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Experimental investigation on the pool boiling heat transfer to aqueous multi-walled carbon nanotube nanofluids on the micro-finned surfaces

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ABSTRACT

The pool boiling heat transfer characteristics of aqueous multi-walled carbon nanotube nano-fluids on modified surfaces are experimentally investigated up to the critical heat flux point. The surface has been modified with diamond-shaped micro-finned with different geometrical properties. Results demonstrated that the pool boiling heat transfer coefficient on the plain surface was deteriorated, while for micro-finned surfaces, it was enhanced up to 56% and 77% for wt.% = 0.1 and wt.% = 0.3 respectively. Likewise, results showed that modified surfaces decreased the rate of fouling in comparison with plain surface. It was also revealed that these surfaces can also form an irregular, non-uniform fouling layer, which improved the number of active nucleation sites and bubble formation. However, for a plain surface, a continual fouling layer was seen on the surface which created a huge thermal resistance and a significant decrease in heat transfer coefficient. In addition, deposition of carbon nanotubes on the surface caused some changes in surface characteristics such that the static contact angle value was found to be decreased and surface wettability to be increased as well. In this case, critical heat flux, CHF was enhanced up to 95% (for wt.% = 0.3). Besides, with increasing the mass concentration of nanofluids, static contact angle was found to be decreased too. In terms of bubble formation, experiments showed that the rate of bubble formation can be intensified, however the generated bubbles can discreetly depart the surface, which led the heat transfer coefficient to be enhanced due to the local agitation and available heat transfer area.

1. Introduction

Despite the extensive researches performed on the boiling heat transfer, this research topic has been remained as one of the major interests of the researchers due to the interesting sub-phenomena such as bubble formation, nucleation and superior heat transfer rate. Because of the superior heat transfer rate as the result of phase change phenomenon, boiling has widely been used as a dominant heat transfer mechanism in two-phase thermal systems, power cycles, refrigeration and heating/cooling thermal processes. In heat exchanging media, one main concern is the poor thermal conductivity of traditional coolants e.g. water or alcohols. Therefore, different passive or active techniques have been applied in order to enhance the thermal performance and efficiency of thermal systems.

Nano-fluids have been regarded as a new window to the future of advanced thermal fluid. Such colloid suspensions are nominated as a promising way to enhance the thermal conductivity and heat transfer coefficient in single-phase convective systems [1–6]. However, they are still under investigation inside the labs for their potential application in two-phase boiling systems. Moreover, passive techniques such as enhancing the heat transfer surface using extended surfaces (e.g. fins and modification of surface) have been found to have great positive impacts on heat transfer performance of cooling system [7–9]. As an evidence, an experimental research has been performed by Sahu and his co-workers [10] to examine the pool boiling thermal performance of ethanol/water coolant on the nano-textured surfaces comprised of copper-plated nano-fibers. Results of this experiment did not follow the standard boiling curve and showed a sharp deviation from that of obtained for pure water. In particular, the heat flux and accordingly, the heat

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transfer coefficient, were found to be significantly higher at low surface superheats. They also claimed that such micro-structures can be used over the extended time without any heat transfer deterioration due to the surface damage or fouling. In their research they did not give specific information about the fouling and deposition of nanoparticles on the surface. Besides, bubble formation was not studied too. Role of time in their study was neglected which could have significant influence on the results. Pastuszko and Wójcik [11] used a modified surface with micro-fins and sintered perforated foil to investigate the thermal boiling performance of water/FC. They found out that for water at low heat fluxes (below 25 kW/m^2) and also for FC-72, surfaces with micro-fins covered with perforated foil produced the highest heat transfer coefficient. Maximum heat flux for such surfaces increased 130% for water and 75% for FC-72 in relation to the smooth surface. However, the exact role for time, extended surface on the bubble formation, the enhancement of CHF or heat transfer coefficient was not determined. In a theoretical study, conducted by Quan et al. [12] a new model has been developed to predict the critical heat flux in pool boiling on a heated surface with micro/nano structures based on a force balance analysis, with effects of the capillary wicking force and modification of the critical instability wavelength taken into consideration. They showed that the exact role of micro/nano-sized cavities is to provide additional sites for vapor formation and to enhance the rate of heat transfer from the surface. However, transient study over the time for fouling formation was not established. Rocha et al. [13] established an experimental study on nucleate pool boiling of R134-a on the plain and micro-finned tubes at pressures between 6.1 bar and 12.2 bar. They found out that micro-fins can enhance the pool boiling heat transfer coefficient of refrigerant in comparison with plain surface. Ahn et al. [14] performed experimental studies on the capillary action of deposited layer of nanoparticles on the micro/nano structures of surface. They introduced a new approach to investigate the nanoparticle surface effect on CHF enhancement using surfaces modified with artificial micro, nano, and micro/nano structures similar to the deposited nanoparticle structures through the anodic oxidation on the zirconium alloy heater. They also investigated the potential influence of the capillary wicking action on the CHF enhancement due to the structured surfaces. The results demonstrated that the CHF enhancement on the modified surfaces was a consequence of the capillary wicking action ability of the artificial micro/nano structures. However, more studies seem to be required in order to obtain the similar results for other nanofluids. In another parametric study, Kwark et al. [15] investigated the role of average nanoparticle size, pressure, heater orientation, and heater size during pool boiling of water using Al_2O_3 nanoparticle coated flat heaters. Results indicate that pool boiling performance is dependent on the parameters tested, except the nanoparticle size, for both uncoated and nano-coated surfaces. The nanoparticle coated heater consistently produced dramatic critical heat flux enhancement relative to the uncoated surface at all tested conditions. It was postulated that the better wettability in the nano-coating, especially its ability to continuously rewet the base of the growing bubbles, was the main cause of enhancement. However, they ignored the study on the deposition of alumina nanofluids which could change the surface characteristics over the extended time. Also, such nano-coatings can create a thermal resistance on the surface which should be evaluated. This point was ignored too. Jo et al. [16] carried out experimental investigation on pool boiling heat transfer on the modified surface. They used a heating surface including a hydrophilic substrate with hydrophobic dots to characterize the effect of spatially-different surface characteristics on nucleate boiling heat transfer. They reported significant improvement of heat transfer coefficient, which depended on pitch size and geometrical properties of micro-structures. Liquid spreading on the micro-structure and inflow streams seem to be major reasons for enhancing the CHF in micro-structure extended surfaces [17] and capillary wicking action is the major factor for enhancing the CHF phenomenon on plain surfaces [14,18–21].

Based on the above-mentioned literature, a common point is: for extended surfaces, enhancement in heat transfer coefficient and system thermal performance have been reported, while following research gap can still be seen:

- In most of studies, role of deposition of nanoparticle on the characteristics of surface has been ignored. Note that, such deposition can create a porous layer which significantly creates a thermal resistance on the surface.
- Deposition is a strong function of time, thus, it is expected, in studies role of time is considered and results are obtained over the standard extended time (e. g. 1000 min of experiments). however, in most of studies, role of time on deposition and surface characteristics is ignored.
- It is critical to investigate the fouling formation and thermal performance of nanofluids on micro-structured surfaces, since it is generally believed that such surfaces can enhance the heat transfer rate. By combining this passive technique and utilizing the nanofluids, rate of enhancement in heat transfer coefficient can be dramatically improved, particularly when it comes to the boiling a wonderful material such as multi-walled carbon nanotubes.

In this work, the pool boiling heat transfer coefficient of a multi-walled carbon nanotube aqueous nano-fluids is experimentally quantified on a plain and micro-finned surfaces with considering the role of particle deposition, time and geometrical properties of micro-structures. A visual study is also performed to investigate the influence of micro-fins on the bubble formation in the pool boiling experiments. In order to investigate the role of deposition on thermal performance quantitatively, a new parameter is defined namely fouling thermal resistance. In addition, deposition can change the surface characteristics. Therefore, simultaneously with the fouling resistance, static contact angle of liquid drop on the surface is measured before and after boiling experiments.

2. Experimental

2.1. Experimental apparatus

In the present work, pool boiling critical heat flux and heat transfer characteristics of carbon nanotubes are investigated on the modified surface of a discoid heater. Fig. 1 presents a schema of experimental setup used for quantifying the pool boiling heat transfer coefficient and critical heat flux of CNT nano-fluids. This test rig consists of four main sections: 1) Discoid copper heater as the main test section. 2) Auxiliaries including: pre-heater, condenser installed inside the test vessel. 3) Temperature measurement instruments including: thermocouples, indicators, data acquisition and a Pentium IV pc computer as a post processor. 4) Imaging system including: a high-speed video recorder and a digital microscope with magnification of 500× (IPU500×).

Nano-fluid is loaded through the inlet port of the vessel. The vessel is a vertical pyrex-made cylinder, which has enough thermal resistance against the thermal stresses. In the bottom section of stainless steel cap, there is a perforated hole, in which a discoid copper-made heater is mounted. A small layer of Teflon insulation is used to prevent any liquid leakage and heat loss between discoid heater and the bottom of the vessel. The discoid heater consists of a dual diameter cylinder with an axial concentric hole at the bottom,