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Enhanced vapor bubble condensation and collapse with ultrasonic vibration

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ABSTRACT

Investigation was carried out concerning the effects of ultrasonic field on the condensation and collapse of vapor bubbles in a quiescent subcooled pool. Experimental results showed that the vapor bubbles were split gradually at liquid subcooling of 15–30 K, while were collapsed into many tiny bubbles when subcooling was higher than 40 K. Once the ultrasonic vibration was applied, capillary waves would arise on the bubble surface, and the threshold of liquid subcooling for collapsing the bubble was diminished to 20–26 K. Further, the presence of capillary wave increased the contacting area of the bubble with the cold bulk, and disturbs the thermal boundary layer in the vicinity of the vapor–liquid interface, resulting in the enhancement of condensation process. Therefore, the inertial shock of liquid on the vapor bubble was much stronger than that without ultrasonic vibration at the same liquid subcooling. This would also accelerate the instability of the bubble surface in turn. Based on the experimental data at liquid subcooling of 15–60 K, empirical correlations were given to predict the condensation heat transfer of vapor bubbles with and without ultrasonic, with deviations within ±30%.

1. Introduction

Due to its high heat transfer ability, boiling is always encountered in many industry fields such as nuclear power, refrigeration, microelectronic and aerospace. Along with the rapid development of science and technology, the cooling requirements of some components and devices, for example, particle accelerator targets, high power X-ray devices, fusion reactor components and microelectronics chips will exceed 10 MW/m^2 in near future. Since the limit of critical heat flux (CHF), it is not easy for taking use of a common boiling process to cool these equipments with extremely high heat generation rate. Therefore, many researchers are seeking new methods to enhance boiling heat transfer. About three decades ago, a special boiling mode with heat flux higher than normal CHF was firstly observed by Inada et al. [1], which was termed as Microbubble Emission Boiling (MEB). It usually occurs under relatively high liquid subcooling conditions, accompanied by the collapse of vapor bubble and the emission of microbubbles on heating surface.

Inada et al. [1] firstly conducted a series of experiments of MEB at 15–85 K subcooling on a copper heating surface to which a thick platinum foil was attached. Then, Shoji and Yoshihara [2], Tange et al. [3] and Kato and Yamaguchi [4] performed experiments of MEB on a thin platinum wire. Suzuki et al. conducted a large number of experiments under both conditions of subcooled pool and flow boiling to research MEB. They studied the effects of heating surface size, channel size and geometry, physical property of working fluids, pressure and gravity on heat transfer performance and pressure fluctuation of MEB [5–9]. Zeigarnik et al. [10] set up an experimental apparatus with a stainless steel foil heating surface to observe MEB and studied the emitted microbubbles. Kumagai et al. [11] investigated the pressure fluctuations when MEB occurred, and found that the pressure fluctuation near the heating surface synchronized with the bubble behaviors and the frequency increased with the increase of heat flux in the region of MEB. Afterward, Suzuki et al. [12] obtained similar results and proposed a simple correlation of MEB. Wang and Cheng [13] first achieved MEB in a microchannel. They used a platinum film microheater as heating element and obtained the maximum heat flux of 14.41 MW/m^2 at liquid subcooling of 80 K.

A key feature of MEB is the collapse process of vapor bubbles which is observed only when liquid subcooling exceeds 20 K for water. Therefore, Ueno et al. [14], Suzuki et al. [12] and Tang

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Nomenclature

c_{pl}	specific heat of liquid (J/kg K)
D_{eq}	bubble equivalent diameter (m)
d_{j}	width of bubble in row j (pixel)
f	ultrasonic frequency (Hz)
f_{b}	bubble collapse frequency (Hz)
h_{c}	bubble condensation heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat of evaporation (J/kg)
K	scale factor (m/pixel)
m	number of the observed processes of bubble collapse or split-up
m_{b}	vapor bubble mass (kg)
N	total number of pixels in a bubble
R	bubble equivalent radius (m)
R_0	bubble initial radius (m)
S	measured bubble surface area (m^2)
S^*	real bubble surface area (m^2)
t	time (s)
u_{b}	bubble velocity (m/s)
V_{b}	vapor bubble volume (m^3)
z_{c}	abscissa of bubble centroid (m)
$z_{\mathrm{i,j}}$	abscissa of pixel in a bubble (pixel)
y_{c}	ordinate of bubble centroid (m)
$y_{\mathrm{i,j}}$	ordinate of pixel in a bubble (pixel)

Greek symbols

Δt_{k}	time interval between two successive bubble collapses (s)
ΔT_{sub}	liquid subcooling (K)
τ	time interval (s)
σ	surface tension coefficient (N/m)
λ	wavelength of capillary wave on bubble surface (m)
λ_{l}	thermal conductivity (W/m K)
v_{l}	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
Ω	set of the bubble locating

Subscripts

l	liquid
v	vapor
ul	ultrasonic

et al. [15,16] considered that the strong condensation effect of cold bulk could accelerate the instability of a vapor bubble and lead to the collapse of vapor bubbles, resulting in the occurrence of MEB. A better understanding of the process of bubble collapse and condensation can provide some valuable information in clarifying the mechanism of MEB. However, it is difficult to fully understand the vapor bubble collapse in MEB due to the complex interaction among gas, liquid, solid phase, interaction between bubbles and complex micro-convection around the bubble in a boiling system. Ueno et al. [14] proposed a simplified approach to investigate this process by extracting the vapor–liquid interaction from a complex boiling system. In their experiments, the vapor bubbles are supplied into the subcooled pool by a vapor generation system instead of an immersed heating surface for most boiling experiments. Due to the absence of the heating surface, Marangoni convection near a vapor bubble and the interaction between the heating wall and the bubble could be avoided and the effect of cold bulk on its condensation process was highlighted. According to their early visualized results, Ueno et al. [14] found that the collapse of vapor bubbles would also occur once the liquid subcooling exceeded a threshold, which was similar to the case of MEB. Naturally, more investigations were carried out on bubble condensation process to help analyze the mechanism of MEB.

It is only when liquid subcooling exceeds 20 K, the occurrence of MEB would be possible. This would limit the application of MEB under some special conditions. Therefore, Suzuki et al. [17] tried to lower the occurrence condition of MEB by using ultrasonic vibration. They studied the effects of ultrasonic vibration of 20 kHz on occurrence and heat transfer of MEB, and found that the ultrasonic vibration could accelerate the occurrence of MEB at liquid subcooling of 20 K. However, the ultrasonic vibration had no remarkable effects on MEB at liquid subcooling higher than 25 K. In investigation of Suzuki et al., of the action of ultrasonic vibration on vapor bubble collapse and MEB was not given clearly. Therefore, in this work, the condensation and collapse of vapor bubbles in a subcooled pool with and without ultrasonic vibration were focused to address the effects of ultrasonic vibration on the collapse and condensation of vapor bubbles and MEB.

2. Experimental apparatus and data processing

2.1. Experimental apparatus

The schematic diagram of the experimental apparatus is shown in Fig. 1. All experiments were carried out using an experimental setup in earlier publication [18]. The inner width, depth and height of the visualized tank were 300 mm, 240 mm and 120 mm, respectively. The vapor generated in a 240 kW electric heating boiler was injected into the water tank through an injection tube with inside diameter of 6 mm. The electric heating boiler and the piping were wrapped up with thermal insulating materials to reduce heat loss. An electric heater and a copper cooler were employed to maintain and control the bulk temperature. The vapor injection rate was controlled by the steam regulating valves as well as a valve on the bypass line. A K-type sheathed thermocouple installed in the steam pipe was used to measure the vapor temperature. Five K-type sheathed thermocouples of 0.5 mm in diameter were placed at 10, 15, 20, 30 and 45 mm horizontally apart from the central axis of the tube and 5 mm above the injection tube outlet to measure the bulk temperature. The drop in temperature between the five positions was less than 1 K. As a result, the water temperature was taken as that measured by the fifth thermocouple which was minimally affected by the bubble condensation. The fluctuation of water temperature was maintained within ±1 K when experimental data were recorded. The measured temperature signals were recorded by a NI acquisition system. The maximum error of the K-type sheathed thermocouples was 0.5 K and that of the NI acquisition system for recording the temperature was 0.25 K. Therefore, the error in temperature measurement was within 0.56 K. An ultrasonic actuator with a diameter of 30 mm was immersed in the water horizontally, as shown in Fig. 1. Its center axis was 10 mm above the exit of the injection tube approximately and its surface was about 62 mm apart from the center axis of the injected tube horizontally. The frequency of the ultrasonic actuator was 20 ± 1 kHz and the power was set to 400 W which were the same as those in experiments conducted by Suzuki et al. [17].