Nucleate pool boiling heat transfer augmentation on hydrophobic self-assembly mono-layered alumina nano-porous surfaces

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ABSTRACT

In this study, we have observed substantial pool boiling heat transfer augmentation by creating one-dimensionally grown Alumina Nano Porous Surface (1-D ANPS). Pre-organized numerous nano pores have structural uniqueness such as enlarged surface area, increase in active nucleation sites, and liquid thin film evaporation at vapor–liquid menisci of the pore mouth. At the same time, the surface wetting of a cylindrical heater is modified with a hydrophobic Self-Assembled Monolayer (SAM) coating. Enhanced water contact angle of the 1-D ANPS yields substantial active nucleation site increase by preventing liquid impregnation into nano pores, which play a role of trapping non-condensible gas. The combination of structural uniqueness of the 1-D ANPS and surface wettability modification achieves significant heat transfer coefficient (HTC) enhancement in the nucleate pool boiling regime. Also, HTC improvement is closely related to bubble interactions on the cylindrical heating surface while they are moving along the periphery. For a hydrophobic surface, bubble sweeps along the heater periphery and efficiently removes adjacent premature bubbles. It leads to reduced waiting time. Enlarged bubbles carry more heat from the surface and yield huge internal/external convection. In order examine bubble motions, an analytical model and high speed camera were used.

1. Introduction

A porous surface has been known as an ideal thermal system design to reduce wall superheat [1–5] because non-condensible gas is entrapped by numerous porous cavities, which play a role of active nucleation sites. Also, the porous surface has enhanced effective heating surface, which can dissipate heat. An early example to introduce porous surface was sand papering [2]. Later on, mechanical fabrication has been widely used [4]. Since 1980s, various surface treatment methods such as a plasma coating [6], ABM coating [7], fused inorganic pore [8], copper foam [9], and electro-deposition [10] were introduced to make porous surfaces.

In addition to structural modifications, surface wetting modification is another method to increase the active nucleation sites. For instance, perfluoro-based polymer coatings of which water contact angle (WCA) was $\vartheta \sim 120°$ showed boiling heat transfer enhancement [11–15]. However, polymer-based coating is difficult to control the thickness within specific ranges (a few micrometers).

Other than that, the WCA of most heating surfaces is limited to $\vartheta < 90°$ [16].

In heating surface design, geometry and inclination angle of heaters are important factors to determine HTC in pool boiling. For a cylindrical heating surface, surface wetting has strong impact on bubble departure motion. Based on the previous observation [11], HTC improvement was significant on the bottom of the heating surface. Bubble on the bottom has large buoyancy force after coalescence. The larger bubble yields to eddies and thermal boundary layer disruption after bubble lift-off. It should be noted the contribution of bubble coalescence on different wetting surfaces over wall superheat change.

In this study, we have focused on the influence of bubble motions/interactions of the Alumina Nano Porous Surface (ANPS) with different surface wetting of cylindrical heaters over boiling heat transfer.

2. Experiment

2.1. Pool boiling experimental setup and procedure

A pool boiling chamber is made of stainless steel in Fig. 1(a). Individual dimension of the rectangular chamber is 101.6 mm in

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Nomenclature

A	surface area [m^2]
D	bubble departure diameter [m]
d	pore diameter [m]
f	bubble departure frequency [1/s]
h	heat transfer coefficient [kW/m^2/K]
i	enthalpy of vaporization [J/kg]
I	current [A]
k	thermal conductivity [W/m/K]
L	length of test section [m]
P	pressure [Pa]
Q	input power [W]
q''	heat flux [W/m^2]
r	radius [m]
T	temperature [K]
ΔT	temperature difference [K]
V	voltage [V]

Greek letters

α	inclination angle [°]
ρ	density [kg/m^3]
ϑ	contact angle [°]
σ	surface tension [N/m]

Subscripts

a	advancing angle
b	bubble

bottom	at the bottom of heater section
l	liquid
g	gas
left	at the left of heater section
lg	liquid–gas
ls	liquid–solid
o	outside
r	receding angle
right	at the right of heater section
s	solid
sat	saturation
sg	solid–gas
sl	solid–liquid
thermo	thermocouple
top	at the top of heater section
w	wall

Abbreviation

ANPS	Alumina Nano Porous Surface
HTC	heat transfer coefficient
LTFE	liquid thin film evaporation
SAM	self-assembly monolayer
SANPS	SAM-coated Alumina Nano Porous Surface
WCA	water contact angle
WCAH	water contact angle hysteresis

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width, 101.6 mm in height, and 177.8 mm in length, respectively. Both ends of the pool boiling chamber were made of Teflon plates with 12.7 mm in thickness. The boiling chamber was thoroughly insulated with 5 mm Styrofoam and 20 mm glass wool. The aluminum alloy (Al 6061) rod was fabricated in Fig. 1(b) with 19.1 mm in diameter and 101.6 mm in length. A cartridge heater (McMaster Carr 120 V 400 W) was inserted into the center hole with 9.5 mm with a high thermal conductive paste (Omega 201) to heat the test section. Four holes with each 2.4 mm in diameter and 70.0 mm in depth were mechanically drilled 90° apart at the top, middle and bottom along the periphery of the heater section. Omega *T*-type thermocouples were inserted into these holes with the thermal conductive paste to measure the temperatures. Variac AC variable transformer supplied the controlled amount of power to the cartridge heater. The output voltage and the current were measured with Agilent 34410A digital multimeter. A reflux condenser was connected to the pool boiling chamber to condense the vapor. Measured temperatures from the thermocouples were acquired by IOtech data acquisition system.

In order to remove dissolved gases, the pool boiling chamber was heated up to saturation temperature (T_{sat}) for two hours. The experiments were carried out under the steady state at the atmospheric pressure condition. The pool temperature was maintained within 0.8 °C of T_{sat}.

In order to create well-ordered nano pore layers (see Fig. 2), anodizing is used at specific conditions. First, the aluminum heater was electropolished to remove surface oxidants. The electropolished heater was anodized in 0.3 M H$_2$SO$_4$ solution at 5 °C for two hours. The anodized surface was removed in ferrichloride solution at 50 °C for two hours. Then, anodizing process was repeated under the same conditions. After two-step anodizing, well-ordered nano pores with diameter $\sim$50 nm was obtained in Fig. 2(a). The porous layer thickness was fixed at $\sim$1.1 μm as shown in Fig. 2(b).

2.2. Surface wettability control: a hydrophobic ANPS

Surface wetting of the ANPS is adjustable by using a Self-Assembled Monolayer (SAM). Without surface treatment, WCA of the ANPS is $\sim$90° in Fig. 3(a), which is similar to that of plain aluminum surface ($\sim$85°). In order to make a hydrophobic surface, the perfluoro-based SAM was used. After hydrophobic surface treatment, the surface wetting of the SAM coated ANPS (SANPS) was dramatically changed from $\sim$90° to $\sim$150° as shown in Fig. 3(b).

2.3. Data reduction

Using Ohm's law in Eq. (1), the input power supplied to cartridge heater of test section was estimated:

$$Q = VI \tag{1}$$

where Q, V, and I represent power, voltage, and current, respectively.

The boiling phenomena on the heater surface happen 1.3 mm away from the thermocouple hole. The actual wall temperature was adjusted by using a one-dimensional heat conduction equation in radial direction in Eq. (2):

$$T_w = T_{thermo} - \frac{Q}{2\pi L}\left[\frac{\ln(r_0/r_{thermo})}{k}\right] \tag{2}$$

where T_w, T_{thermo}, L, r_o, r_{thermo}, and k are wall temperature, temperature measured by thermocouples, heater length, outside radius, radius of thermocouple location, and thermal conductivity of heater.

In order to obtain the local heat transfer coefficient (HTC, h), the corrected wall temperature from Eq. (2) was plugged into Eq. (3):

$$h = \frac{Q/A}{(T_W - T_{sat})} \tag{3}$$