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Experimental studies of condensing vapor bubbles in subcooled pool water using visual and acoustic analysis methods

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ABSTRACT

In this study, smooth bubble condensation that occurs in subcooled pool water was examined to understand condensation phenomena at the beginning of boiling. The behaviors of condensable and non-condensable bubbles were investigated with respect to various temperatures and bubble sizes. The experimental data were analyzed using visual and acoustic methods including Phase Interface Binarization (PIB), Tridimensional Reconstructing Assumption (TRA), and acoustic data conversion. For visual analyses, (1) the PIB method determined bubble departure frequency, condensation time, and rising distance, and (2) the TRA method determined departure bubble size and volume reduction rate. The bubble detached with smaller volume and occurred more frequently with a smaller nozzle and a higher subcooling degree. Because the condensation always occurred during the growth, necking, and detachment of a bubble, the bubble was detached before it grew sufficiently. Lower condensation time and rising distance were associated with higher subcooling degrees and smaller injected bubbles. With respect to the acoustic analysis, sound signals were measured using a hydrophone, and the obtained analog data were converted to sound pressure units. The results revealed that higher volume reduction rate resulted in stronger sound pressure. As a result, the condensation phenomena in the smooth bubble regime were visually observed, and the possibilities of acoustic monitoring for earlier boiling were investigated.

1. Introduction

In the field of nuclear engineering, it is important to understand boiling phenomena under subcooled pool boiling conditions due to various heat transfer effects such as pressure drop, flow instability, and cooling efficiency. As shown in Fig. 1, different boiling phenomena occur with excess temperature and heat flux. In nucleate boiling, Onset of Significant Void (OSV) exists from the Onset of Nucleate Boling (ONB) to the Departure from Nucleate Boiling (DNB). Prior to the OSV, vapor bubbles that are detached from the heating surfaces collapse and disappear since the flow in the core continues to be subcooled. Following the OSV, the bubbles detached from the heating surfaces survive, coalesce, and form large bubbles, which may lead to flow instability and Critical Heat Flux (Faghri and Zhang, 2006). Therefore, detection of boiling is important to prevent unfavorable flow behaviors.

Void fraction measurement is widely used to monitor boiling occurrences. Several researchers measure void fraction using electrical conductivity probes, gages for differential pressure, optic fibers, and electro-magnetic sensors (Hetsroni, 1982). The start point of boiling is ONB. However, existing methods to detect boiling occurrence have focused on OSV to predict Critical Heat Flux (CHF) that should be avoided to maintain the fuel integrity. These methods are not appropriate to detect boiling occurrences prior to the OSV since vapor bubbles collapse and disappear due to condensation in this regime. Hence, a new methodology for monitoring boiling is required to detect earlier boiling when compared with conventional techniques.

Several researchers examined condensation phenomena to understand detailed processes of condensation. Representatively, Tang et al. (2015a,b) defined regimes that showed that the bubble condensation became significant and rough based on the temperature of sub-cooled water and the flow rate of the injecting gas. Four different condensing characteristics were defined and included a capillary wave, transition, shape oscillation, and smooth bubble regimes. Fig. 2 shows two representative regimes; (1) capillary wave regime and (2) smooth bubble regime. The smooth bubble condensation is observed in a low flow rate condition, and the bubbles possess clear phase interfaces. In contrast, capillary wave condensation occurs in a high flow rate condition, and fine waves are formed on the bubble surfaces.

Additionally, Jeon et al. (2011) and Pan et al. (2012) showed numerical simulations of collapsing bubbles using a Volume of

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Nomenclature

d	Diameter of injecting nozzle [mm]
d_{in}	Inner diameter of nozzle [mm]
d_{px}	Number of pixel in the nozzle region
F_i	Interfacial tension force [mN]
F_b	Buoyancy force [N]
f_d	Bubble departure frequency [Hz]
h	Rising distance [mm]
L_{SP}	Sound pressure level [dB re 1 μPa]
l	Distance of hydrophone from the nozzle [m]
l_{ref}	Reference distance of sound pressure level [m]
n_d	Number of bubble departure
n_{left}	Pixel number of left boundary
n_{right}	Pixel number of right boundary
q''	Heat flux [W/m^2]
r	Radius [mm]
r_n	Inner radius of nozzle [mm]
r_k	Radius of unit cylinder generated on the k*th* row [mm]
Ref_{dBSPL}	Reference pressure level in water [dB]
$Ref_{V/\mu Pa}$	Reference voltage at a micro-pascal [V]
S_{dB}	Sensitivity [dB]
$S_{mV/Pa}$	Sensitivity [mV/Pa]
T	Temperature [°C]
t_c	Time distance between detachment and condensation [s]
t_d	Time distance between an departure of a bubble and that of follow-up bubble [s]
V	Volume [ml]
$\dot{V}$	Volume reduction rate [ml/s]
V_{in}	Indicated voltage [V]
y	Highest pixel number of y-axis in the image

Greeks

α	Sound attenuation coefficient [dB/m]
θ	Contact angle [deg]
σ	Surface tension [N/m]
ρ_l	Density of water [kg/m^3]
ρ_g	Density of gas [kg/m^3]

Subscripts

sat	Saturated
sub	Subcooled
sur	Surface

Abbrevations

CHF	Critical Heat Flux
DAQ	data acquisition system
DNB	Departure from Nucleate Boiling
ONB	Onset of Nucleate Boiling
OSV	Onset of Significant Void
PIB	Phase Interface Binarization
RMS	root mean square
SPL	sound pressure level
TRA	Tridimensional Reconstructing Assumption
VOF	Volume of Fluid
VRR	volume reduction rate

Fluid (VOF) model with various conditions of condensation such as different subcooling degrees, inlet pressures, and initial bubble sizes.

In addition to these phenomenological studies, new measurement techniques were studied by a few researchers. Specifically, an acoustic measurement was suggested because sound waves occur when a bubble collapses by cavitation or condensation. Acoustic sensing methods were introduced by Minnaert (1933) who studied sound from occurrence and breakage of a non-condensable bubble. These methodologies were further developed by Leighton (1997). Vanquez et al. (2005) reviewed and applied these measurement techniques to determine bubble size. The acoustically measured results were compared with other data obtained from video imaging and inverted funnel techniques.

Based on the fore-mentioned techniques, several researchers applied hydrophones to various experiments in which the behaviors of non-condensable bubbles were observed. For example, acoustic measuring was applied to check the effects of antifoam agents (Al-Masry et al., 2006), predict transitions of flow regimes (Al-Masry et al., 2007; Ajbar et al., 2009), detect bubbles from a sediment (Vanquez et al., 2014), and detect bubbles generated in a cross-flow (Chicharro and Vanquez, 2014). Furthermore, acoustic sound measurement was applied to a few experiments related to cavitation. Staudenraus and Elsenmenger (1993) and Osterman et al. (2009) characterized cavitation by measuring ultrasonic waves and shockwaves using a hydrophone. Additionally, sound pressure waves from the collapse of cavitation bubbles were detected in a study by Tinguely (2013).

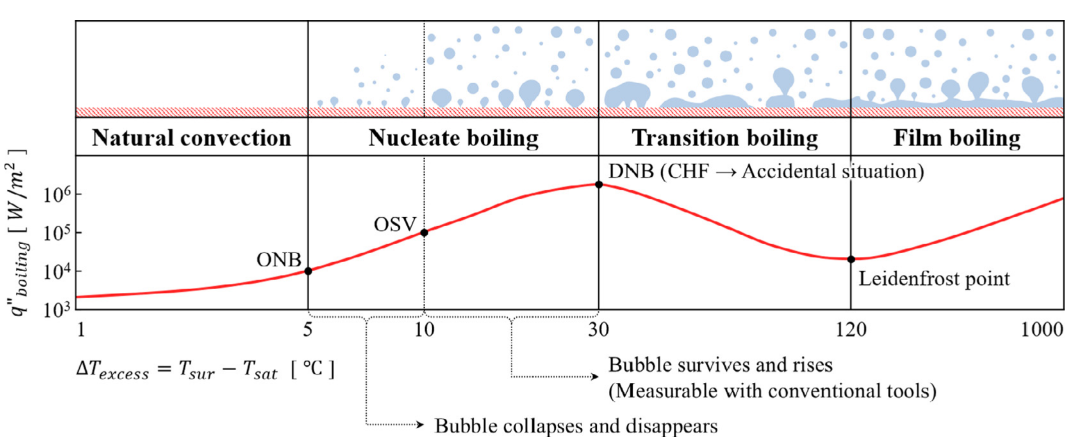

Fig. 1. Boiling curves in pool boiling.