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Flow boiling heat transfer enhancement on copper surface using Fe doped Al_2O_3–TiO_2 composite coatings

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ABSTRACT

In the present work, flow boiling experiments were conducted to study the effect of spray pyrolyzed Fe doped Al_2O_3–TiO_2 composite coatings over the copper heater blocks on critical heat flux (CHF) and boiling heat transfer coefficient. Heat transfer studies were conducted in a mini-channel of overall dimension 30 mm × 20 mm × 0.4 mm using de-mineralized water as the working fluid. Each coated sample was tested for two mass fluxes to explore the heat transfer performance. The effect of Fe addition on wettability and porosity of the coated surfaces were measured using the static contact angle metre and the atomic force microscope (AFM), and their effect on flow boiling heat transfer were investigated. A significant enhancement in CHF and boiling heat transfer coefficient were observed on all coated samples compared to sand blasted copper surface. A maximum enhancement of 52.39% and 44.11% in the CHF and heat transfer coefficient were observed for 7.2% Fe doped TiO_2–Al_2O_3 for a mass flux of 88 kg/m^2 s.

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1. Introduction

Mini- channel and micro-channel two phase flow boiling systems have a potential role in high heat dissipating applications like super computers, nuclear reactors, high power electronics, defense and aerospace due to the high heat transfer by latent heat of boiling. Critical heat flux (CHF) is the limiting parameter in two phase heat transfer studies, during which a sudden rise in temperature causes the catastrophic failure of the devices [1]. Critical heat flux varies according to the mass flux because of the size and nature of the vapour blanket formed. For lower mass flux a continuous vapour layer covers the whole heated surface, leading to a sudden increase of surface temperature and thereby occurrences of lower critical heat flux. In high mass flux, higher CHF is produced by local dryout below the discrete vapour blanket [2]. CHF can be improved by increasing the subcooling temperature; during subcooling the heat carrying ability of the fluid increases significantly due to the energy absorption in the form of sensible heat prior to vaporization [3]. Channel dimension is another important factor which has significant influence on flow boiling performance and CHF. In small channels, CHF occurs due to downstream dry out. Improvement in heat transfer rate of two phase flow is high, due to sudden acceleration of fluid in microchannel and close propinquity of bulk fluid with the heated surface. The main drawback of reducing the channel dimension is the increase in pressure drop [4], this leads to necessity of passive techniques like modifying the base fluid by adding nanoparticles, surface modification and coating on the surface [5–11]. Modification of the boiling surface by changing the wettability and roughness improves the heat transfer [6]. Another promising technique for improving the two phase heat transfer is surface coating.

Development in the field of nanotechnology and characterization leads to the implementation of nanostructured surface coating for heat transfer applications [7–11].

Nanostructured surface coatings have emerged as the preferred mode of CHF enhancement in micro and mini devices, due to the high heat transfer achieved for thinner coating, significantly reducing the pressure drop experienced. It is found that CNT coating enhances CHF, in low mass flux conditions, due to high thermal conductivity and fin action [8–10]. The increase of mass flux causes bending of nanotubes as well as scaled effects which lead to

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Nomenclature

k	thermal conductivity (W/m k)
q	heat flux (W/m^2)
h_{avg}	average boiling heat transfer coefficient (W/m^2 k)
T_1, T_2	temperature measured from heater section in vertical direction (°C)
$T_{f\,avg}$	average fluid temperature (°C)
T_{fout}	local fluid temperature at outlet (°C)
T_{savg}	average surface temperature (°C)
h	Planck constant (6.626×10^{-34} J s)

Subscripts

in	inlet
out	outlet
s	surface
f	fluid

Abbreviations

AFM	atomic force microscopy
CHF	critical heat flux (W/cm^2)
CNT	carbon nanotube
DLC	diamond like carbon
PEEK	polyether ether ketone
PID	proportional integral derivative
XRD	X-ray diffraction

Greek symbols

Δx	vertical distance between thermocouples (m)
υ	frequency (s^{-1})
α	absorption coefficient (cm^{-1})

diminishing of CHF enhancement. Nanowires are a group of materials that have the properties of boiling enhancement such as wettability, porosity, and wicking structure. Morshed et al. [11] investigated the effect of copper nanowires on flow boiling heat transfer and observed a CHF enhancement of 56% in comparison to the bare copper surface. Li et al. [12] conducted flow boiling heat transfer enhancement study in microchannels using monolithically integrated silicon nanowires. Integration of silicon nanowires results in a delayed onset of flow oscillation, suppresses the temperature instability, pressure drop and the augmented heat transfer coefficient (HTC). In nanocoated microchannel a stable flow boiling trend was observed over a wide range of heat flux. Yang et al. [13,14] observed flow boiling regimes and conducted heat transfer studies on silicon nanowire coated microchannel. They visualized the flow regimes for various high heat flux conditions on silicon nanowire coated microchannel and obtained single annular flow regime instead of multiple flow regime as present in microchannel without coating. They obtained an enhancement of 300% in CHF for the coated surface as compared to the uncoated. Such a remarkable enhancement in CHF was due to the unified flow regime, which is highly stabilized and also causes a large pressure drop. Porous metal coatings have been investigated as a suitable candidate for the CHF enhancement. Particle size, shape, coating thickness and porosity of the coating influence the CHF. Bai et al. [15] studied the effect of porous metallic coatings using the solid sintering technique on flow boiling heat transfer. Anhydrous ethanol was used as the working fluid. A significant enhancement in heat transfer was found in porous metal coated micro channel as comparing with the bare microchannel. The higher heat transfer rate at lower vapour quality was obtained due to higher nucleation density. Wang et al. [16] used sintered aluminium coating in vertical micro channel and observed 2–5 times enhancement in boiling heat transfer coefficient as compared to an uncoated surface. Sarwar et al. [7] studied the heat transfer enhancement in flow boiling using porous alumina and titanium dioxide coatings. Different sized alumina and titanium dioxide particles were coated over the substrate using omega bond epoxy and it was found that porous alumina coatings of <10 μm size and 50 μm thickness produce maximum CHF enhancement. Subcooling temperature had significant influence on CHF, with an increase in subcooling temperature CHF will also increase.

Surface wettability has significant impact on the boiling heat transfer. In lower heat flux conditions, the lower free energy requirement for nucleation induces early onset of boiling in hydrophobic surfaces. But at higher heat fluxes, the sudden formation of bubbles across the surface result in lower heat transfer for the hydrophobic surfaces as compared to hydrophilic. Sarwar et al. [6] studied the effect of hydrophilicity and surface roughness on the flow boiling heat transfer. Wettability of the coated surfaces increased, with progress in time due to the entrapment of water inside the micro pores. Phan et al. [17] compared the flow boiling heat transfer in diamond like carbon (DLC) and TiO_2 and obtained an enhancement of 10% in CHF for TiO_2 coated sample. Takata et al. [18] investigated the effect of surface wettability on pool boiling heat transfer by using a super hydrophilic TiO_2 coating. Significant increase of CHF was observed for coated surface as compared to the uncoated surface. A rise of 100 K in the maximum surface temperature was found in the coated surface. Wu et al. [19] conducted pool boiling heat transfer experiments using hydrophilic titanium oxide coatings, with saturated water and F72 as the working fluids. TiO_2 coated surface increased CHF by 50.4% and 38.2% for water and F72 respectively, as compared to the smooth uncoated surface. Hydrophilic TiO_2 coating increases the effective liquid-solid interaction and reduces the dry patches caused by growing bubbles and eventually enhances both nucleate boiling and CHF. Weng et al. [20] studied the hydrophilicity effect of Fe^{3+} doped TiO_2 coatings produced by using the spray pyrolysis technique. They used UV-visual spectroscopy to determine the effect of doping concentrations on hydrophilicity. An appreciable improvement in surface wettability was observed with increase in Fe^{3+} doping.

There are various techniques available for coating metal oxide on substrates, namely, sol–gel synthesis, thermal spraying, sintering, spray pyrolysis, and using adhesives. Among these, spray pyrolysis is widely used because of ease of doping, control of thickness, variation of film composition, scalability of the process, cost-effectiveness with regard to equipment costs and energy needs, and operation at moderate temperatures (100–500 °C). Variation of deposition parameters such as substrate temperature, spraying distance, solution flow rate and molarity of the solution allows us to produce the desired coatings [21].

In this study, the spray pyrolysis technique was used to produce Al_2O_3–TiO_2 (9:5 molar ratios) with different at% of Fe (0%, 1.8%, 3.6%, and 7.2%). The flow boiling heat transfer characteristics of the coated as well as the bare blocks were tested for different mass flux conditions. The boiling heat transfer coefficient and CHF enhancement were obtained and compared with the uncoated sand blasted copper substrate.

2. Experimental

2.1. Fe–Al_2O_3–TiO_2 composite deposition and characterization

The Fe–Al_2O_3–TiO_2 composite coatings were obtained using spray pyrolysis apparatus (HOLMARC HO-TH-04). TiO_2 solution was prepared using, butyl titanate ($Ti(OC_4H_9)_4$, Alfa Aesar) and iron (III) nitrate ($Fe(NO_3)_3$, Merck) as precursors, acetyl acetone ($CH_3COCH_2COCH_3$, Alfa Aesar) as the stabilizer and ethanol (C_2H_5OH, Alfa Aesar) as the solvent. Butyl titanate, iron (III) nitrate

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