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Experimental research of bubble characteristics in narrow rectangular channel under heaving motion

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A B S T R A C T

Subcooled flow boiling is a commonly applied technique for achieving efficient heat transfer. Although numerous works have been done on two-phase flow phenomena, most of these works focus on land-based channels. Therefore, for identifying the heat transfer phenomena in the barge-mounted system, it is necessary to know the local flow condition in an oscillating acceleration field. In this study, forced convection subcooled water boiling experiments are conducted in narrow rectangular channels at low frequency oscillations. The bubble size, bubble velocity and bubble number density have been statistically analyzed under different heaving conditions and at different flow rates. The results of the bubble size distribution have been presented as cumulative distribution functions, which exhibit in reality a very wide spread of bubble size. The results show that an increase of the oscillation frequency causes an increase fluctuation of bubble size, bubble velocity and bubble number density. Under the same heaving condition, an increase of mass flow rate leads to a decrease fluctuation of bubble size and bubble velocity. A correlation has been sought for the fluctuation of bubble diameter due to heaving motion. The proposed model agrees well with the experimental data within the averaged relative deviation of ±19.2%.

1. Introduction

In recent years, sea research requires offshore power source [1]. In coastal area, there has been a growing interest in barge-mounted floating nuclear desalination plant to provide potable water [2,3]. The main difference between land-based and barge-mounted equipments is the influence of sea wave oscillations on the latter ones. An oscillating environment changes the effective gravity and, as a result, generates periodic force on the working fluid. Previous investigators have already performed several researches on flow under oscillating conditions. The influence of rolling, pitching and heaving motion upon natural circulation has been investigated by Gao et al. [4,5]. A series of single-phase natural circulation experiments have been carried out by Murata et al. [6], for analyzing the effect of rolling motion on thermal hydraulic characteristics of reactor. Pendyala et al. [7,8] have studied the effect of oscillations on heat transfer, flow rate and pressure drop in a vertical tube experimentally. Yan et al. [9,10] have investigated the laminar flow under rolling, heeling and heaving motion. Akdag et al. [11] have investigated heat transfer from a surface having constant heat flux subjected to oscillating flow in a vertical annular liquid column experimentally. In two-phase flow field, an experimental and theoretical study has been carried out for the upward gas-liquid two-phase flow under rolling and steady state conditions [12]. Otsuji and Kurosowa [13–15] reported that the critical heat flux of forced convection boiling under oscillating flow conditions was considerably reduced. Ishida and Yoritsune [1], Ishida et al. [16] studied deep sea research reactor DRX and concluded that under the condition of both density wave oscillation and heaving, the system showed oscillating with the overlapped effect. Furthermore, bubble dynamics and interactions are important phenomena, which affect the performance of two-phase flow systems. Under ocean conditions, motions such as heeling, heaving and rolling/pitching could change the effective forces acting on the two-phase flow, which lead to changes in bubble dynamics and interactions. As we know, the two-fluid model [17] as well as the interfacial area transport equation [18] and the bubble number density transport equation [19,20] can offer an advanced analysis for nuclear reactor systems. Several parameters, such as bubble size, bubble departure frequency and bubble velocity, are required to estimate the interfacial transport of mass, momentum and energy. Many works have even been established to describe dynamics, such as bubble departure diameter [21–23], bubble departure frequency [24–26] and

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bubble size distribution [27–29]. Almost all of the studies are based on steady state. Therefore, the studies of bubble dynamics affected by effective gravity are limited. Kamp et al. [30] developed a mechanistic model for bubble coalescence in microgravity bubbly pipe flow. Qing and Gao [31] analyzed the forces acting on bubbles in subcooled boiling flow under rolling motion without experiments.

Literature review shows that bubble dynamics under steady state have been studied extensively, bubble dynamics researches under heaving motion are still under development. In this paper, an experimental study is carried out to reveal the influence of heaving motion on bubble characteristics in subcool boiling flow.

2. Experimental setup

2.1. Heaving platform

The heaving platform is a six degrees-of-freedom platform. It is used to generate the low frequency oscillations in the test section. The vertical displacement $x(t)$ of the platform is shown as follows.

$$x(t) = x_m \sin\left(\frac{2\pi t}{T}\right) \tag{1}$$

The velocity and the acceleration of the test section can be established by differentiating Eq. (1) once and twice, respectively.

The velocity $u(t)$ is shown as follows.

$$u(t) = \frac{dx(t)}{dt} = \frac{2\pi x_m}{T} \cos\left(\frac{2\pi t}{T}\right) \tag{2}$$

The acceleration $a(t)$ is shown as follows.

$$a(t) = \frac{du(t)}{dt} = -\frac{4\pi^2 x_m}{T^2} \sin\left(\frac{2\pi t}{T}\right) \tag{3}$$

In this paper, the conditions of heaving motion are shown in Table 1. Fig. 1 depicts the phase curves of H3. In order to identify different phases in a cycle of heaving motion, four varied positions are defined in Fig. 1.

2.2. Experimental loop

The experimental loop is shown schematically in Fig. 2. The direction of the flow in the test section is vertical upward. Some of the experimental apparatuses, such as condenser, preheater and test section are mounted on the platform. The rest apparatuses are connected to the platform with flexible pipe. The subcooled water is held in the water degassing tank. The tank removes non-condensable solved gas by heating the water up to the saturation temperature. The degassing process is started hours before the experiments. A piston pump drives the deionized water through the facility. The volumetric flow rate is measured with a venturi flowmeter. The water is preheated via a preheater, then directs into the test section. After exiting the test section, the vapor liquid mixture enters a condenser, which returns the water to a single-phase state. Then the water goes back to the water tank. The thermal conditions of heaving motion are shown in Table 2.

Table 1
Conditions of heaving motion.

S. no.	x_m (m)	T (s)	$\lvert u_{max}\rvert$ (m/s)	$\lvert a_{max}\rvert$ (g)
H1	0.2	2.5	0.503	0.129
H2	0.2	2	0.628	0.201
H3	0.2	1.64	0.767	0.300
H4	0.2	3.33	0.377	0.073
H5	0.2	5	0.251	0.032

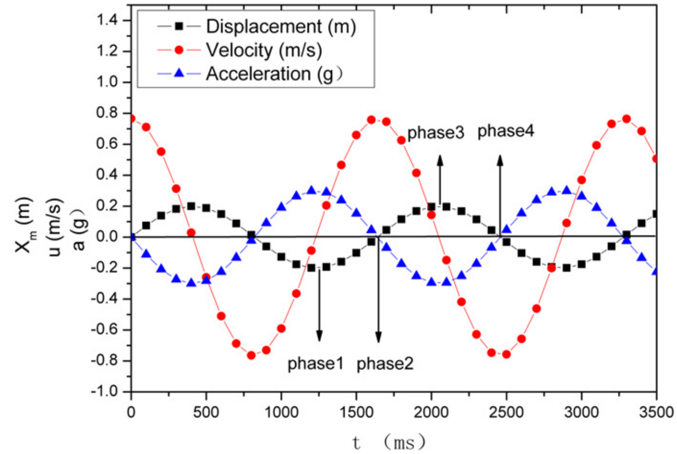

Fig. 1. Phase changed curves in H3.

2.3. Test section

The schematic diagram of test section is described in Fig. 3. The test section is a rectangular channel with a cross section of 40 mm × 2 mm. The length of the channel is 700 mm. The aspect ratio ($\alpha = W/H$) is 20. The hydraulic diameter, $D_h = 4A_c/P$, is about 3.81 mm. The test section mainly consists of two holders, quartz glass, heating plate and "O" type ring. The heating plate is made of 0Cr18Ni10Ti stainless steel. The center of heating plate has a thickness of 3 mm. In order to avoid an excess of heating in the edge of heating plate, the edge of heating plate has a thickness of 0.5 mm. The roughness of the heating plate is less than 3.2 μm. Because of the position of both copper plates for inputs, the effective heating length is 530 mm. The waterproof of the narrow channel is guaranteed by a silicon latex "O" type ring. Two holders are used to mount the narrow channel. By using a 20 kW DC power supply, a large range of heat fluxes are applied to the test section.

2.4. Optical measurement techniques

The setup of the flow visualization system is described in Fig. 4. Images are captured with a high-speed CMOS camera Phantom V9.0. It can capture at the rate of 15,000 fps at reduced resolution.

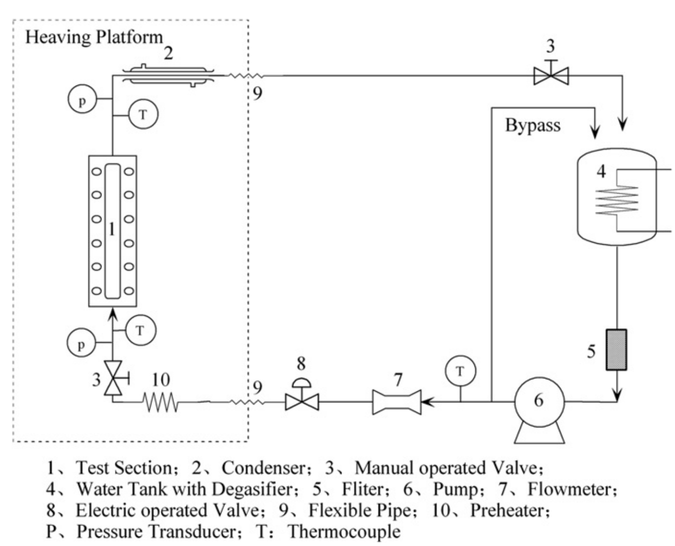

Fig. 2. Schematic diagram of experimental loop.