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Flow boiling heat transfer enhancement using carbon nanotube coatings

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HIGHLIGHTS

- Vertically aligned carbon nanotubes were coated on the copper substrate.
- Diamond used as the intermediate diamond layer for improving the adhesion.
- Leftward shift in boiling curve was obtained for carbon nanotube coating.
- Enhancement in the critical heat flux was achieved using carbon nanotube coating.

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ABSTRACT

In the present study, experiments are performed to understand the effect of carbon nanotubes (CNTs) and diamond coating over copper substrates on flow boiling heat transfer performance. Using demineralized water as the working fluid, heat transfer experiments were conducted in a mini-channel with an overall dimension of 25 × 20 × 0.4 mm. Each of the coated surfaces was tested repeatedly at different velocities to explore the dependence of heat transfer performance on parameters, especially the critical heat flux (CHF). The effect of wettability of the surface on flow boiling heat transfer was also studied. A remarkable increase in the critical heat flux was observed on CNT-coated surface when compared with 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 s.

1. Introduction

Miniaturization of electronic devices leads to an increase in heat dissipation per unit area. The performance and lifetime of the electronic devices depend on their ability to dissipate the waste heat safely. Conventional cooling methods like air cooling are inefficient to cool down those electronic devices. The heat extraction rate can be increased by using a liquid coolant due to its high heat carrying capacity. But even these liquid cooling methods are not efficient enough to extract the heat due to the small size of the electronic devices [1]. Among different available cooling devices, microchannel heat sinks are found to be efficient in extracting heat from MEMS (micro electro mechanical system) based devices [2]. Condensation and boiling heat transfer mechanism in microchannel has attracted increasing research interest recently due to its high heat transfer coefficient [3,4]. Because convective heat transfer coefficient is inversely proportional to the hydraulic mean diameter of the channels, it is much higher for microchannels than for conventional channels. A microchannel holds great potential in two-phase flow applications, because of the high fluid acceleration along the length, the closeness of the bulk fluid to the heated surface and absence of stratified flow due to presence of permanent liquid film over the surface [3–5]. Due to the high heat transfer coefficient of the two-phase flow, the surface temperature can be maintained more uniformly when compared to single- phase flow [6–8].

Chen et al. [4] reviewed experimental and theoretical analysis of condensation in microchannels. In this study they investigated the effect of channel diameter, surface conditions on different flow regimes of condensations. Among the different governing forces, surface tension was found more dominant in the case of smaller diameter channels like microchannels. Stratified or annular flow was absent in microchannel fluid flow application due to the

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Nomenclature

A_c	area of cross section (m^2)
f	wetting force
k	thermal conductivity (W/m k)
p	perimeter of contact line
q	heat flux (W/m^2)
T	temperature (°C)
h	boiling heat transfer coefficient (W/m^2 k)
G	mass flux (kg/m^2 s)
T_1, T_2	temperature measured from heater section in vertical direction (°C)
T_f	average fluid temperature (°C)
T_s	average surface temperature (°C)

Subscripts

act	actual
in	inlet
out	outlet
w	bottom wall
f	fluid
c	cross section
tot	total
sub	subcooled
vap	vapourization

Abbreviations

CHF	critical heat flux (W/cm^2)
HFCVD	hot filament chemical vapour deposition
CNT	carbon nanotube
DLC	diamond-like carbon
ONB	onset of nucleate boiling
SEM	scanning electron microscope
XRD	X-ray diffraction
MEMS	micro electro mechanic system
sccm	standard cubic centimetres per minute
DC	direct current

Greek symbols

Δx	vertical distance between thermocouples (m)
μ	dynamic viscosity of fluid (N s/m^2)
ρ	density (kg/m^3)
ω	uncertainty
γ_{lv}	liquid tension
θ	contact angle

smaller hydraulic mean diameter. Surface roughness and wettability are the key factors affecting condensation. Authors concluded that these factors must be optimized to get the maximum condensation rates. Chen et al. [9] investigated and visualized the effect of condensation of steam in a series of triangular microchannel. They observed that, during condensation droplet, annular, injection and slug-bubbly flow were dominated by surface tension and shear stress on vapour–liquid interface. They also observed the location of injection flow moved towards the channel outlet as the vapour mass flow rate increases. They found out that average heat transfer and average condensation Nusselt number increase with increase of inlet vapour Reynolds number. Chen et al. [10] reviewed condensation in microgravity environment to study the influence of microgravity, shear stress, surface tension and centrifugal forces on condensation phenomenon. They found that in the absence of gravity vapour shear stress can be used to remove the condensate in systems designed for space craft applications. Wu et al. [11] developed 3-D numerical simulation model in rectangular model with constant heat flux to predict steady annular condensation. Simulated results show that film thickness in the thin-film region increases at upstream locations and decreases at the downstream. They found that highest heat transfer coefficient occurred at the intersection of the thin-film region and the region at which the maximum wall temperature exists.

Liu and Garimella [12] conducted flow boiling heat transfer in a rectangular microchannel using water as the coolant. They measured and compared the convective heat transfer coefficient of the microchannel using the existing correlation for larger channel. The obtained results were satisfactory for subcooled region but not for the saturated region. So they developed a new super position model which incorporated specific features of flow boiling in microchannel to correlate the heat transfer data in saturated boiling region. Kandlikar [13] studied the effect of forces due to momentum and surface tension change during evaporation in addition to the viscous shear and inertia forces which governs two-phase flow pattern and heat transfer characteristics in the case of flow boiling in microchannel. From the studied results he derived two non-dimensional grooves which represent surface tension forces around the contact line region, momentum change forces due to the evaporation at the interface and inertia forces. Tibiriçá and Ribatski [3] reviewed the recent work related to macro to micro scale transition flow patterns, pressure drop, heat transfer coefficient void fraction and liquid entrainment. From the obtained results of the different literatures they concluded that microchannels differ from the conventional channel due to the absence of stratified flow. Microchannels produces permanent liquid layer over the surface which in turn increases the heat transfer rate.

Recently, nano-structured coatings are being developed to enhance boiling heat flux. These coatings can be either nano-porous or composed of nano-fin. A nano-porous coating augments the boiling heat transfer rate due to the water entrapping capability of pores [14]. During heating the trapped water will flow out from the pores due to the local pumping action, which leads to an increase in nucleation sites for heat transfer and thus an enhancement in heat transfer. Nano-fins like CNTs increase the two-phase heat transfer due to the fin action and scale effect [15,16].

Since the discovery of CNTs, researchers have been using their unique thermal, electrical and mechanical properties for various engineering applications. Kim et al. [17] have found that the thermal conductivity of CNTs can be as high as 3000 W/m K, which makes them a very promising candidate for heat transfer applications. There are two main mechanisms to explain the heat transfer enhancement with CNT such as scale effect (increased surface area or “nano-fin” effect) and high heat conductivity. The increased surface area by CNT coating leads to effective vapour embryo entrapment [18], which initiates and enhances the nucleation for boiling heat transfer. Singh et al. [15] used CNT coating to enhance flow boiling on a horizontal heater and have found that CNT coating can remarkably enhance the heat transfer on Si surfaces and that the heat transfer augmentation decreases with the increase of flow rate and subcooling effect. At higher flow rates and subcooling, the CNTs contribute much of its total heat flux to single-phase forced convection. Khanikar et al. [19] examines the heat transfer characteristics of CNTs applied to a rectangular microchannel using