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Bubble activation from a hydrophobic spot at "negative" surface superheats in subcooled boiling

Biao Shen [a, b, *], Bambang Joko Suroto [b, c], Sana Hirabayashi [b], Masayuki Yamada [b], Sumitomo Hidaka [b], Masamichi Kohno [a, b], Koji Takahashi [a, d], Yasuyuki Takata [a, b]

[a] International Institute for Carbon-Neutral Energy Research (I^{2}CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[b] Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[c] Department of Physics, Faculty Mathematic and Natural Science, Lampung University, Jl. Prof. Sumantri Brojonegoro No. 1, GedongMeneng, Bandar Lampung 35145, Indonesia
[d] Department of Aeronautics and Astronautics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

HIGHLIGHTS

- Bubbles occurred on hydrophobic PTFE spots at nominally negative superheats.
- Bubble departure frequency and diameter were obtained by high-speed imaging.
- Estimate of the bubble content was given based on inner temperature measurements.
- Heat-pipe effect explains the slow bubble growth under the subcooled condition.

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ABSTRACT

We present experimental results on the controlled bubble generation from a single PTFE (polytetrafluoroethylene) spot—with diameter varying from 2 mm to 6 mm—deposited on a flat polished copper surface that was submersed in subcooled pure water. The static contact angle of the PTFE coating was measured to be over 120°, which conveniently produced a clear contrast with the copper substrate in terms of wettability that ensured controlled bubble nucleation. By making use of a high-speed camera, statistical details about the bubble formation that include the departure frequency and diameter have been obtained at various surface temperatures. An interesting observation was made of repeated cycles of bubble nucleation and detachment at nominally negative surface superheats (i.e., the wall temperature being below the saturation temperature at the system pressure), which featured particularly long bubble growth time and seemingly no waiting time. The vertical temperature distribution inside the bubble, which was measured by a micro-thermocouple of about 250 μm in diameter, suggests a relatively stable bubble composition of water vapor and dissolved air. A heat-pipe analogy was drawn to describe the internal heat transfer mechanism of bubble growth on a mixed wettability surface under subcooled conditions.

1. Introduction

Due to the large latent heat of evaporation and, perhaps more importantly, strong bubble-induced agitation in the superheated liquid layer [1,2], boiling offers an extremely efficient means of heat transfer and consequently finds a wide range of industrial applications from electronics cooling to refrigeration and cryocoolers to nuclear reactors. The performance of boiling heat transfer depends on two critical parameters: (i) the heat transfer coefficient (HTC), which is defined as the ratio of the imposed heat flux to the corresponding wall superheat $\Delta T_w = T_w - T_{sat}$; and (ii) the critical heat flux (CHF), which demarcates the boundary between the nucleate boiling regime and the less desirable regime of film boiling. The latter stage often entails a dangerous dry-out condition in which the vapor-covered surface is likely to suffer severe physical damages owing to the drastic wall temperature hike.

* Corresponding author. Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan. Tel.: +81 92 802 3905; fax: +81 92 802 3098.
E-mail addresses: shen.biao.604@m.kyushu-u.ac.jp (B. Shen), laks102@yahoo.com (B.J. Suroto), m.yamada@heat.mech.kyushu-u.ac.jp (M. Yamada), kohno.masamichi.607@m.kyushu-u.ac.jp (M. Kohno), takata@mech.kyushu-u.ac.jp (Y. Takata).

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Nomenclature

D_d	bubble detachment diameter (m)
f_d	bubble detachment frequency (s^{-1})
g	acceleration due to gravity (m s^{-2})
L	specific latent heat (kJ kg^{-1})
ΔT_b	subcooling (°C)
ΔT_w	wall superheat (°C)
T	temperature (°C)
Δv	specific volume change (m^3 kg^{-1})
Greek symbols	
θ	contact angle (°)
λ	thermal conductivity (W m^{-1} °C^{-1})
σ	surface tension (N m^{-1})
ρ	density (kg m^{-3})
Subscripts	
w	wall
b	bulk
c	copper
l	liquid
P	PTFE
sat	saturation condition
top	near the bubble top
v	vapor

Despite past decades of theoretical, numerical, and experimental efforts [2–5], a comprehensive mechanistic understanding of boiling heat transfer—which accounts for all relevant subprocesses—is still lacking. As a result, most of the recent attempts to enhance boiling efficiency (i.e., HTC and CHF improvements) are either parametrically or empirically based [6,7]. Among the large collection of factors that could potentially affect boiling performance, surface wettability, which is usually measured in terms of the contact angle θ, plays a unique role [8]. On the one hand, hydrophilicity (defined as $\theta < 90°$) can effectively suppress bubble formation and merging, leading to delayed onset of film boiling. Takata et al. [9] demonstrated that TiO_2-coated surfaces, when exposed to UV irradiation, exhibit an unusually high affinity for water (that is, $\theta \approx 0°$). The CHF of pool boiling on such surfaces was found to be about two times that of an uncoated surface. Through careful surface engineering, O'Hanley et al. [10] were able to separate to some extent the individual effect of the wetting property on boiling from other variables such as surface roughness and porosity. The results showed a significantly increased transition temperature for film boiling on porous hydrophilic surfaces, which was attributed to the considerably enlarged capillary force. In nanofluids boiling, surface topology is likely to be modified as a result of nanoparticles deposition, which in turn improves surface wettability and helps explain the exceptionally high CHF [11]. Specifically, the buildup of a porous layer of nanoparticles as a result of microlayer evaporation underneath the growing bubbles might fundamentally alter the surface adhesion tension and roughness, leading to, among other things, significant reduction of the contact angle [12]. According to Gerardi et al. [13], the contact angle of the ITO (indium–tin-oxide) heater seemed to drop from around 100° to 6–16° subsequent to being boiled in water-based nanofluids of silica and diamond, respectively. The resulting nanoparticles coatings on the heater surface were found to be responsible for significantly enhanced pool boiling heat transfer thanks to the pronounced effect of capillary wicking [14,15]. However, the boiling HTC might deteriorate owing to the markedly increased thermal resistance and declining bubble nucleation sites. Forrest et al. [16] reported up to 50% HTC degradation on the superhydrophilic thin-film nanoparticles-deposited surfaces made by the layer-by-layer assembly method. On the other hand, hydrophobicity is known to promote bubble generation, and thus results in greatly improved HTC. By means of electrolytic nickel plating with a suspension of fine PTFE (polytetrafluoroethylene) particles, Takata et al. [17] made a super water-repellent surface (with $\theta > 150°$), on which bubbles appeared at extremely low superheats and quickly coalesced into a vapor film without departing from the surface.

On account of the opposite effects of surface wettability on the boiling CHF and HTC, it requires careful trade-offs between hydrophilicity and hydrophobicity to optimize surface design for boiling applications. Betz et al. [18] were able to create superhydrophobic patterns (made by Teflon fluoropolymer coating) by using photolithography on a silicon wafer that was decorated with random superhydrophilic nanostructures. The resulting so-called *superbiphilic* surface showed remarkable improvements in both the CHF and HTC compared with a plain surface. In our previous study [19], spot coating of PTFE on a hydrophilic TiO_2 surface was found to lead to generally enhanced heat transfer performance. In addition, one interesting observation caught our attention: bubbles actually appearing on the mixed wettability surface at very low—even *negative*—surface superheats, which was conjectured to be a result of some incondensables inside the bubbles. For subcooled water ($\Delta T_b = T_{sat} - T_b > 0$), for instance, the onset of nucleate boiling (ONB) was found to occur at the surface temperature as low as $T_w = 95.8$ °C, well below the nominal saturation temperature at atmospheric pressure (namely, $T_{sat} = 100.0$ °C). The present work represents our first attempt at understanding the origin of this unexpected phenomenon. By using a high-speed camera, bubble dynamics—including the departure frequency and diameter—on a hybrid surface (polished copper surface coated with a single PTFE spot) was examined. In addition, the temperature distributions within a growing bubble were obtained with the help of a microthermocouple, from which we are able to derive a rough estimate of the vapor/gas bubble content.

2. Experiment apparatus and procedure

A schematic diagram of the pool boiling test facility is shown in Fig. 1. Surrounded by foam insulation, the glass boiling vessel had a volume of about 5 L (450 mm high and 120 mm in diameter). An air heater was used to compensate for heat loss to the surroundings

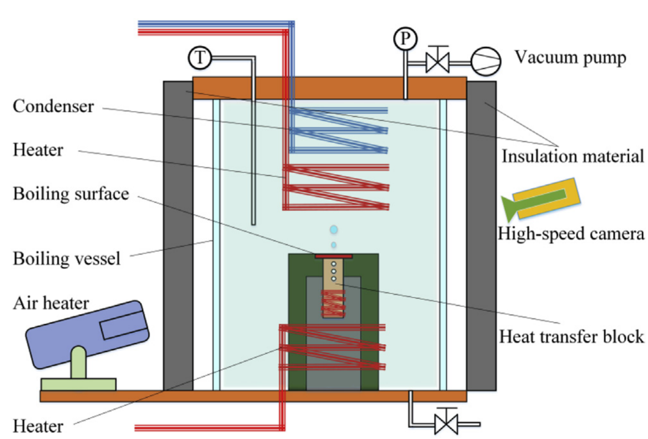

Fig. 1. A schematic representation of the pool boiling experimental setup.