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An experimental investigation on flow boiling heat transfer enhancement using spray pyrolysed alumina porous coatings

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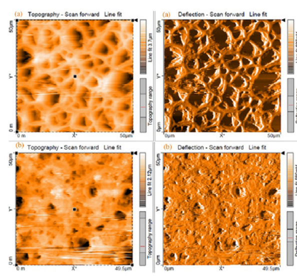
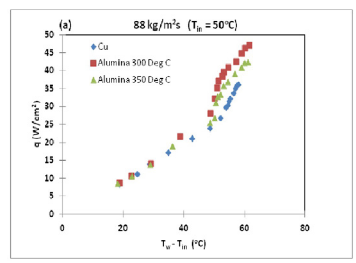
HIGHLIGHTS

- Porous alumina coatings were coated on the copper using spray pyrolysis.
- Effect of coating temperature on porosity was determined.
- Higher enhancement in boiling heat transfer was obtained for 300 °C coated sample.
- Local heat transfer coefficient at outlet increased with increase in subcooling.

GRAPHICAL ABSTRACT





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ABSTRACT

In this work, flow boiling heat transfer experiments were conducted to investigate the effect of a spray pyrolysed porous alumina coatings over a copper substrates. Two different porous alumina coatings were produced by varying the deposition temperature of the spray pyrolysis technique. The heat transfer experiments were conducted in a mini-channel of dimensions 30 × 20 × 0.4 mm, with de-mineralized water as the working fluid. The coated samples were tested repeatedly for three different mass fluxes and two subcooled temperatures, to investigate their effect on the heat flux, surface temperature and average heat transfer coefficient. An appreciable enhancement in heat flux was observed for the 300 °C spray pyrolysed alumina coated sample, when compared to the bare Cu and 350 °C spray pyrolysed alumina coated sample. An enhancement of 28.3% in the heat flux was observed for the 300 °C spray pyrolysed alumina coated sample compared to the bare Cu sample, for a lower mass flux of 88 kg/m^2s.

1. Introduction

A two phase flow heat transfer under high heat flux conditions is found to have immense applications in supercomputers, power devices, electrical vehicles, nuclear reactors, defence and aeronautical fields. This can be attributed to the high heat carrying capacity during the phase change from liquid to vapour, occurring in such flows. But, a major limitation that is hindering further developments in this field, is the critical heat flux (CHF), which causes a sudden increase in the surface temperature leading to the failure of the devices [1,2]. Hence, it is necessary to limit the maximum safe heat flux of the application below the CHF. In the last decade, extensive research has been carried out to improve the CHF by means of flow separation, surface modifications and surface coatings. In the case of the microchannel and micro gaps with subcooled flow boiling, the temperature difference between the inlet and outlet of the heater wall is higher, which in turn, reduces the average heat transfer coefficient. The temperature difference can be reduced by passing a part of the fluid through a passive microjet, and mixing this fluid at the centre of the channel [3].

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Nomenclature

A_{sur}	top surface area of heating block (m^2)
A_{ch}	cross sectional area of the channel (m^2)
Cp	specific heat capacity of water (J/kg K)
h	boiling heat transfer coefficient (W/m^2K)
i	enthalpy (J/kg)
k	thermal conductivity (W/mk)
G	mass flux (kg/m^2s)
q	heat flux (W/m^2)
T_1, T_2	temperature measured from heater section in vertical direction (°C)
T_{favg}	average fluid temperature (°C)
T_{fout}	local fluid temperature at outlet (°C)
T_{savg}	average surface temperature (°C)
T_{sout}	local surface temperature at outlet (°C)
T_{sat}	saturation temperature of the fluid
x	dryness fraction

Subscripts

avg	average
in	inlet
out	outlet
s	surface
f	fluid
sat	saturated
lg	latent
tp	two phase

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
SEM	Scanning Electron Microscope
XRD	X-ray diffraction

Greek symbols

Δx	vertical distance between thermocouples (m)

Micro surface modifications primarily increase the surface roughness which in turn, enhances the area of heat transfer, thereby increasing the CHF [4]. Surface coatings generally increase the heat transfer by fin action and porosity effect [5–9].

Nowadays, surface coatings have emerged as a more competent approach for CHF enhancement in Micro and Mini scale devices, since larger enhancement in heat transfer is achieved with thinner coatings, resulting in a minimized pressure drop. Among these methods, Nano fins obtained using CNT coatings have emerged as potential candidates for improving the CHF, because of their high thermal conductivity and fin action. Previous studies have observed a maximum enhancement in CHF in a CNT coated surface compared to the uncoated surfaces, under lower mass flux conditions. But as the mass flux increases, the enhancement in the CHF is found to decrease in the CNT coated surface. Hence, further studies were carried out to correlate the stability of the CNT coatings with respect to time. The results indicate that the CNT coatings are stable only for lower mass fluxes due to the bending of the CNTs towards the surface, as a result of their high aspect ratios [7,8]. Another promising candidate for flow boiling heat transfer enhancement in a microchannel, is Metal nano wires and silicon wires. Morshed et al. [9] investigated the effect of copper nanowires on flow boiling heat transfer. They found an approximately 56% enhancement in the heat transfer coefficient in the two phase flow using metal nano wires compared to the bare copper surface. D. Li et al. [10] conducted a flow boiling heat transfer enhancement study in microchannels, using monolithically integrated silicon nanowires (SiNWs). They experimentally found that the integration of nanowires produced an early onset of nucleate boiling (ONB), a delayed onset of flow oscillation (OFO), suppressed oscillating amplitude of temperature and pressure drop, and an augmented heat transfer coefficient (HTC). A stable flow boiling trend was observed for the nanowire coated microchannel over a range of heat fluxes, where as the uncoated microchannel produced rapid growth of bubbles which led to an unstable boiling at a higher heat flux. F. Yang et al. [11–13] observed flow boiling regimes and conducted heat transfer studies on a silicon nanowires coated microchannel. They visualized the flow regimes for various high heat flux conditions on a silicon nanowires coated microchannel and obtained a single annular flow regime instead of multiple flow regimes, as seen in the microchannel without coating. They also obtained 300% enhancement in the CHF for the coated microchannel, compared with that of the uncoated microchannel. They concluded that such a remarkable enhancement in CHF was due to the unified flow regime, which is highly stabilized. This phenomenon also leads to 48% reduction in the pressure drop.

Porous coatings using metals and ceramics are also found to be a competent method for improving the, CHF where parameters like the particle size, particle shape, coating thickness and porosity determine the CHF. Sarwar et al. [5] conducted a subcooled flow boiling CHF enhancement with porous alumina and titanium oxide coatings. They coated varied sizes of nano particles using omega bond epoxy. The experimental results show that the alumina microporous coating with <10 μm particle size and thickness 50 μm has the maximum CHF enhancement. They calculated the effect of subcooling on CHF, and obtained greater enhancements at higher inlet subcooling temperatures. Bai et al. [14] conducted flow boiling heat transfer studies in parallel microchannels with metallic porous coatings. They used the solid state sintering method for coating and compared the boiling heat transfer of the porous coated microchannel with that of a bare microchannel, where anhydrous ethanol was used as the working fluid. The experimental result shows the dramatic enhancement of boiling heat transfer in the porous coated microchannel, compared to a bare microchannel. They also found that the enhancement of CHF diminishes with the increase in vapour quality. The enhancement of heat transfer in lower vapour quality is mainly due to the higher nucleation density, while in a higher the vapour quality heat transfer enhancement reduces due to the deterioration of nucleation density. Wang et al. [15] studied the flow boiling heat transfer enhancement in vertical narrow channels coated with sintered aluminium powder. They obtained an enhancement of 2–5 times the boiling heat transfer coefficient with porous aluminium coating. Y. Sun et al. [16] investigated the subcooled flow boiling heat transfer from micro porous surface in a small channel. They found that a small channel even without the coating, showed enhancement in heat transfer at lower vapour quality due to the size effect of the channel. Further enhancement in heat transfer was also found using six microporous coatings. They also found that under the optimum condition, the microporous coating produced three times the enhancement in the