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Pool boiling heat transfer to aqueous alumina nano-fluids on the plain and concentric circular micro-structured (CCM) surfaces

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ABSTRACT

The present work mainly focuses on the pool boiling heat transfer of aqueous alumina nano-fluids up to critical heat flux point on a circular surface at two mass concentrations of 0.1%, 0.3% and nanoparticle size of 20 nm and 50 nm. Nano-fluids were prepared using two-step method and were stabilized by nonylphenolethoxylate (NPE), non-ionic surfactant. Surface of the heater was modified by CNC micro-machinery technique and concentric circular microstructures (CCM) were created on the surface with different geometrical specifications. Results demonstrated that the heat transfer coefficient (HTC), could be deteriorated and enhanced for the plain and micro-structured surface respectively. However, rate of enhancement depended in part, to the particle size and geometrical specifications of microstructures. Rate of enhancement was found to be intensified with increasing the heat flux and mass concentration, decreasing the nanoparticles size and the interspace between microstructures, however height of microstructures had no particular influence on HTC. In terms of critical heat flux point (CHF), nano-fluids expectedly enhanced the CHF value. The enhancement rate of CHF was intensified with increasing the mass concentration of nano-fluid, nano-particle size and interspace between microstructures. The main reason for enhancing the heat transfer coefficient over the micro-structured surface was due to the larger heat transfer area in comparison with plain surface. While for the plain surface, deterioration of heat transfer coefficient was due to the continual fouling formation of nanoparticles on the surface, which increased the static contact angle of nano-fluid on deposited layer and subsequently reduced the number of active nucleation sites. Capillary wicking action and constitution of inflow liquid inside the fouling layer were the main reasons for CHF enhancement since can diminish the surface dry-out regions and enhance the surface toleration against the CHF crisis. Accordingly, a modified mechanism was proposed for enhancing the CHF in nano-fluids, which was the combination of liquid absorption from the bulk of nano-fluids, by the deposition layer and inflow capillary wicking action inside the deposition layer, which leads to the rewetting phenomena in dry-out regions.

1. Introduction

Quenching the high heat flux surfaces such as semi-conductors (e.g. micro-electronic devices (e.g. chipsets and integrated circuits)) and chemical reactors (e.g. pressurized water reactors) has been an interesting challenge for heat transfer experts. Boiling is an ideal heat transfer mechanism, which can be used in power cycles, refrigeration and cooling systems. Moreover, superior heat transfer coefficient can be achieved in case of utilizing the boiling as a dominant cooling–heating mechanism, due to the phase change phenomena, micro/macro bubble transports and local agitations. Thus, smaller surface is required for a system working at boiling condition. Note that, boiling systems face complexities and limitations when they are utilized in industrial sector, therefore more fundamental studies are still required on the boiling mechanism and its practical applications.

Critical Heat Flux (CHF crisis), as a definition, is the limited point in which, phase change process acts in a way that bubbles can fully cover and overwhelm the heating surface and lead to the poor heat transfer. Subsequently, heat transfer coefficient decreases over the higher given heat fluxes, which can finally damage the surface or explode the heater. Generally, a nucleate

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Nomenclature

H	height of microstructures
h	heat transfer coefficient, kW/m^2 K
h_c	clean surface heat transfer coefficient, kW/m^2 K
h_f	clean surface heat transfer coefficient, kW/m^2 K
I	current, A
k	thermal conductivity, W/m K
q	heat flux, kW/m^2
R	heater radius, m
R_f	fouling resistance, m^2 K/kW
s	microstructure wall space, m
T	temperature, K
V	voltage, V
W	width of microstructures
z	axial distance, m
Greek letters	
α	equation constant,
β	equation constant
Abbreviations	
CCM	concentric circular microstructure
CHF	critical heat flux
DI	deionized
HF	heat flux
HTC	heat transfer coefficient
PS	plain surface

boiling system is comprised of three heat transfer mechanisms: (1) heat conduction through liquid from the boiling surface to the liquid–vapor equilibrium interface, (2) evaporation at the liquid–vapor interface towards the vapor phase (3) heat transfer by the bubbles. The critical heat flux phenomena occur, when either bubble formation or escape of vapor is restricted or hindered.

Nano-fluids [1] are promising option for the future of advanced thermal fluids due to their outstanding thermal features, especially thermal conductivity. In fact, nano-fluids represent the higher thermal conductivity rather than conventional coolants, sometimes 2–3 fold larger than that of the base fluid. Thus, many efforts have been made to investigate the potential application of nanofluid in convective systems with emphasis on the enhancement of heat transfer coefficient [2–10]. Although heat transfer enhancement was satisfactory, a small penalty for pressure drop and pumping power have been reported though. However, there is another controversial story for the nucleate boiling heat transfer. Some researchers believe that boiling heat transfer coefficient can be enhanced by nano-fluids, since nano-fluids have better thermal conductivity and convection coefficient [11–14]. The second group insists that due to the deposition of nanoparticles on the heating surface, number of nucleation sites can be reduced over the extend time and surface characteristics can be changed in a way that heat transfer coefficient is decreased over the extended time [15–18]. Interestingly, both groups have a point in common that nano-fluids can enhance the boiling CHF crisis point. For example, Ahn and his co-workers [19] performed experiments on the forced convection and CHF characteristics of nano-fluids. The experimental results showed that CHF point was distinctly enhanced at the forced convection mechanism region in comparison with pure water. Subsequent to the boiling experiments, the heater surfaces were examined with scanning electron microscope and by measuring the contact angle as well. The surface characterization results showed that CHF enhancement is mostly caused by the nanoparticles deposition on the surface during vigorous boiling of nano-fluids with a significant enhancement in wettability of surface. Kim et al. [20] conducted an experimental study on flow boiling critical heat flux (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 considerable difference in the CHF results between two methods. The obtained results also indicated that the CHF enhancement of alumina nano-fluid was surely due to the deposition of nanoparticles on the inner surface of test section. Somewhere else, 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 showed that there exist great differences between pool boiling heat transfer characteristics of functionalized and traditional nano-fluid. The differences mainly resulted from the changes of surface characteristics of the heated surface during the boiling. Therefore, the pool boiling heat transfer of nano-fluids may be 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 values were enhanced up to 105% for volume concentration of 0.01%. CHF enhancement trend was interesting, because it did 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 Mourgues et al. [23] and similar findings were reported as a support of the previous literature review.

In this work, experimental study is conducted on the pool boiling heat transfer to alumina nano-fluids on a disc heater with plain and modified surfaces. To modify the surface, CNC micro-machinery was utilized and microstructures were created on the surface at different geometrical parameters. Influence of different operating parameters such as heat flux, mass concentration of nano-fluids, particle size and microstructure specifications on the pool boiling heat transfer and CHF has been experimentally investigated and deeply discussed. Surface characterizing experiments including the measurement of static contact angle, analysis of surface thermal fouling resistance and capillary wicking action were performed and their influences on the enhancement of CHF crisis point are deeply studied. Potential role of fouling thermal resistance on the heat transfer coefficient is also investigated.

2. Experimental

2.1. Experimental setup

Fig. 1 illustrates a schema of experimental setup used for quantifying the pool boiling heat transfer coefficient and CHF value of alumina nano-fluids. The test rig consists of four main sections:

(1) Discoid copper heater as the test section, (2) auxiliaries including pre-heater, condenser installed inside the test vessel, (3) temperature measurement instruments including thermocouples, indicators, data acquisition and a post PC processor, (4) imag-