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Comparatively experimental study on the boiling thermal performance of metal oxide and multi-walled carbon nanotube nanofluids

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ABSTRACT

This work aims to focus on the flow boiling heat transfer characteristics of metal oxide and multi-walled carbon nanotube nanofluids inside an annulus heat exchanger. The flow boiling heat transfer coefficient and thermal fouling resistance parameter is experimentally quantified at different operating conditions including different heat and mass fluxes, mass concentration of nanofluid, and bulk temperature of nanofluid. In order to prepare the nanofluids, multi-walled carbon nanotubes (MWCNT), alumina and copper oxide nanoparticles were dispersed into deionized water. Based on the type of nanoparticle, different techniques were implemented for stabilizing the nanofluids such as functionalizing process for MWCNT, pH setting, ultra-sonic dispersion and adding the surfactant for metal oxide nanofluids. Results of time-Settlement experiments showed that functionalizing process can provide longer and reliable stability for MWCNT nanofluid. As a continuation, thermal conductivity of nanofluids was experimentally measured and compared to those of available in the literature. Then, experiments were carried out on the upward flow boiling heat transfer characteristics of nanofluids. According to the results, MWCNT/water nanofluid had higher thermal conductivity, higher boiling thermal performance and lower thermal fouling resistance value in comparison with other nanofluids. Likewise, boiling thermal performance of MWCNT nanofluids was found to be intensified, when heat and mass flux and concentration of nanofluids increased. The experimental heat transfer coefficients were also validated by comparing to the well-known correlations and available data in the literature.

1. Introduction

Despite the great potential of nanofluids in energy-saving and their wide applications in industrial and commercial aspects, deposition of nanoparticles inside the heat exchanging media has been an indispensable challenge amongst the heat transfer experts. Boiling heat transfer has long played a major role in heat transfer systems such as cooling of power cycles, refrigeration, air-conditioning, heat pumping as well as chemical–thermal processes [1,2]. Many efforts have been made to enhance the thermal performance of cooling systems using active or passive techniques. One of the cost-effective and efficient techniques is to use the advanced thermal engineering fluids (with enhanced thermal properties) such as nanofluids.

In fact, solid particles of the nominal size 1–100 nm are called nanoparticles, and low-concentration dispersions of such particles in a base fluid are called nanofluids. Nanofluid is a possible effective way to enhance the thermal conductivity over that of the base fluid, however, in some nanofluid-related studies, deteriorated or unchanged thermal conductivity has been reported [3–8]. Thus, a large number of experiments have been performed to investigate the thermal conductivity and behavior of nanofluid in cooling systems. In these studies, different types of nanofluid have been utilized such as: spherical or cubic metal oxide nano-powders, nanowires and nanotubes. Multi-walled carbon nanotube is regarded as an innovative material with wonderful thermal properties which can be considered as a promising option for using in heat transfer media due to its enhanced thermal features such as anomalous thermal conductivity and specific heat. However, instability of CNT nanofluids is still a significant drawback of its application in heat exchanging systems. Therefore, in this research, stabilizing of MWCNT nanofluid is carefully considered to overcome this problem. Forthcoming literature review presents some studies on the thermal performance of different CNT and metal oxide nanofluids.

1.1. Literature review

In this section, an overview is performed on the boiling-related publications. For instance, recently, Amiri et al. [9] has conducted experiments on the pool boiling heat transfer of MWCNT/water nanofluids. They investigated the influence of carbon nanotubes structures and different functional groups on the pool boiling heat transfer coefficient (HTC), using a functionalizing method as a major stabilizing process.

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Results showed that the HTC of the non-covalent nanofluid was lower than that of the deionized water, however the covalent nanofluids demonstrated a significant increase in HTC. In their research authors did not give specific information on depositing behavior of nanofluids or surface characteristics. In another empirical study, Kumar et al. [10] performed investigations on the boiling heat transfer of multi-walled carbon nanotube nanofluids in pure water and water containing 9.0% by weight of sodium lauryl sulfate anionic surfactant (SDS) over the flat plate heater. Results demonstrated that the addition of carbon nanotubes can increase the boiling heat transfer coefficient in comparison with the base fluid. Moreover, surfactants had positive impacts on the enhancement of heat transfer coefficient of CNT nanofluids. Results also revealed that by increasing the heat flux, the enhancement was concealed due to vigorous bubble generation for both water/CNT and water/CNT/surfactant nanofluids. Foaming was also observed due to the presence of surfactant over the liquid-free surface in water/CNT/surfactant nanofluids during the investigation. Neither fouling nor deposition layer was seen or reported over the heating surface after experimentation. In other researches, Kumar et al. [11] showed that enhancement in boiling heat transfer can be intensified by implementing the CNT coating on the heating surface. Each of the coated surfaces was tested repeatedly at different velocities to explore the dependence of heat transfer performance on operating parameters, especially the critical heat flux (CHF). The effect of wettability of the surface on the flow boiling heat transfer was also studied. A remarkable increase in the critical heat flux was observed on CNT-coated surface, when compared to the bare Cu or diamond coated Cu substrate. An enhancement of 21.6% in the CHF was observed for a mass flux of 283 $kg/m^2 \cdot s$. In this research, the role of surface coating and its internal fouling resistance on the boiling thermal performance was not studied. Liu et al. [12] studied the pool boiling heat transfer of CNT nanofluids under sub-atmospheric pressure and concluded that pressure can have great impacts on the boiling heat transfer coefficient, while no specific information was given regarding the role of pressure on the stability, deposition behavior of nanotubes and fouling thermal resistance. They also showed that the addition of CNTs in the base liquid can apparently enhance both the heat transfer coefficient (HTC) and the critical heat flux (CHF) and deposition of nanoparticles can change the surface characteristics which can change the thermal performance. However the exact role of deposition (e. g. deposition thickness and fouling resistance behavior) was not determined. Jung et al. [13] established several experiments to quantify the nucleate pool boiling heat transfer coefficient and characteristics of aqueous CNT nanofluids up to the CHF point on a square flat copper heater. Experimental results demonstrated that the pool boiling heat transfer coefficient of the CNT nanofluids is lower than that of measured for pure water in the entire nucleate boiling regime. Also, experiments showed that a thin layer of CNT deposit can be formed on the heater, which changes the surface characteristics and number of nucleation sites. In fact, deposition porous layer could decrease the number of active nucleation sites of the surface and may create a significant thermal resistance on the surface over the time. However, similar to the previous studies, no specific information was given regarding the fouling thermal resistance. Based on the summarily above-mentioned literature, boiling heat transfer coefficient can be enhanced by addition of carbon nanotubes to the conventional coolants such as water or ethylene glycol. But the main point is: to the best of our knowledge, no transient studies on the fouling thermal resistance parameter (considering the role of time, stability and deposition behavior with time) have been performed on different nanofluids. Moreover, boiling thermal performance of different nanofluids has not been comparatively studied. In fact, fouling formation due to the deposition of CNTs can create a non-uniform deposition layer, which induces undesired thermal resistance to the boiling system. Such layer can be a porous medium with irregularities and micro-cavities, which can also influence on the bubble formation and bubble transport mechanism during the boiling heat transfer. Therefore, fouling has a strong influence on boiling thermal performance and study over the time is necessary to obtain the thermal resistance behavior of nanofluids over the extended time.

For metal oxide nanofluids, there is another controversial story. For instance, Yang and Maa [14] investigated the boiling performance of Al_2O_3–water nanofluids around the horizontal tube. Results showed that when concentration of nanoparticles increases, boiling heat transfer can be enhanced considerably. By contrast, Prakash et al. [15] reported the significant deterioration of boiling heat transfer coefficient for a horizontal and inclined tube. The conditions of experiments for both works [14,15] were almost the same, while results were significantly different. In another study, Sarafraz et al. [16,17] investigated the fouling resistance of CuO/water and CuO/ethylene glycol nanofluids and postulated that micro-layer of boiling can have a constant concentration of nanoparticles, if nanoparticles are stabilized. They showed that flow boiling heat transfer coefficient drastically deteriorates due to the fouling of nanoparticles around the heating section. They also explained that fouling behavior can be asymptotic and somewhere rectilinear, however the exact behavior of thermal resistance was not fully explained. Also, no specific study was performed on the surface characteristics e.g. roughness, deposition thickness and surface wettability. A study on forced convection heat transfer and fluid flow of TiO_2/water nanofluids under turbulent flow condition has been experimentally carried out by Duangthongsuk and Wongwises [18] on a horizontal double-tube counter flow heat exchanger. They observed a very slight enhancement in heat transfer coefficient (about 6–11%) in comparison with pure water. They also reported some scale formation regions inside the heat exchanger. They reported that by increasing the mass flow rate of the hot water and nanofluid, the heat transfer coefficient considerably increases without mentioning the exact mechanism of enhancement of heat transfer (likely thermal conduction or forced convective heat transfer) due to the presence of nanoparticles. Kim and Ahn [19] and Kim et al. [20] studied the boiling heat transfer of alumina nanofluids up to the critical heat flux. They showed that nanoparticle deposition on the heater leads to the formation of thicker macro-layer around the heating section which leads the CHF to be enhanced due to the wettability enhancement. They did not specify any significant enhancement or deterioration on heat transfer coefficient. There are also more controversial studies, in which fouling and scale formation of nanofluids on the surface have been visually studied, which can be found in the literature [21–25]. Based on the conducted researches, it can be stated that some researchers believe that boiling heat transfer in metal oxide nanofluids can enhance the boiling heat transfer coefficient, while there are other researchers who insist on the deterioration of boiling heat transfer coefficient, when boiling comes to the nanofluids. Both of the groups have a point in common which implies on this fact that fouling formation is a common phenomenon for nanofluids, when they are used as a coolant. Also, CHF point can be enhanced, when nanofluid is used as a working fluid. Likewise, in most of studies, enhanced thermal conductivity over the base fluid has been considered as the main feature of nanofluids. Xie et al. [26], Chen et al. [27], Assael et al. [28] reported that thermal conductivity of CNT/water nanofluid can be enhanced up to 7%, 12% and 38% respectively (for volumetric concentration of 1%). In some other studies, thermal performance of CNT nanofluids were examined using surfactant as a dispersant within the base fluid up to 21% for SDS, 13% for Triton-x100 [29–33]. For metal oxide nanofluids, the same conclusion is drawn [3, 29]. So, the main question is: despite the enhancement in thermal conductivity, can nanofluid enhance the boiling thermal performance of a system? In this study, we try to find an answer for the contraries raised in the literature and fill the research gap regarding the thermal resistance behavior of nanofluids.

In the present work, in order to investigate the boiling thermal performance of nanofluids, Al_2O_3, CuO and MWCNT aqueous nanofluids are utilized inside an annulus vertical heat exchanger. Initially, stability of nanofluids is improved using functionalizing process for CNTs and for metal oxide nanofluids, pH setting, stirring and addition of surfactant