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Research Paper

On the fouling formation of functionalized and non-functionalized carbon nanotube nano-fluids under pool boiling condition

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HIGHLIGHTS

- Pool boiling heat transfer characteristics of CNT/water nano-fluid is studied.
- Functionalized and non-functionalized CNT nano-fluids are investigated.
- Fouling formation of both nano-fluid is experimentally studied.
- Non-functionalized nano-fluid are found to enhance the CHF.
- Functionalize nano-fluids are found to enhance the heat transfer coefficient.

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ABSTRACT

Pool boiling heat transfer coefficient (HTC) of functionalized carbon nanotube (FCNT) and non-functionalized carbon nanotube (CNT) is experimentally quantified at high-heat flux conditions up to the critical heat flux (CHF) point. Nano-fluids are prepared using two-step method and are well dispersed within the deionized water, followed by functionalizing (by carboxyl group), sonication and adding the nonylphenolethoxylates nonionic surfactant as a dispersant. In terms of stability, results showed that FCNT could be stable up to three successive weeks, while seven days of stability was registered for non-FCNT. In addition, FCNT considerably enhance the heat transfer coefficient and CHF point. Since this nano-fluid does not change the roughness of surface considerably and has great wettability in comparison with CNT nano-fluid. Results also demonstrated although fouling formation of functionalized carbon nanotube is insignificant in comparison with CNT, the lower contact angle between liquid droplet and the surface caused more liquid to be absorbed by the porous fouling layer. Therefore, more liquid are available on the surface, which leads the dry-out regions to be re-wetted. Consequently, significant enhancement in CHF point was registered for FCNT nano-fluids in comparison with CNT. In terms of fouling behavior, asymptotic behavior for fouling resistance is seen for CNT, while the rectilinear fouling behavior was seen for FCNT.

1. Introduction

Efficient cooling in high heat flux surfaces such as semi-conductors (e.g. processors), microelectronics or chemical reactors (e.g. pressurized water reactors) has been an interesting challenge for heat transfer experts. Boiling heat transfer provide superior heat transfer rate, which can be used in power cycles, refrigeration and cooling systems. This large quantity of heat can be achieved in case of utilizing the boiling mechanism, due to the phase change phenomenon, micro/macro bubble transports, and local agitation due to the bubble interactions. Therefore, smaller surface is required for a system working in boiling condition. However, due to the complexities and limitations encountered in utilization of boiling, more studies are still required. Critical Heat Flux (CHF) in boiling heat transfer, as a definition, is a limited point in which, phase change process acts in a way that bubbles can cover and overwhelm the heating surface, which leads to the overheating problem. In this condition, heat transfer coefficient starts decreasing over the higher given heat fluxes, which can finally damage to the surface or explode the heater. Therefore, it is required to use efficient but high performance coolants in high heat flux systems. Nano-fluids (a traditional coolant such as water comprising the solid particles with size of 0–100 nm, which was called "Nano-fluids" by Choi [1]) are promising nominations for future of advanced thermal fluids due to their outstanding thermal conductivity. In fact, nano-fluids represent the

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higher thermal conductivity rather than conventional coolants, sometimes 2-fold or 3- fold larger than that of the base fluid. Many efforts have been made to investigate the potential application of nano-fluid in convective systems [2–10]. In general, positive results on enhancement of heat transfer have been obtained for the convective systems working with nano-fluid; although small penalties for pressure drop and pumping power have also been reported through the literature.

For nucleate boiling heat transfer, controversial literature has been found, which can be categorized in two different groups. The first group believes that boiling heat transfer coefficient can be enhanced by nano-fluids, since nano-fluids have better conductivity and convection coefficient [11–14]. The second group believes that due to the fouling of nanoparticles on the heating surface, number of nucleation sites can be reduced over the extend time [15–18]. However, both groups have a point in common, which implies in this fact that nano-fluids can enhance the boiling CHF. For example, Ahn and his co-workers [19] established experiments on forced convection and CHF characteristics of nano-fluids. The experimental results showed that the nano-fluid flow boiling CHF was distinctly enhanced under the forced convection flow conditions compared to that in pure water. Subsequent to the boiling experiments, the heater surfaces were examined with scanning electron microscope and by measuring contact angle. The surface characterization results implied on this fact that CHF enhancement is mostly caused by the nanoparticles deposition of the heater surface during vigorous boiling of nano-fluids and the subsequent wettability enhancements. Kim et al. [20] conducted an experimental study on flow boiling CHF of alumina nano-fluid and alumina coated tubes. The flow boiling CHF of alumina nano-fluid with a plain tube and de-ionized water with an alumina-coated tube were enhanced up to about 80% for all experimental conditions. There was no big difference in the CHF results between two methods. The obtained results indicate that the CHF enhancement of alumina nano-fluid is surely caused by deposition of nanoparticles on the test section tube inner surface. An experimental study was carried out by Yang and Liu [21] to investigate the pool boiling heat transfer characteristics of functionalized nano-fluid at atmospheric and sub-atmospheric pressures. Experimental results show that there exist great differences between pool boiling heat transfer characteristics of functionalized and traditional nano-fluid. The differences mainly result from the changes of surface characteristics of the heated surface during the boiling. Therefore, the pool boiling heat transfer of nano-fluids is governed by both the thermo-properties of nano-fluids and the surface characteristics of the heated surface. In another study, Song et al. [22] experimentally investigated on boiling characteristic of SiC nano-fluid and evaluated the thermal performance of SiC nanoparticles in water pool boiling up to CHF. The volume concentrations of SiC nano-fluid were 0.0001%, 0.001%, and 0.01%. The CHF has been enhanced up to 105% for volume concentration 0.01%. CHF enhancement trend was interesting because it was not linearly dependent on nanoparticle concentration. The wettability change of SiC nanoparticle deposited surface was discussed as main reason of CHF enhancement variation. Boiling behaviors of ZnO nano-fluid on a horizontal and vertical plate in saturated pool boiling was experimentally studied by Mourgous et al. [23]. According to the previous works, it can be stated that CHF enhancement is the obvious consequence of using nano-fluid at boiling condition. The main reason for this fact can be referred to the fouling formation of nanoparticles on the surface, intensification of capillary wicking which causes changing in surface characteristics due to the deposition. Among the different nano-fluids that have been investigated by several authors, carbon nanotubes, CNTs are regarded as promising materials, which have superior thermal conductivity when they are dispersed uniformly within the base fluid. Table 1 presents the summary of some significant researches conducted on thermal conductivity measurement of carbon nanotube.

According to Table 1, a clear conclusion can be drawn as CNT nano-fluids have anomalous thermal properties, particularly thermal conductivity, while their boiling thermal behavior is not currently well known or is still understudied. In a recent work, Amiri et al. [32] has conducted experiments on pool boiling heat transfer of MWCNT/water nano-fluids. They investigated the influences of carbon nanotubes structures and different functional groups on the pool boiling heat transfer coefficient, HTC, using functionalizing method as a major stabilization process. Results showed that while the HTC of the non-covalent nano-fluid was lower than that of the deionized water, the covalent nano-fluids demonstrated a significant increase in HTC, while no information on deposition of MWCNT on the surface were reported. Kumar et al. [33] performed investigations regarding boiling heat transfer of multi-walled carbon nanotube suspension in pure water and water containing 9.0% by weight of sodium lauryl sulphate anionic surfactant (SDS) over the flat plate heater. The experimental data demonstrated that with adding the carbon nanotubes, boiling heat transfer coefficient could be increased in comparison with the base fluid. Moreover, surfactants had positive influences on the enhancement of heat transfer coefficient in boiling condition of CNTs. Results also revealed that with increasing heat flux, the enhancement was concealed due to vigorous bubble generation for both water/CNT and water/CNT/surfactant nano-fluids. Foaming was also observed due to presence

Table 1
Researches on thermal conductivity of CNT nano-fluids.

Author	CNT	Base fluid	Remarks
Xie et al. [24]	MWCNT	DI-water	Thermal conductivity was measured using hot wire method for multi-walled CNT, Thermal conductivity enhancement = 7% at vol. % = 1.
Chen et al. [25]	MWCNT	DI-water	Thermal conductivity was measured using hot wire method for multi-walled CNT, Thermal conductivity enhancement = 12% at vol. % = 1.
Assael et al. [26]	MWCNT	DI-water	Thermal conductivity was measured using hot wire method for multi-walled CNT, Thermal conductivity enhancement = 38% at vol. % = 0.6, SDS was used as dispersant.
Hwang et al. [27]	MWCNT	DI-water	Thermal conductivity was measured using hot wire method for multi-walled CNT, Thermal conductivity enhancement = 21% and 13%, respectively for SDS and Triton X-100 at vol.% = 0.6%, SDS and Triton X-100 were used as dispersant
Aravind [28]	MWCNT	Water/ethylene glycol	Thermal conductivity was measured using Lambda instrument for multi-walled CNT, Thermal conductivity enhancement = 33–40% at vol. % = 0.03.
Ding et al. [29]	MWCNT	DI-water	Thermal conductivity was measured using KD2 Pro instrument for CNT (type was not specified), Thermal conductivity enhancement = 25% at wt. % = 0.5.
Jha et al. [30]	Ag/MWCNT	DI-water	Thermal conductivity was measured using KD2 Pro instrument for Ag/MWCNT composite nano-fluid, Thermal conductivity enhancement = 37.3% at vol. % = 0.03.
Kim et al. [31]	MWCNT	DI-water	Thermal conductivity was measured using hot wire method for multi-walled CNT, Thermal conductivity enhancement = 25% at wt. % = 0.01.