International Journal of Heat and Mass Transfer 121 (2018) 46–63

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Saturated pool boiling enhancement using porous lattice structures produced by Selective Laser Melting

K.K. Wong, K.C. Leong [*]

Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Republic of Singapore

ARTICLE INFO

Article history:
Received 14 July 2017
Received in revised form 24 November 2017
Accepted 28 December 2017

Keywords:
Nucleate pool boiling
Porous media
3D printing
Selective Laser Melting
FC-72

ABSTRACT

Pool boiling heat transfer of saturated FC-72 under atmospheric pressure was studied for porous lattice structures fabricated using the Selective Laser Melting (SLM) technique. The substrates possess repeating geometry of octet-truss unit cell and were varied with unit cell sizes of 2.0 mm, 3.0 mm and 5.0 mm and structure heights of 2.5 mm, 5.0 mm and 10.0 mm. In comparison with a plain surface, the porous structures show significant enhancement in nucleate boiling heat transfer coefficients and delay of Critical Heat Flux (CHF). The enhancement is attributed to the increased surface area, increased nucleation site density and capillary-assisted suction of the porous structure. The porous structure allows sustained liquid replenishment which delayed the hydrodynamic choking and CHF significantly. The best performing substrate with the 3-mm unit cell size and 5-mm structure height has an average nucleate boiling heat transfer coefficient of 1.35 $W/cm^2 \cdot K$, which is 2.81 times that of the plain surface at 0.48 $W/cm^2 \cdot K$. Heat transfer mechanisms are proposed for the different heat flux levels of the porous structures based on visual observations. The boiling patterns are classified as low, mid, high and very-high heat flux levels. At high heat flux level, two separate modes of stable and unstable boiling patterns are observed. For the stable boiling pattern, there are distinct bubble departure and liquid replenishment pathways, thus allowing a good convection flow. However, for the unstable boiling pattern, there is major liquid–vapor counter-flow, which disrupts the orderly liquid replenishment pathway.

1. Introduction

Thermal management is of crucial importance to the advancement of the electronic industry due to the exponential increase in heat flux over the past decades. Conventional natural and forced convection cooling methods of single-phase fluid are not capable of removing the resulting high heat fluxes for maintaining an acceptable operational temperature. Pool boiling, which is a phase change cooling method, is widely applied to cool high power electronic equipment by researchers over the past decades. Dielectric liquids such as FC-72 and HFE-7000 were often used in pool boiling studies due to the electrical and chemical compatibility with electronic parts.

Extensive research efforts have been conducted to enhance the nucleate pool boiling heat transfer coefficient using surface modification techniques and porous media in the last decades. At high heat fluxes, a phenomenon known as the Critical Heat Flux (CHF) occurs when the vapor forms a film at the heated surface and impedes fluid replenishment. The vapor film introduces a high thermal resistance which usually results in a large increase in the surface temperature. Thus, CHF is typically the upper limit for pool boiling systems and researchers have attempted to delay the onset of CHF with enhanced surfaces.

1.1. Surface modification

A thorough literature review on the use of surface microstructures for pool boiling enhancement was performed by Honda and Wei [1]. Shojaeian and Koşar [2] and Kim et al. [3] compiled comprehensive reviews of pool and flow boiling with micro- and nanostructured surfaces. More recently, Leong et al. [4] conducted a review of pool boiling heat transfer of dielectric fluids on enhanced surfaces.

For pool boiling, the total surface area and active nucleation sites play a major role to enhance heat transfer at the solid–liquid interface. Many researchers have applied fins with dimensions ranging from tens of micrometers to ten millimeters to enhance the boiling heat transfer. Wei and Honda [5] studied the effect of fin geometry on boiling heat transfer from silicon chips with micro-pin-fins immersed in FC-72. The silicon chip has a base area of 10 mm by 10 mm and the micro-pin-fin was produced by a dry

---

[*] Corresponding author.
E-mail address: mkcleong@ntu.edu.sg (K.C. Leong).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.148
0017-9310/

Nomenclature

A	area (m^2)
C_p	liquid specific heat (J/kg·K)
D_p	average pore diameter (mm)
D_s	average strut diameter (mm)
h	heat transfer coefficient ($W/cm^2 \cdot K$)
q''	heat flux (W/cm^2)
k	thermal conductivity (W/m·K)
L	length (m)
p	pressure (Pa)
R	thermal resistance (K/W)
T	temperature (°C)

Greek symbols

σ	surface tension (N/m)
ρ	density (kg/m^3)
θ	contact angle (°)
η	relative enhancement

Subscripts

al	aluminum
ave	average
cu	*copper*
ep	*epoxy*
sat	saturated
w	wall
ref	reference

etching technique. Significant enhancement in heat transfer coefficients and delay of CHF were reported using micro-pin-fins surfaces. Yu and Lu [6] performed pool boiling experiments on copper blocks with a base area of 10 mm by 10 mm in saturated FC-72. Finned surfaces with fin thickness varying from 0.5 mm to 2.0 mm and heights varying from 0.5 mm to 4.0 mm were compared to a plain copper block. The results showed that the finned surfaces improved heat transfer due to their larger surface areas. However, the heat transfer enhancement was not proportional to the total surface area increase due to the finned surfaces. It was also observed that coalescence of bubbles occurred more readily for substrates with fins of small gaps, resulting in longer lift-off times. Rainey and You [7] also studied pool boiling on copper blocks with finned surfaces of different heights of 1–8 mm. It was reported that heat transfer enhancement occurred for fin heights up to 5 mm and further increase in the height did not contribute to increasing nucleate boiling as the surface temperature of the upper portion of the fin was too low to sustain boiling.

Coated surfaces have also been explored to enhance pool boiling heat transfer. O'Neill et al. [8] proposed that the pores formed by inter-connected particles act as active nucleation sites, such that vapor is generated in the inter-particle space and squeezed out of the open pores. The escaped vapor is then refilled with liquid from adjacent pores that act as liquid supply channels. Cieśliński [9] produced metallic coatings using various methods of deposition such as electrolytic treatment, plasma spraying and gas-flame spraying on flat surfaces and external surfaces of stainless steel tubes. It was indicated that good metallic contact of the coatings and the substrate base was important for heat transfer. Webb [10] studied nucleate boiling from coatings of different parameters such as particle diameter, coating thickness and pore sizes. His results indicated that the maximum heat transfer coefficient was obtained for coating thickness of about three to four times the mean particle diameter for a highly conductive surface such as copper although it was not so for a less conductive material such as bronze. The pore size was suggested to produce a more significant effect as compared to particle size. Chang and You [11] coated diamond particles on a square heater. Pool boiling with saturated FC-72 yielded increased CHF from about 15 W/cm^2 to 28 W/cm^2 as compared with a plain surface. The porous surfaces also allowed reduction in boiling incipience superheat of about 80% to 90%, and 30% enhancement of heat transfer coefficients, as compared to plain surface. The enhancement was attributed to increased number of active nucleation sites. Liter and Kaviany [12] developed a modulated porous surface of conical shapes with copper powder of 200 μm for pool boiling tests with pentane as working fluid under saturated conditions. It was suggested that in the porous layers, the liquid supply and vapor escape occurred as a liquid–vapor counter-flow which tended to resist the motions of each other. The liquid and vapor flow resistance increased as the heat flux increased, leading to choking of liquid replenishment and local dry-out, which caused CHF. Patil and Kandlikar [13] fabricated microporous coatings selectively on fin tops of open micro-channels on a 10 mm by 10 mm copper substrate. Pool boiling was tested with water at saturated conditions. The CHF was enhanced and a significant reduction in wall superheat was achieved as compared to a plain surface and a micro-channel surface with no microporous coatings. From high-speed visualization, it was observed that the bubbles nucleated from the top of the fins with microporous surface. It was proposed that the micro-channels acted as passages for water supply from all sides, creating a convective flow. Chemical vapor deposition has been investigated by Ho et al. [14] to coat carbon nanotubes on silicon surfaces for pool boiling study. In their investigation, the average heat transfer coefficient of coated surface showed improvement of up to 86% as compared to a plain surface. However, one drawback of this method is the tendency of the coating to degrade and peel off over time.

1.2. Porous foams

Recent developments in material processing technology have led to an emergence of lightweight porous foams for structural and thermal applications. According to the review on the thermal transport of metal foams by Zhao [15], these open-celled foams have high surface-to-volume ratio of 1000–3000 m^2/m^3. Additionally, heat transfer can be improved by enhanced fluid flow mixing due to the tortuosity of metal foams. The porous foams are typically classified under factors of material, porosity and pore density. The materials available are aluminum, steel and copper alloys. The porosity is determined by the volume fraction of void against bulk solid volume. The pore density is typically measured in pores per inch (PPI) by taking the average of the linear line pore density.

Some researchers have conducted measurements on the effective thermal conductivities of porous foams. Paek et al. [16] showed that the effective thermal conductivity increased as the porosity was decreased; however, when the porosity was fixed, no obvious change in effective thermal conductivity was detected when the cell size of the foam was varied. Due to the differences in material and pore geometry for different foams, theoretical modeling of thermal transport in porous foams is still very limited. Leong and Li [17] used a unit cell model to represent the pore structure of graphite foam in order to obtain the effective thermal