucleation site density are also maximised.
For the dilute Al₂O₃-H₂O nanofluid, a similar trend for the boiling activity is observed, since more nucleation sites become active with the increase of the heat flux. Compared to DI water, the nucleation site density for the nanofluid appears to be lower, whereas the size of the bubbles (or merged bubbles) is two to three times larger at both the horizontal and vertical parts of the wire. This could be due to modification of the nucleation sites on the heating wire due to the presence of nanoparticles that could also lead to extended bubble coalescence.

Fig. 3 shows sequential images of bubble formation in Al₂O₃-H₂O nanofluid, φᵥ = 0.0024 vol.%, during subcooled pool boiling under the maximum heat flux 313.46 kW/m² (c). It is observed that the boiling behaviour of the nanofluid is visually the same with that of the previous nanofluid with φᵥ = 0.0012 vol.%. Therefore, the nanoparticle volume fraction between 0.0012 vol.% and 0.0024 vol.% is not a key parameter for the modified bubble dynamics under the specific operating conditions. However, for lower concentrations of nanoparticles in the base fluid, the nanoparticle loading can play an important role.

At the end of the nanofluid experiment, an evaluation of the condition of the pool boiling cell was performed. This included visual inspection of the cubic glass, where the nanofluid was housed, and the employed NiCr wire. Fig. 4 shows the condition of the cubic glass and heating wire, one day after the experiment was conducted. It is observed that all four lateral walls of the cubic glass are fouled with Al₂O₃ nanoparticles, mainly at the nanofluid surface level. The next step involved the use of a scanning electron microscope, SEM (S-3400 N, Hitachi) for a detailed analysis of the surface of the NiCr heating wire. For comparison reasons, SEM analysis of a new, unused NiCr wire was also performed. Fig. 5 presents SEM images of the horizontal part of the two wires, while Fig. 6 focuses on the vertical part of the wires.

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**Fig. 2.** Images of bubble formation in deionised water (left) and Al₂O₃-H₂O nanofluid (right), φᵥ = 0.0012 vol.%, during subcooled pool boiling at three sequential frames: dt1, dt2 and dt3 with a frequency of 15.2 Hz.

**Fig. 3.** Images of bubble formation in Al₂O₃-H₂O nanofluid, φᵥ = 0.0024 vol.%, during subcooled pool boiling at three sequential frames: dt1, dt2 and dt3 with a frequency of 15.2 Hz.

**Fig. 4.** Nanoparticle fouling at the side walls of the cubic glass and at the heating wire of the pool boiling cell, by two different angles, one day after an Al₂O₃-H₂O nanofluid experiment.

**Fig. 5.** SEM images of (a) unused and (b) contaminated NiCr heating wire (horizontal part) at the end of an Al₂O₃-H₂O nanofluid experiment.
The SEM imaging clearly demonstrates nanoparticle deposition on the heating wire. The observed deposits are either highly porous or relatively dense layers of nanoparticles. However, in either case there are pores that can act as nucleation sites. These findings are consistent with the literature, where nanoparticle deposition on the heating surface after boiling experiments has been reported [22–24].

4. Conclusions

A qualitative visualisation study of subcooled pool boiling of Al2O3-H2O nanofluids was conducted and compared to DI water that served as a benchmark. The purpose was to evaluate the contribution of nanoparticles to the bubble dynamics and bubble formation mechanisms primarily at the heating surface. A custom-made pool boiling system was used that provided maximum optical access. It was observed that the addition of alumina nanoparticles to the aqueous base fluid remarkably modifies the bubble dynamics and nucleation site activity at the NiCr heating wire. The modifications included the nucleation site density, the size of the bubbles at departure and the area of influence of the nucleation sites at the wire, at both the horizontal and vertical part. When a denser nanofluid was tested under maximum heat flux, it was observed that the bubble behaviour is visually the same with that of the initial nanofluid. Consequently, the nanoparticle volume fraction between 0.0012 vol.% and 0.0024 vol.% was not a major factor for the modified bubble dynamics under the specific operating conditions.

Visual observations of the pool boiling cell at the end of a nanofluid experiment revealed intense nanoparticle fouling of the lateral walls of the cubic glass, where the nanofluid was housed. Furthermore, scanning electron microscopy analysis of the heating wire, before and after a nanofluid experiment, confirmed intense nanoparticle deposition on the wire. Specifically, a coating of Al2O3 nanoparticles was observed on the surface of the wire, while nanoparticles had filled the microscopic cracks of the wire. By comparing the boiling behaviour of nanofluids at the horizontal and vertical parts of the wire, no differences were visually reported. Also, SEM images of both parts of the wire revealed a similar pattern in terms of nanoparticle deposition. In conclusion, deposition of Al2O3 nanoparticles on the heating wire was found to hold the key to the modified behaviour of the fluid during subcooled pool boiling conditions rather than the properties of the nanofluid.

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