International Journal of Heat and Mass Transfer 108 (2017) 1393–1405

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Orientation effects on bubble dynamics and nucleate pool boiling heat transfer of graphene-modified surface

TaeJoo Kim [a,1], Ji Min Kim [b,1], Ji Hoon Kim [c], Su Cheong Park [d], Ho Seon Ahn [c,*]

[a] Korea Atomic Energy Research Institute, Daejeon, Republic of Korea
[b] Division of Advanced Nuclear Engineering, POSTECH, Pohang, Republic of Korea
[c] Department of Mechanical Engineering, Incheon National University, Incheon, Republic of Korea
[d] Department of Mechanical Engineering, POSTECH, Pohang, Republic of Korea

ARTICLE INFO

Article history:
Received 18 July 2016
Received in revised form 7 December 2016
Accepted 27 December 2016

ABSTRACT

Modified surfaces with graphene coatings were evaluated experimentally to enhance nucleate boiling performance on an orientated surface, from upward to downward (0°, 45°, 90°, 120°, 135°, 150°, 160°, and 170°). Two-dimensional (2D) laminate and three-dimensional (3D) porous graphene were prepared for surface modification, and their boiling heat transfer coefficient (BHTC) and critical heat flux (CHF) values were evaluated according to orientation angle. Moreover, their boiling structures were observed and analyzed using high-speed visualization. The results showed that the surfaces coated with 2D and 3D graphene had enhanced BHTC and CHF performance in comparison with the bare surface with no graphene modification. The 2D graphene surface showed increased nucleate site density and early onset of nucleate boiling, resulting in enhanced BHTC, by 40%, in the downward condition. The enhancement ratio of CHF was 40% on 2D graphene and 20–25% on 3D graphene.

1. Introduction

Nucleate boiling is an applicable heat transfer mechanism for removing a high density of heat to maintain the temperature of a system so as not to exceed a critical temperature for system failure. For this reason, nucleate boiling has been adopted in the energy conversion systems of power plants, cooling systems of aerospace vehicles, and cooling devices of integrated circuit (IC) chips, among other applications. Trends in system development demand compact sizes and operation with movement; thus, for the reliability of systems, dynamic operating condition should be considered, including the orientation of the system. Nucleate boiling is limited by the critical heat flux (CHF) phenomenon, in which a vapor film covers the heating surface and causes a transition to film boiling with a relatively low heat transfer coefficient, so that the CHF performance is considered a major parameter for evaluating the safety margin of the system. Accordingly, evaluation and prediction of boiling performance are important with regard to surface orientation, in which a downward-facing condition could cause a bottleneck due to deterioration of CHF performance versus an upward-facing condition. For this reason, nucleate boiling characteristics, including CHF, were investigated on a downward-facing surface to predict and increase the heat capacity margin of the system.

The effects of orientation angle of downward-facing heating surfaces in nucleate boiling heat transfer have been investigated using various working fluids under saturated conditions, such as water [1–3], liquid helium [4–6], and refrigerants [7–12]. As the angle of the heating surface increased, from vertical to downward-facing, the CHF value decreased rapidly, and several correlations have been derived for flat plates in various working fluids [8,12–14]. These studies, however, focused on CHF performance according to orientation angle, and only a few researchers have reported its effects on boiling heat transfer coefficient (BHTC).

El-Genk and Glebov [15] conducted quenching experiments of down-facing copper surfaces with curvature. In a transient boiling procedure, they observed an increase in BHTC as orientation angle changed from downward (180°) to near-downward (171.74°), especially in a low wall superheat region. The reason was that bubble on the near-downward surface could escape easier compared with that on the downward surface. Parker and El-Genk [16] conducted nucleate pool boiling experiments according to orientation angle using copper and porous graphite surfaces. Compared with a plane copper surface, the porous graphite surface showed enhanced BHTC and CHF at various orientation angles, resulting from the superior nucleate side density (NSD) induced by inherent pores in the porous graphite surface. Parker and El-Genk [17,18] reported nucleate boiling performance, including BHTC and CHF,

---

* Corresponding author at: Department of Mechanical Engineering, Incheon National University, Incheon 406-772, Republic of Korea.
E-mail address: hsahn@inu.ac.kr (H.S. Ahn).

[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.099
0017-9310/

Nomenclature

a	calibration coefficient of resistance of heater
A_{heater}	area of platinum heater (m^2)
b	calibration coefficient of resistance of heater
C_{CHF}	coefficient of CHF correlation
g	gravity (m/s^2)
h	boiling heat transfer coefficient (BHTC) (kW/m^2 K)
h_{lg}	latent heat of water (kJ/kg K)
n'_a	activated site density ($\#/m^2$)
P	pressure (N/m^2)
q''	Heat flux (kW/m^2)
R_{ref}	resistance of reference resistor (Ω)
T_{sat}	saturation temperature of water (°C)
T_{wall}	wall temperature (°C)
U	experimental uncertainty
V_{heater}	voltage applied to heater (V)
V_{ref}	voltage applied to reference resistor (V)
θ	surface contact angle (rad)
ρ_g	vapor density (kg/m^3)
ρ_l	liquid density (kg/m^3)
σ	surface tension of water (N/m)

on plane copper with and without milli-scaled pins in saturated dielectric HFE-7100 liquid according to various orientation angles. They reported that the BHTC showed similar features on surfaces with orientation from upward to vertical, and it decreased from vertical to downward. Moreover, the decrease ratio of BHTC according to orientation angle was more predominant on a copper surface without pins, rather than on a copper surface with pins. Here, the decrease ratio meant the ratio of BHTC value on oriented surface to that on upward surface.

Graphene-modified surfaces have been reported to be an efficient method to alter nucleate boiling performance. The application of graphene to heating surfaces started to attract interest as a new nanofluids after the synthesis of reduced graphene oxide (RGO) colloids was reported [19]. Graphene has extraordinary thermal conductivity (5000 W/m/K) [20] and mechanical strength (120 GPa) [21]. Moreover, it is a two-dimensional (2D) monolayer of carbon atoms with hexagonal covalent bonding, so it is inherently suitable to apply to a surface as a coating material. First, RGO colloids and GO colloids were evaluated in pool boiling experiments with a wire heater, in which they were reported to form a deposition layer after boiling and to enhance the CHF value: by 179% in Ref. [22], by 220% in Ref. [23], and by 63% in Ref. [24]. Next, RGO and GO colloids were evaluated in pool boiling experiments with a plate heater. The RGO colloids formed three-dimensional (3D) porous structures on the surface, resulting in enhanced CHF and BHTC, by 80% each, and the elimination of wall temperature jump in CHF [25,26]. It was suggested that the 3D porous structure of the RGO would act as a liquid-saturated porous layer, so that it would slow the transition phenomenon from a nucleate-boiling to a film-boiling regime. Furthermore, a 2D film coating of RGO showed marked CHF enhancement, up to 61%, according to its thickness, up to 200 nm [27]. The RGO film was supposed to act as a heat spreader to prevent dry spot formation causing CHF trigger. Moreover, GO colloids formed only 2D laminate structures on the surface, resulting in enhancement of CHF by 139% with a 1004 nm layer thickness [28]. As mentioned above, 3D and 2D graphene structures are good candidates for surface modifications, but previous studies were carried out only with upward-facing surfaces. To apply a graphene-modified surface to thermal systems, it should also be evaluated on downward-facing surfaces.

In this study, nucleate pool boiling experiments at various orientation angles, from upward to downward, were conducted using graphene-modified surfaces under saturated water conditions at atmospheric pressure. Graphene-modified surfaces were prepared with 3D porous graphene films and 2D graphene films, which have been reported to have excellent boiling performance on upward-facing surfaces. To evaluate and analyze nucleate boiling performance on downward-facing surfaces, boiling performance analyses and visualization studies were performed with orientation angles of 120, 135, 150, 160, and 170°.

2. Experimental

2.1. Pool boiling experimental apparatus

Fig. 1(a) shows schematics of the experimental apparatus for pool boiling. The experimental apparatus consisted of a container vessel, the main heater mount, the main heater, and a data acquisition system. The container vessel was designed to maintain 27 L of working fluid (here, distilled (DI) water) saturated at atmospheric pressure for the boiling experiments. The aluminum vessel of 30 × 30 × 30 cm used two 700W cartridge heaters to heat the water and two reflux condensers using tap water to maintain the water level and inside pressure at atmospheric. Moreover, polycarbonate windows were installed for visualization.

The main heater mount was designed to control the orientation of the main heater. Worm gear was mounted on the cover of the container vessel and connected with a cylindrical mount to install the main heater. The worm gear could rotate 90°, and the mount could be installed with the worm gear facing upward or downward. Thus, the orientation of the main heater could be controlled from 0° (upward) to 180° (downward).

The main heater was a mirror-polished silicon wafer plate of 20 mm × 25 mm × 475 μm, with 500-nm SiO_2 layers on both sides. A platinum film heater was deposited on the bottom of the main heater, as shown in Fig. 1(b), and connected to a DC power supply (Sorensen SGI 60 V/500 A). The main heater was mounted on a PEEK jig, as shown in Fig. 1(c), which was installed with the cylindrical mount. The inside of the cylindrical mount was sealed with an O-ring for insulation, and decompressed with vacuum suction. Here, the decompression was to avoid seal-breaking by any increase of inside pressure caused by the temperature rise in the boiling experiments.

A data acquisition system was used to gather data on the heat flux and wall temperature of the main heater. The heat flux was calculated as follows:

$$q'' = \frac{I_{heater}V_{heater}}{A_{heater}} = \frac{V_{ref}V_{heater}}{R_{ref}A_{heater}} \tag{1}$$

where I_{heater}, V_{heater}, A_{heater}, V_{ref}, and R_{ref} are the current applied to the Pt heater, the voltage applied to the Pt heater, the area of the Pt heater, voltage applied to the reference resistor, and the reference resistance, respectively.The current was measured using an applied voltage on a reference resistance of 1 Ω in a constant-temperature bath maintained at 10 °C. The wall temperature was measured in terms of the resistance of the platinum film, which showed high linearity with temperature. Thus, the main heater was calibrated from 100 to 150 °C using a constant temperature oven before boiling experiments.

The experimental uncertainty was determined as follows [29–31]: