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Performance of pool boiling with 3D grid structure manufactured by selective laser melting technique

Chi Zhang [a], Li Zhang [a,*], Hong Xu [a], Pei Li [b], Bo Qian [b]

[a] State-Key Laboratory of Chemical Engineering, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China
[b] School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China

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ABSTRACT

3D thin wall grid structures were manufactured with selective laser melting (SLM) technique for boiling enhancement. To precisely control the structure parameters and investigate their influences on boiling heat transfer characteristics, the scan line spacing method was adopted to manufacture various grid width and wall height structures. The stainless steel was chosen as the building material. Pool boiling experiment results showed that grid structures could significantly influence nucleate boiling behavior and enhance critical heat flux (CHF). The nucleate boiling heat transfer coefficient generally decreased with grid width except for the 0.4 mm grid width samples, the grid channels of which were blocked. The decrease trend was caused by the decreasing effective heating area. The CHF increased with grid width until 1.1 mm, then slightly decreased when the grid width was greater than 1.1 mm. The maximum CHF on the grid structure surface achieved at the transition point was 303 W/cm^2, which was three times that of the plain surface. The enhancement was attributed to the grid structure's "partition effect" that inhibited Helmholtz instability, confined bubble and hot spot expansion in the near surface region. The results provide important guidance for the design of future 3D structured surfaces for boiling enhancement. SLM technique provides a new and effective way for the manufacturing of innovative structured surfaces with controllable parameters and opens a new direction for boiling heat transfer mechanism research.

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1. Introduction

In recent years, more and more techniques and theories have been proposed to enhance and predict boiling heat transfer due to its high efficiency. Researches concerning passive boiling heat transfer enhancement technique generally concentrate on the following aspects: machining of original surfaces (fins, reentrant cavities or micro-electro-mechanical technique made microstructures) [1–4], surface deposition (chemical vapor deposition, liquid phase deposition, plasma deposition, etc.) [5–9], various metal particle porous structures (sintering or coating) and some newly developed techniques [10–19]. From the angle of surface morphology, these surface modification techniques usually generate uniform or non-uniform surface structures. Uniform structures denote single homogeneous surface characteristic such as uniform porous coating. The enhancement of critical heat flux (CHF) for one technique is either through increased surface area, wettability or capillary wicking. Non-uniform structures denote surfaces with characteristics of different scales and the advantages of different scales are combined through modulation, phase separation, further increased area and nucleation sites density.

For uniform surface structures, Chang and You [10] first fabricated the "micro-porous" surface through sintering small metal particles on the surface. It was noticed that bigger particle size brought higher CHF. El-Genk and Ali [6] prepared copper micro-porous surfaces using electro-chemical deposition technique. The CHF increased 70% and superheat was much lowered. Jun et al. [19] sintered different particle sizes and formed porous layer of different thickness and porosity on copper surface. A maximum CHF of 210 W/cm^2 was obtained for water, which is twice of the plain surface. For uniform surface structures, CHF enhancement lies in the liquid supply of porous layer along the surfaces. Capillary flow in the porous layer supports the liquid supply to promote the wetting front. When surface became extremely hot, the capillary flow reaches its maxima or balance point. To overcome the CHF limit of uniform porous structures, more complex surface structures are needed.

Non-uniform or structured surface was developed on the basis of uniform structures. It has become increasingly prominent in

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* Corresponding author.
E-mail address: lzhang@ecust.edu.cn (L. Zhang).

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Nomenclature

A	surface area
D_v	diameter of vapor jets
g	gravity constant
h	heat transfer coefficient
h_{fg}	latent heat
I	current
K	empirical parameter
q_{CHF}	critical heat flux
q	heat flux
T_{sat}	saturation temperature
T_{wall}	wall temperature
U	voltage

Greek symbols

λ_d	most dangerous Taylor instability wavelength
λ_T	Taylor instability wavelength
λ_H	Helmholtz wavelength
ρ_g	vapor density
ρ_f	liquid density
σ	surface tension

Subscripts

g	vapor
f	fluid
sat	saturation
wall	wall

Abbreviations

CHF	critical heat flux
SLM	selective laser melting

Constants

K	constants in Eq. (4)

the past few years. Stubos and Buchlin [20] first noticed the importance of structure in porous material. An unconstructed bed of ferrite particles was place in saturated water and then heated volumetrically. Self-constructed vapor channels were formed which shapes like inter-connected fractal root that went through the whole matrix. Liter and Kaviany [11] prepared modulated sintered porous surfaces using graphite mold. The modulated porous surface could separate liquid vapor counter flow and change Rayleigh-Taylor instability wavelength. Subsequently similar researches were conducted concerning 2-D and 3-D modulated porous surfaces to further increase the CHF [12,13,15,17]. Recently Sun et al. [14] sintered microporous copper coatings on small rectangular channel surfaces. Jaikumar and Kandlikar [18] further applied the porous coated microchannels for pool boiling enhancement. The sintered-channel surface sustained stable convective flow under high heat flux and thus increased CHF to 420 W/cm^2. Bai et al. [16] designed a new porous artery structure through sintering. A CHF of 610 W/cm^2 was achieved. The phase separation was achieved by the wide channels and large interconnected pores. Apart from sintering, Xu et al. [7] prepared composite porous surfaces using electrochemical deposition method. Cross-scale porous structure (from 400 nm to 2 μm, 200 μm) was observed. Surtaev et al. [8,9] obtained novel structured capillary-porous coatings fabricated by plasma spraying technique. Capillary-porous coatings have a significant influence on development of the transition process and crisis phenomena at stepwise heat release. Aznam et al. [21] used nanoparticles and honeycomb porous ceramic plate on a ceramic heater surface. The nanoparticles deposition increased surface wettability and liquid spreading while the vapor liquid separation flow was achieved through the ceramic plate.

Existing non-uniform structure manufacturing methods was mainly developed from traditional sintering method. They have some shortcomings such as uncontrollable pore structure and complex manufacturing technique. The pore structure parameters are important for CHF enhancement. The current studies did not go further into the basic porous structure's effect on boiling heat transfer because of the uncontrollable structure. It is necessary to produce controllable structures and find out the mechanisms behind different structures and parameters. The traditional technique used to manufacture structured surface is complicated and is not applicable for larger scale usage. It is urgent to find out an easier way to efficiently produce structured surfaces for practical application.

Selective laser melting (SLM) technique is a newly developed metal additive manufacture technology. It uses scanning laser to precisely build complex 3D metal structures. Compared with traditional machining technique, SLM technique can easily build any complicated geometry shape that traditional manufacturing cannot or difficult to accomplish. It is especially helpful if used to produce structured surfaces with cross-scale heterogeneous composites that was proved to maximize CHF. With SLM technique, the complex structure was directly formed and the sintering and mould manufacturing was avoided. It could simplify the manufacturing process of structured surface and produce controllable structures for further research into the mechanism of porous structures. Based on the needs of structured surface manufacturing and advantage of SLM technique, SLM would be of great potential in building complex structures for boiling heat transfer enhancement.

SLM has been successfully applied in some frontier material manufacturing area like aerospace, human body implant parts, complex mould design and so on. It is especially helpful when building complex inner structure or biomimetic structures. For porous structures, the structure parameter such as pore size, porosity and geometry could be precisely controlled. Existing SLM porous material manufacturing method can be categorized into three: through 3D modeling [22–25], material modifying [26] and parameter control [27]. For SLM porous material manufacturing that were initially used in surgery area, 3D modeling was the most used method. For ordinary SLM manufacturing, porosity should be minimized through controlling parameters such as laser power, scan speed, hatch distance and layer thickness. Yet they can also be changed to generate porosity. Yadroitsev et al. [22] manufactured 3D porous filter using SLM and SLS technique. The samples were proved to be with good repeatability. Similar researches were conducted by Sun et al. [23], Arabnejad et al. [24] and Fousová et al. [25] for biomedical applications. Other methods were also proposed. Wang et al. [26] used TiH and Ti mixed powder to manufacture interconnected porous structures. The intrinsic porosity was up to 70% and the pore size was 200 to ~500 μm. Zhang et al. [27] changed the laser scanning line spacing to produce grid stacked porous structures with both high porosity and high strength.

Yet, there are few examples using such technique for boiling heat transfer surface structures. Ho et al. [28] used SLM to manufacture micro-fin surfaces and micro-cavity surfaces. The material used is AlSi10Mg. Pool boiling experiment was conducted with

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