International Journal of Heat and Mass Transfer 128 (2019) 1114–1124

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effective and uniform cooling on a porous micro-structured surface with visualization of liquid/vapor interface

Hyunwoo Noh [a], Junseon Yoo [b], Jin-Oh Kim [c,1], Hyun Sun Park [d], Don Koan Hwang [d], Dong-Pyo Kim [c], Moo Hwan Kim [a,d,*]

[a] Department of Mechanical Engineering, POSTECH, Pohang 37673, Republic of Korea
[b] Department of Industrial and Management Engineering, POSTECH, Pohang 37673, Republic of Korea
[c] Department of Chemical Engineering, POSTECH, Pohang 37673, Republic of Korea
[d] Division of Advanced Nuclear Engineering, POSTECH, Pohang 37673, Republic of Korea

ARTICLE INFO

Article history:
Received 11 June 2018
Received in revised form 8 September 2018
Accepted 17 September 2018

Keywords:
Cooling efficiency
Cooling uniformity
Porous micro-structure
Temperature distribution
Liquid/vapor interface
Pool boiling

ABSTRACT

This study examines cooling efficiency, uniformity, and bubble dynamics on a porous surface. We use infrared (IR) thermometry to visualize results of temperature fields and liquid/vapor interfacial dynamics. Porous and non-porous micro-structured surfaces are prepared using soft-lithography and a ceramic precursor, allylhydropolycarbosilane (AHPCS). The surface cavities promote nucleation, and the heat transfer coefficient on the porous surface is approximately 30% higher than that on the non-porous surface. Additionally, the porous surface exhibits a more uniform temperature field with lower spatial and temporal variations than the non-porous surface. Bubble dynamics is visualized via an IR camera through the bottom side of the test specimens using the IR transparent characteristics of the substrate and micro-structures. The porous surface reveals higher nucleation site density and contact line density and lower equivalent bubble diameter when compared with those of the non-porous surface, and this is consistent with more effective and uniform cooling on the porous surface.

1. Introduction

Boiling corresponds to a vigorous phase change from liquid to vapor. During boiling, a large amount of heat transfer occurs due to the enthalpy difference between liquid and vapor. Using this characteristic, boiling can be exploited to remove high heat flux from a surface to maintain its coolability. Therefore, boiling is adopted for cooling devices such as electrical chips, spacecraft, and power plants [1–6]. The cooling efficiency is the most important factor that maximizes heat removal rate from the target surface. The efficiency is represented by the heat transfer coefficient (HTC) that corresponds to the ratio of applied heat flux to temperature increases in the surface. Cooling uniformity and reliability are also important parameters since they guarantee constant operating performances of a system in practical applications [1,7,8]. For example, with respect to electrical chip cooling, spatial temperature variation can result in destructive thermal stress and deterioration in the electronic performance [1].

A porous surface exhibits high cooling efficiency during boiling. Numerous cavities are present on a porous surface and act as the seeds for the bubble nucleation. A classical cavity theory [9] indicates the presence of the minimum and maximum cavity radii to induce boiling at a certain surface temperature. A porous surface provides surface cavities with a radius between the minimum and maximum value that promote nucleation on the surface. Therefore, the required temperature to generate bubbles on a porous surface is lower than that on a non-porous surface. Given the lower temperature required for nucleation on the porous surface, numerous bubbles are generated concurrently and result in high cooling efficiency with a large amount of heat transfer via evaporation. Several types of porous surfaces are fabricated using electrochemical deposition [10], particle sintering coating [11,12], laser texturing [13], and several other methods [14–16]. Additionally, higher HTCs are observed on porous surfaces than on non-porous surfaces.

Fabrication of engineered porous structures entails complicated methods or high costs, and methods proposed in previous studies exhibit limitations in terms of realizing porous structures with a micro-scale geometry. Soft lithography is an alternative fabrication

* Corresponding author at: Division of Advanced Nuclear Engineering, POSTECH, Pohang 37673, Republic of Korea

E-mail address: mhkim@postech.ac.kr (M.H. Kim).

[1] The author is currently working at Korea Advanced Institute of Science and Technology. This work was performed when he was working at POSTECH.

https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.086
0017-9310/

Nomenclature

CLD	Contact line density [mm/mm^2]
D	Diameter [mm]
DAF	Dry area fraction [mm^2/mm^2]
HTC	Heat transfer coefficient [kW/m^2 K]
NSD	Nucleation site density [#/mm^2]

Subscripts

eq	Equivalent

method that is adopted to prepare porous micro-structures for boiling applications. Soft lithography is a replicating method that uses elastomeric stamps and molds [17]. By stamping and curing a liquid-type prepolymer or ceramic-precursor, solid micro-structures can be replicated and exhibit exactly identical geometries with the stamp. An extant study reported on the fabrication of a porous structure using soft lithography with polystyrene (PS) beads as a sacrificial layer to create open pores inside the stamped structure [18]. Soft lithography is versatile in terms of the fabrication of surface structures with highly controlled geometry and chemistry. Furthermore, it is also appropriate for large-area fabrication, manufacture on a curved surface, and cost-effective recipe development [17,19].

Cooling efficiency can be analyzed via infrared (IR) thermometry to visualize the temperature distribution on the heating surface [20–25]. Several previous studies [20,21,23] used IR thermometry to visualize changes in the temperature field during boiling. On a nucleation site, temperature changes cyclically due to the temperature drop with bubble growth and temperature recovery during the waiting period prior to the formation of the next bubble [20,21,23]. The visualized temperature field can be used to calculate heat flux, which exhibits intensive heat transfer beneath a nucleated bubble due to microlayer evaporation [21,22]. Cooling efficiency and uniformity can be quantitatively evaluated by comparing temperature distribution from various structured surfaces [24].

The analysis of bubble dynamics is valuable in the study of the heat transfer mechanism because microlayer evaporation near the bubble contact line causes intensive heat transfer [25]. Bubble dynamics can be visualized using a high-speed IR camera to observe liquid/vapor interfaces [26–29]. In this case, bottom view visualization to observe the heating surface can be achieved using IR-transparent substrates such as silicon. Bottom view visualization enables the measurement of bubble dynamics such as nucleation site density (NSD), contact line density (CLD), and dry area fraction (DAF), and these parameters can contribute to the HTC. For example, bottom view visualization via the IR thermometry of Si specimens detected linear relationships between the NSD and HTC and between the CLD and HTC on flat, micro-structured, and nano-structured surfaces [26].

A porous surface increases HTC by promoting bubble generation and significantly changes bubble dynamics. However, comprehensive studies of the effects of a porous surface on cooling efficiency, uniformity, and bubble dynamics are hindered by difficulties in fabricating a porous surface on an IR-transparent material. In this study, we use soft lithography to manufacture Si-based ceramic micro-structured surfaces. Using this method, quantitatively controlled porous and non-porous micro-structures are realized on a Si substrate. Given that both the substrate and micro-structures are transparent to IR, bottom-view visualization is used to observe liquid/vapor interfaces. We analyze cooling efficiency, temperature distribution, and bubble dynamics on porous and non-porous surfaces in pool boiling experiments. The porous surface exhibits higher cooling efficiency with a lower temperature distribution when compared with those of the non-porous surface and exhibits uniform cooling ability with consistent temperature field on the surface. The porous surface exhibits significantly higher NSD and CLD when compared with those of the non-porous surface. The aforementioned observations indicate that the HTC value increases due to vigorous bubble nucleation. This study contributes to the understanding of increases in efficiency and uniformity of cooling on the porous surface. It also contributes to the analysis of liquid/vapor interfacial behavior via the post-processing of bottom-view images.

2. Experiments

2.1. Surface fabrication

Porous and non-porous micro-structured surfaces were prepared using a method similar to that in a previous research (Fig. 1) [24]. Allylhydropolycarbosilane (AHPCS) was adopted as the base material for the micro-structures on the top side of the silicon substrate. Specifically, AHPCS is a liquid-type ceramic precursor that contains Si, and it can be solidified by exposure to UV light and heat. Fabrication of micro-structures was conducted via the sequence as described below (Fig. 1a). A small drop of liquid type AHPCS was deposited on a Si substrate (with a thickness of 500 μm) and stamped using a polydimethylsiloxane (PDMS) mold that bore an array of cylindrical micro-structures wherein each exhibited a diameter of 50 μm, gap of 30 μm, and height of 20 μm. In the process, the PDMS mold was firmly pressed to guarantee complete infiltration of AHPCS to the mold without trapped air. The assembly was exposed to UV light (wavelength of 250–420 nm with a peak at 365 nm corresponding to 30 mW/cm^2) for 20 min, the PDMS mold was removed, and the substrate was placed on a hot plate for thermal curing at 120 °C for 3 h. Fabrication of the porous surface entailed additional steps to create micro-pores inside the micro-structures (Fig. 1b). Prior to stamping, polystyrene (PS) beads with a diameter of 1.5 μm were closely packed inside the cavities of the PDMS mold. Following the same process used to prepare the non-porous surface, the PS beads were removed by soaking them in toluene for 12 h at room temperature. Thus, the micro-structures exhibited micro-pores with a diameter of 1.5 μm where the PS beads were located. Both the porous and non-porous surfaces exhibited hydrophilic characteristics with static contact angles of 0° and 12°, respectively, with a water droplet [24].

2.2. Experimental facility

The pool boiling experimental facility consisted of an aluminum bath, an immersion heater, a reflux condenser, and visualization windows (Fig. 2). Specifically, 2 L of de-ionized water (DI water) was loaded into the aluminum bath and then heated by an immersion heater to set the bulk liquid at the saturation temperature. Evaporated steam was condensed by the reflux condenser that was installed in the lid of the aluminum bath. The condensed droplets fell back into the bath, and thus the water level remained