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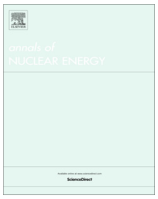

Bubble behavior and its contribution to heat transfer of subcooled flow boiling in a vertical rectangular channel

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ABSTRACT

In the present work, a visual investigation was carried out to study the bubble behavior including growth, sliding and coalescence on subcooled flow boiling in a narrow channel with a gap of 2.0 mm. At low heat flux, it was found that the bubble grew up rapidly on its nucleation site and then condensed subsequently at the pressures of 0.1 MPa and 0.3 MPa. Under the system pressure of 0.6 MPa and 1.0 MPa, the bubble generated and slid continually along the heating surface with very slow growing. At low pressure of 0.1 MPa and 0.3 MPa, the bubbles coalesced occasionally during growing on different nucleate sites and then condensed by subcooled bulk flow. At high pressure of 0.6 MPa and 1.0 MPa, the coalescence of bubbles mainly occurred during sliding on the heating wall with high heat flux. According to the energy balance, it was found that the sliding process of bubble had significant contribution to the enhancement of heat transfer than that that of stationary bubble. The bubble coalescence was analyzed, and found that the bubble growth rate and the bubble sliding velocity played an important role on bubble coalescence with different pressures.

1. Introduction

It is known that the presence of bubbles in a system can enhance the heat transfer between coolant and heated surfaces in nuclear sub-cooling flow boiling, which is widely used in heat exchangers, aerospace, electronics cooling, chemistry and nuclear energy including boiling water reactor (BWR).

It is significant to understand the characteristics of bubble growth, bubble departure and bubble coalescence. Over the years, many authors experimentally or numerically investigated the bubble behaviors. Zuber (1961) adopted the first models of bubble growth proposed by Bosnjakavic (1930) and Jakob and Linke (1935) to analyze the bubble growth. Thorncroft et al. (1998) visually investigated the growth and the departure of bubbles in vertical upward and downward flow with FC-87 as working fluid. The results showed that the bubble growth rate increased with the increase of Jacob number under otherwise identical conditions in up-flow and down-flow. Ma (2001) studied the nucleation and growth of a single vapor bubble on a flat surface with FC-72 in terrestrial gravity and microgravity. Prodanovic et al. (2002) studied the bubble behavior from inception to collapse in a vertical test section with high-speed camera. Basu et al. (2005) measured the waiting time, the growth time, the departure size and frequency of bubbles in an upward-vertical subcooled flow boiling facility using water as working fluid with contact angle varying from 30° to 90°. Siedel et al. (2008) carried out an experimental analysis of bubble growth, departure and interactions during pool boiling on artificial nucleation sites with 99% purity n-pentane ($T_{sat} = 35.7\ °C$ at $p = 1$ bar). Wua (2008) studied the bubble dynamics under subcooled nucleate horizontal flow boiling conditions. The R134a was chosen as a simulating fluid due to its merits of smaller surface tension, low latent heat and boiling temperature.

The sliding of bubbles can disturb the thermal boundary layer and velocity boundary layer, which leads to the enhancement of heat transfer between coolant and heating wall. Therefore, many experimental and theoretical researches have been carried out to study the effect of bubble sliding on heat transfer. Yan and Kenning (1996) used liquid crystal thermography to examine the temperature distribution on the surface of an inclined plate in a pool of water subjected to a sliding vapor bubble. They reported that the local heat transfer coefficient in the wake of a sliding vapor bubble was approximately three times of that for single-phase natural convection ahead of the bubble. Brucker (1999) obtain the temporal evolution of the flow field in the near wake of single rising bubbles of 5–7 mm diameter in water. And it was found that the existence of a pair of counter-rotating vortices close to the

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Nomenclature

A	Area (m^2)
c_p	Constant pressure specific heat capacity (J/kgK)
D	Diameter of bubble (mm
h	Forced convection heat transfer coefficient (W/m^2K), Enthalpy (J/kgK)
k	Thermal conductivity (W/mK)
K	Factor of the area influence
l	Bubble sliding distance (mm)
n	Nucleation density, ($1/m^2$), Ratio of the lift-off diameter D_{st} to initial diameter of sliding bubble D_{so}
p	Pressure (MPa)
Pr	Prandtl number, $\Pr = \nu/\alpha$
q	Heat flux (W/m^2)
Q	Heat (J)
G	Mass flux (kg/m^2s)
R	Resistance of heating strip (Ω)
Re	Reynolds number
t	Time (s)
T	Temperature (K)
V	Voltage acted upon the heater (V)

Greek symbols

α	Thermal diffusivity (W/m^2K), Ratio of the number of sliding bubble to total bubble
β	Fraction of different mechanisms
γ	Disturbance intensity of sliding bubble
ρ	Density (kg/m^3)

Subscripts

d	Departure
fg	Latent heat of evaporation
fc	Force convection
l	Liquid
mef	Micolayer evaporation of stationary bubble
mes	Micolayer evaporation of sliding bubble
s	Sliding
tcf	Transient conduction caused by stationary bubble
tcs	Transient conduction caused by sliding bubble
tol	Total
w	Heating wall

bubble base. Kenning et al. (2000) concluded that micro layer evaporation could account for only a small fraction of the heat energy transferred from the hot surface to the bubble for a micro layer thickness of proximately 60 μm. Yoon et al., 2001) numerical studied boiling heat transfer with a flat surface, it was concluded that fluid agitation caused by bubble development and detachment contributes to 80% of the overall predicted enhancement of heat flux. Qui and Dhir (2002) used PIV to observe the wake of the bubble with different angles of plate and it concluded that these vortices of the wake of the bubble can impact on a heated surface, transporting heated fluid away and allowing cooler fluid from the bulk to replenish it, thus increasing the heat transfer coefficient. In the Bayazit et al., 2003 study, the results showed that both the microlayer under a sliding bubble and the wake behind the bubble contribute substantially to the local heat transfer rate from the surface. Mohamed (2005) reported a study into the effects of bubble-induced motion on heat transfer around a cylinder.

In the nucleate boiling stage, the bubble coalescence is one of the typical bubble dynamics phenomena, which has significant effect on the thermal-hydraulics. Over the years, many authors investigated the bubble coalescence. Wang et al. proposed (Wang et al., 2005) that three main mechanisms of bubble coalescence existed in the two-phase system, the turbulent eddies, the differences of bubble rise velocities and the wake entrainment. In the study of Nguyen et al. (2013), the consecutive coalescence process was composed of the following steps: the approach and collision of bubbles, the formation and drainage of liquid film and the rupture of film as the critical thickness reached. Grienberger (1992) suggested that the bubble collision frequency was an essential factor for determining the occurrence of bubble coalescence, which was essentially affected by the hydrodynamics of bulk flow, including the turbulent field and the difference of rise velocity due to the liquid velocity gradient and the buoyancy. Zhang and Shoji (2003) aimed at the physical mechanisms of nucleation site interaction in the pool boiling. It was concluded that the occurrence of bubble coalescence had great influence on the bubble departure frequency. Morokuma and Utaka (2016) experimentally investigated the liquid film thickness distribution during the coalescence process by means of the modified laser extinction method. It was found that the thinnest area of the liquid film appeared just before coalescence at the center of the liquid film as the bubble approach velocity was less than 10 mm/s. As the bubble approach velocity was larger than 10 mm/s, the bubble bouncing usually occurred, and the thinnest area moved from the center toward the outer periphery of the liquid film in the form of a ring. According to the studies of Bonjour et al. (2000), as well as Chen and Chung (2002); the heat transfer deterioration would occur as lots of vapor bubbles were coalesced on the heating wall, and CHF (Critical Heat Flux) would untimely happen, which was mainly dependent on the ratio of the area covered by the liquid film and the dry-out area. Fu et al. (2010) suggested that the vapor bubbles could rapidly grow to the size of the mini-channel, which induced the bubble coalescence and the generation of vapor slug. Moreover, the liquid film evaporation between the vapor slugs and the heating wall was found to be the dominant heat transfer mechanism of flow boiling in the mini-channel.

According to the above discussion, there are not enough studies focusing on the bubble sliding and the bubble coalescence in the narrow channel. Meanwhile, the characteristics and the influence mechanisms of bubble behavior on the heat transfer is still unclear. In this study, a visual investigation was conducted to research the bubble behavior including growth, sliding and coalescence in a narrow channel with a gap of 2.0 mm.

2. Experiment facilities and setup

The schematic diagram of experimental loop system is shown in Fig. 1. Deionized water is selected as the working fluid and heated for about 24 h to eliminate non-condensing gases. A Venturi flow meter is adopted to measure the mass velocity with the flow rate ranging from 35 kg/h to 1189 kg/h. The temperature and pressure before the Venturi flow meter are measured by a T-type thermocouple with an accuracy of 0.5 K. The fluid is preheated by a heater (with power of 0–10 kW) before flowing to the test section.

A rectangular narrow channel test section is composed of two thick stainless steel plates, as shown in Fig. 2. The right side of the test section is a visual side which includes five windows for observation and the inlet and outlet ports. The narrow channel formed by the surface of heating section and observation side. The observation windows are made of quartz glass with thickness of 33 mm and diameter of 45.5 mm. The left side of the test section