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Investigation on two-phase distribution in a vibrating annulus

Xiu Xiao [a], Qingzi Zhu [b], Shao-Wen Chen [c], Yajun Zhang [a], Haijun Jia [a], Mamoru Ishii [b,*]

[a] Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China
[b] School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, IN 47907, USA
[c] Institute of Nuclear Engineering and Science, National Tsing Hua University, Hsinchu 30013, Taiwan

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ABSTRACT

Seismic vibration can induce additional interphase forces acting on bubbles and change flow characteristics in two-phase flow system. Local measurements of air-water two-phase flow parameters, namely void fraction, interfacial area concentration and Sauter mean diameter, were conducted in a vibrating annulus. The vibration acceleration ranged from 0.05 g to 0.24 g. Nine inlet flow conditions were selected, which covered bubbly and slug flows. No significant difference was observed in the time-averaged flow parameters between reference and vibration experiments. During vibration cycle, the radial two-phase flow distribution varied continuously with vibration phase. The change in non-dimensional line-averaged void fraction decreased with the increase of void fraction. As the vibration amplitude increased from 3.04 mm to 10.08 mm, the vibration effects on variations of local flow parameters were greatly enhanced with the mean relative variation (MRV) of void faction reached up to 55%. The study on MRV of local parameters showed that the vibration effects were strongly related to specific flow conditions. With the increase of superficial gas velocity and void fraction, the vibration effects were reduced and the MRV of void fraction decreased from 55% to 18%.

1. Introduction

Two-phase flow structure plays an important role in determining the performance of nuclear reactor system during normal operation and transient conditions. A great number of experiments have been performed to study two-phase flow behaviors within various channel geometries (Hibiki and Ishii, 1999; Shen et al., 2006; Manera et al., 2009; Fu and Liu, 2016). In recent years, there has been a growing interest in the earthquake impact on nuclear reactor safety. Under earthquake condition, the forced vibration could change the effective forces acting on bubbles in two-phase flow, leading to changes in bubble dynamics and thermal-hydraulic characteristics. But there is little knowledge of how coolant and void fraction in a reactor core would response when earthquake acceleration is added. The void fraction is one of the most important parameters in determining neutron flux in reactor core. Fluctuations of void fraction as well as other interfacial parameters are expected to directly affect reactor power distribution under vibration condition. Therefore, the knowledge of two-phase flow distributions under seismic vibration is needed in reactor safety analysis.

A few researchers have performed investigations on two-phase flow behaviors under unsteady condition. Table 1 summarized the existing major works in recent years. Three major categories of vibration condition were found: rolling motion, earthquake vibration and flow-induced vibration. The vibration effects on two-phase flow were mainly focused on boiling heat transfer, the critical heat flux (CHF) and two-phase flow parameters. Hong et al. (2012) conducted experiments of subcooled boiling flow under heaving motion. The results indicated that an increase in oscillation frequency resulted in an increased fluctuation of bubble number density, bubble velocity and bubble size. As to the adiabatic two-phase flow experiments under rolling motion, the local parameters were found to fluctuate periodically with the rolling motion (Tian et al., 2014) and no obvious difference was found among interfacial parameters between inclined and rolling conditions (Yan et al., 2014). The buoyancy component in the radius was used to explain the experimental results. However, the vibration parameters induced by earthquakes are quite different from those rolling parameters investigated in the above literatures. Chen et al. (2010) studied the magnitude and intensity scales of earthquakes extensively. Based on this work, Chen et al. (2010, 2014) and Xiao et al. (2016) conducted two-phase flow experiments under vibration condition. In the boiling flow experiment, the heat transfer was enhanced under large vibration

* Corresponding author.
E-mail address: ishii@purdue.edu.cn (M. Ishii).

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Table 1
List of existing major works of two-phase flow under unsteady condition.

Investigators	Vibration Condition	Measurement Method	Remarks
Hong et al. (2012)	Rolling motion	Image processing	An increase in the oscillation frequency resulted in an increased fluctuation in bubble number density, bubble velocity and bubble size
Tian et al. (2014)	Rolling motion	Optical probe	Local parameters presented periodical variation with the rolling motion. The buoyancy component in the radius played an important role in determining the peak positions
Yan et al. (2014)	Rolling motion	Image processing	No obvious difference was observed among interfacial parameters under inclined and rolling conditions. The lateral component of buoyancy caused by gravity was a dominating factor in the distribution of local parameters
Chen et al. (2010) and Chen et al. (2014)	Earthquake vibration	Thermocouples and impedance meter	In boiling flow experiments, the heat transfer was enhanced under large displacement; In adiabatic air-water two-phase flow, vibration effects on the area-averaged void fraction were very limited
Arai et al. (2013) and Mizuno et al. (2014)	Earthquake vibration	Image processing	Periodical bubble formation and trajectory were observed
Xiao et al. (2016)	Earthquake vibration	Conductivity probe	Preliminary experimental result including the periodical change of void fraction and interfacial area concentration along with vibration motion was observed in bubbly flow
Hibiki and Ishii (1998)	Flow-induced vibration	Conductivity probe	For relatively low gas velocity, flow-induced vibration promoted bubble coalescence. The void fraction profile changed from ‘wall-peak’ to ‘core-peak’ or ‘transition’
Lee et al. (2004)	Flow-induced vibration	Thermocouples	The heat transfer and CHF was enhanced by tube mechanical vibration. Generally, the CHF increased with vibration intensity
Miwa et al. (2015)	Flow-induced vibration	Optical probe, conductivity probe and impedance meter	Reported studied on internal two-phase flow induced vibration were extensively reviewed. In general, slug and churn flow regimes had the strongest fluctuation compared to other flow regimes

displacements (Chen et al., 2010). As to the adiabatic experiments, it was found that the vibration effects on area-averaged void fraction were very limited (Chen et al., 2014). But the measurements of local parameters indicated periodical changes of void fraction and interfacial area concentration (IAC) with vibration motion in bubbly flow (Xiao et al., 2016). Arai et al. (2013) and Mizuno et al. (2014) also conducted a series of experiments on two-phase flow dynamics under earthquake acceleration. Periodical bubble deformation and trajectory were observed. But the researchers didn’t provide any information on local flow parameters. Flow-induced vibration is an important phenomenon in two-phase flow system. Hibiki and Ishii (1998) investigated the effect of flow-induced vibration on local parameters in air-water two-phase flow. The vibration promoted bubble coalescence for relatively low superficial gas velocity. The void fraction profiles changed from ‘wall-peak’ to ‘core-peak’ or ‘transition’. To find out the effect of tube vibration on CHF, Lee et al. (2004) carried out experimental studies under vertical upward flow. The CHF was enhanced by tube vibration and it generally increased with vibration intensity. Recently, the reported studies on internal two-phase flow induced vibration were extensively reviewed by Miwa et al. (2015). Based on the review, it was agreed by the authors that slug and churn flow regimes have the strongest fluctuation compared to other flow regimes. But the effect of two-phase flow regime needed to be investigated further.

Literature review shows that two-phase flow distributions under static condition have been investigated extensively and some researchers have performed investigations on two-phase flow behaviors under unsteady condition. But very limited studies have been conducted to investigate the distribution of local two-phase flow parameters under earthquake vibration. In order to fully understand the effects of seismic vibration on local interfacial parameters, two-phase flow experiments under vibration conditions were performed. The test facility was scaled down from Boiling Water Reactor (BWR) core sub-channel (Chen et al., 2010). Four-sensor conductivity probe was used to measure local interfacial parameters. Measured flow parameters included void fraction, interfacial area concentration, Sauter mean diameter and bubble frequency. A total of nine flow conditions were investigated such that the interfacial structures in bubbly and slug flows were acquired in the vibrating annulus. The effects of vibration amplitude as well as vibration acceleration on variations of local flow parameters were discussed in detail.

2. Experimental setup

2.1. Experimental loop

Experimental investigation of vertical upward two-phase flow under vibration conditions has been performed on a test facility available in Thermal-Hydraulics and Reactor Safety Laboratory (TRSL) of Purdue University. Both adiabatic and boiling two-phase flow experiments can be conducted on this facility. In this study, the research is focused on local interfacial parameters in adiabatic air-water two-phase flow. Fig. 1 shows the schematic of the experimental loop.

The experimental loop mainly consists of the test section, water tanks, a circulation pump, water lines and compressed air lines. The test section is attached to the vibration module through a vibration beam. The working fluids are deionized water and air. Filtered and chemically treated water with conductivity of approximately 300 μS/cm is held in the main tank while air is stored in a compressed-air storage tank. The liquid driven by the circulation pump firstly passes through a ball valve and a liquid magnetic flowmeter. The water is then delivered to the test section uniformly through four separate lines. A two-phase mixer is located at the bottom of the test section. Compressed air from the gas storage tank passes through a ball valve and then mixes with liquid in the two-phase mixer. A porous tube having porosity of 10 μm is fixed in the central of the two-phase mixer. Water is injected into the mixer through the annulus gap between the porous tube and the mixer wall while air is injected from the bottom of the porous tube. While water and air enter the mixer, gas is sheared off from the porous tube wall by the liquid flow and near uniform bubbles are produced. The design of this injection system can help to minimize the initial entrance effect of two-phase flow. After flowing through the test section, two-phase mixture enters the separation