Nuclear Engineering and Design 268 (2014) 41–50

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Experimental research of bubble number density and bubble size in narrow rectangular channel under rolling motion

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HIGHLIGHTS

- Bubble number density and bubble size under rolling motion are studied.
- Automatic processing algorithm dealing with bubble parameters is proposed.
- The fluctuation amplitude is mainly affected by rolling amplitude.
- Variation of the effective wall superheat is the main reason for the fluctuation.

ARTICLE INFO

Article history:
Received 27 August 2013
Received in revised form
17 November 2013
Accepted 22 November 2013

Keywords:
Rolling motion
Bubble size
Bubble number density
Narrow rectangular channel
Ocean condition

ABSTRACT

Bubble number density and bubble size are two important parameters in the research of subcooled flow boiling and the channel power of water-cooled nuclear reactor are greatly affected by the two parameters through the neutron feedback caused by the variation of local void fraction. By using the high speed camera in combination with the digital image processing technology, the bubble number density and bubble mean diameter in an up-flow narrow rectangular channel under rolling motion are experimentally researched. Experimental results indicate that the bubble number density and the bubble mean diameter under rolling motion periodically fluctuated with the same period as that of the rolling motion. The camera captured bubbles consisted of sliding bubbles coming from the upstream flow and nucleation bubbles emerging in the scope of the observing window. Variations of the bubble mean diameters under rolling motion are analyzed by the distribution of the bubble diameters. Both the diameters of sliding bubbles and nucleation bubbles periodically changed under the effect of the rolling motion, and the two kinds of bubble share the same variation trend. The fluctuation amplitude of the bubble number density and the bubble mean diameter is determined by the rolling period and amplitude. The fluctuation amplitudes of the above two parameters are intensified by the rolling amplitude, whereas the effect of the rolling period is weak. At the same time, local pressure, wall temperature and local fluid velocity oscillated periodically in the rolling motion. Effect of the fluid velocity oscillation can be neglected due to its tiny fluctuation amplitude in this research. Variation of the effective wall superheat induced by the change of wall temperature and local pressure is the main reason accounting for the fluctuation of bubble parameters under rolling motion.

1. Introduction

Nuclear propulsion may be a worth considering option for bigger, high-speed and long period of working time commercial vessels (Khlopkin and Zotov, 1997; Vergara and McKesson, 2002). The safety and thermal hydraulic characteristics of reactor, as well as other boiling heat transfer equipment such as evaporator, on the nuclear vessel will be changed inevitably under the effect of ocean condition. Bubble number density and bubble mean diameter are two of the basic parameters in the study of subcooled flow boiling and determining the distribution of void fraction and interfacial area concentration. Interfacial area concentration is the key parameter in the construction of interfacial area transport equation of the two-fluid model (Ishii and Hibiki, 2005). In addition, the variation of the void fraction is not only related to the cooling capacity of

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http://dx.doi.org/10.1016/j.nucengdes.2013.11.084

Nomenclature

A	fitting parameter
A_f	observing window area (cm^2)
B	fitting parameter
C	fitting parameter
D	bubble diameter (mm)
D_a	bubble mean diameter (mm)
D_e	bubble equivalent diameter (mm)
D_i	pixel value of the diameter (pixel)
D_r	D_x or D_y (mm)
G	mass flux (kg/m^2 s)
h	channel height (mm)
K_p	calibration of the image (μm/pixel)
n	bubble number density (cm^{-2})
N	total number of the bubble
P	pressure (kPa)
q''	heat flux (kW/m^2)
t	time (s)
T_0	rolling period (s)
T_{sat}	saturation temperature (°C)
T_w	wall temperature (°C)

Greek letters

ΔD	fluctuation amplitude of D_a (mm)
Δn	fluctuation amplitude of n (cm^{-2})
ΔT_{sub}	inlet subcooling (°C)
$\Delta T_{w,eff}$	effective wall superheat (°C)
θ	rolling angle (°)
θ_m	rolling amplitude (°)

Subscript

eff	effective
i	number of the bubble
sat	saturation
sub	subcooling
x	*x* direction
y	*y* direction

nuclear reactor but also affecting the reactivity of the reactor core (Jitka and Wallenius, 2011).

Numerous theoretical and visible experimental researches have been conducted to study the bubble behaviors such as bubble nucleation (Hsu, 1962; Hibiki and Ishii, 2003), bubble growth (Zuber, 1961; Gerardi et al., 2010), bubble departure and lift-off (Situ et al., 2008; Wu et al., 2008; Cho et al., 2011) and bubble sliding (Donnelly et al., 2009; Li et al., 2013) in static condition with varied system pressure, subcooling and heat flux. Furthermore, flow boiling in narrow channel has been studied in recently years and it has been found that the two-phase flow regimes and the associated heat transfer differ significantly from those in conventional channels as the channel size is smaller than certain critical value (Kandlikar, 2004; Vlasie et al., 2004). However, the successful prediction of nucleate boiling has not yet been achieved due to the complex properties of flow boiling (Dhir, 2006).

The flow and heat transfer characteristics of coolant under ocean conditions has been studied by many researchers before the research of bubble behavior under ocean conditions, including natural and forced circulation (Ishida et al., 1990; Murata et al., 2002; Pendyala et al., 2008). The flow rate and pressure drop in a vertical tube under heaving motion has been experimentally researched by Pendyala et al. (2008). The results indicated that the induced flow fluctuation is dependent on Reynolds number and stronger fluctuations can be found at lower Reynolds number. Tan et al. (Si-Chao et al., 2009a,b) performed experiments to study the flow and heat transfer properties of natural circulation under rolling motion condition. The experimental results showed that the flow rate fluctuation of the single-phase natural circulation can be easily induced by the additional inertia force caused by rolling motion. The heat transfer performance of the channel is enhanced and the heat transfer coefficient increases with increasing the rolling amplitude and frequency. Besides, the flow resistance coefficient under rolling motion is larger than that in the non-rolling cases and the increase of rolling amplitude and frequency also leads to an increase of flow resistance coefficient. Xing et al. (2012, 2013) experimentally and theoretically investigated the rolling motion effects on single-phase flow with different pressure heads. They found that the fluctuation amplitude of the flow rate decreases rapidly as the increase of the pressure head and the fluctuation may vanish with extreme higher pressure head, namely the fluid flow is unaffected by rolling motion. In addition, they mentioned that the variation of rolling amplitude has more influence than that of rolling period on the amplitude of the flow oscillation under rolling motion.

Bubble departure behavior in subcooled flow boiling channel under the effect of rolling motion has been theoretically researched by Qin and Gao (2008). Bubble departure under rolling motion was modeled based on the force balance combined with the effects of rolling motion. The results indicated that the bubble departure diameter under rolling motion, with the assumption that the flow rate is invariable, is almost identical to that under the static condition. While great affections may be arose by rolling motion only if the intensity of the induced flow rate fluctuation is strong enough, this may present in some natural circulation system. Similar method has been adopted by Hong et al. (2011) to analyze the bubble departure characteristics under heaving condition. By comparing the forces acted upon the bubble under different conditions, it came to a conclusion that the influence of heaving motion depends on the flow rate fluctuation for natural circulation and on the weight of buoyancy among the various bubble forces for forced circulation. A series of experimental and theoretical studies relating to bubble behaviors under heaving condition have been done by Hong et al. (2012a,b) subsequently. The experimental results shown that the fluctuation of bubble size, bubble velocity and bubble number density increases with the increase of heaving frequency. Bubble departure diameter was found to be influenced by additional heaving acceleration and the variation of flow rate caused by heaving motion. Moreover, a bubble departure model was proposed for the calculation of the bubble departure diameter under heaving motion by considering the additional acceleration and flow rate fluctuation. From the above results we can see that the most important effect of ocean conditions on bubble departure can be came down to the influence of flow rate fluctuation. However, if a time-independent flow rate under rolling condition is presented, whether the influences on bubble still exists needs further research.

The above literature review indicates that the bubble behavior in subcooled flow boiling channel under static condition has been studied extensively and some works also has been done in the field of bubble behavior under ocean condition. However, most of the researches are confined to single bubble behavior and static condition. The study of bubble group characteristics such as bubble number density and bubble mean diameter in a narrow channel under rolling condition are absent at present. The aim of this study is to fill this gap considering the important role of bubble number density and bubble mean diameter in determining the flow and heat transfer performance of boiling channel. The characteristic of bubble number density and bubble mean diameter in a narrow rectangular channel under rolling condition is experimentally studied by adopting the high speed visualization technique and digital