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A visualized study of the motion of individual bubbles in a venturi-type bubble generator

Liang Zhao, Zhengyu Mo*, Licheng Sun**, Guo Xie, Hongtao Liu, Min Du, Jiguo Tang

State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource & Hydropower, Sichuan University, Chengdu, 610065, China

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ABSTRACT

As an equipment for generating millimeter- or micrometer-sized bubbles, venturi-type bubble generator has a great potential application in online poison gas removal for molten salt reactor, water treatment, mineral flotation, flue gas desulphurization, even in drug delivery, etc. While the process of generating bubbles in a venturi tube is quite different from that in a conventional tube. A visualized study was carried out to illustrate the details of the transportation of individual bubbles in a venturi-type bubble generator. Sizes, velocity, acceleration of the bubbles were obtained by Digital Image Analysis (DIA) method. An extremely rapid deceleration and intense breakup process was observed nearby the entrance of the diverging section of the bubble generator. Bubbles with average diameter larger than 1.5 mm were usually split before collapse, while the smaller one collapsed directly without split. Within several millimeters, the velocity of the bubbles were almost reduced by half, which is believed to play a key role for triggering their collapse. Once a bubble was decelerated to its minimum velocity, it was collapsed promptly into many tiny bubbles around the position of 8–10 mm from the inlet of the diverging section. Increasing the liquid flow rate could intensify the collapse process, while its influence on the position of collapse was weak.

1. Introduction

Bubbles or microbubbles have a broad application in engineering fields covering chemical reactor (Najafi et al., 2008; Sujatha et al., 2015), waste water treatment (Khuntia et al., 2012), molten-salt breeder reactor in nuclear system (Gabbard, 1972; Tang et al., 2014; Yin et al., 2015) and ship drag reduction technology (Hashima et al., 2015), etc. One of the most important characteristics of microbubble flow is the larger interfacial area between the two phases compared with the other flow patterns, thereby the exchange of mass, momentum and energy between the disperse and continuous phases is enhanced (Parmar and Majumder, 2013).

Several different type bubble generators have been reported. Sadatomi et al. (2005) designed a microbubble generator with a sphere installed in its center to create a strong turbulence flow inside the generator for breaking up large bubbles into microbubbles. Later on, Sadatomi et al. (2007) replaced the sphere in the generator by an orifice for simplifying the structure. Several works (Sadatomi et al., 2005; Sadatomi et al., 2007, 2012; Kawahara et al., 2009) were continued to optimize the sphere diameter or the orifice diameter and the position of the air suction holes for a better performance. Terasaka et al. (2011) compared the performances of four different type generators (spiral liquid flow type, venturi-type, ejector type and pressurized dissolution type) and three different typical gas distributors (constant flow nozzle plate, porous plate and perforated plate) for the waste water treatment system. They found that these generators could generate much smaller bubbles than the distributors, leading to a more quickly dissolving velocity of the oxygen in the sludge tank. Although the generators had larger power consumption than the gas distributors, they were still recommended due to their better overall performance for the desired industrial process.

A venturi-type bubble generator is employed in current work. As a simple and robust design, venturi structure equipments have an abroad application in engineering and research, such as single/multiphase flow measurement device (van Werven et al., 2003), scrubber (Ali et al., 2013; Zhou et al., 2016), bioreactor injector

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* Corresponding author.
** Corresponding author.
E-mail addresses: mozhengyu@scu.edu.cn (Z. Mo), leechengsun@sohu.com (L. Sun).

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(Thalasso et al., 1995), microbubble generator (Gabbard, 1972; Tang et al., 2014; Yin et al., 2015; Ju et al., 2014; Mo et al., 2016), and hydrodynamic cavitation nozzle (Ishimoto and Kamijo, 2003; Tomov et al., 2016), etc. In the design of a molten-salt breeder nuclear reactor (MSBR) by ORNL (Oak Ridge National Laboratory), the venturi-type bubble generator is taken to remove the gaseous fission product poison ^{135}Xe to obtain a larger breeding ratio (Gabbard, 1972). Helium bubbles were continuously injected into the salt fuel to absorb ^{135}Xe, which was stripped out of the salt as the helium bubbles were separated and removed (Gabbard, 1972; Tang et al., 2014; Yin et al., 2015). Due to using of the molten salt as the carrier of the nuclear fuel, a proper design of the bubble generator is necessary for a MSBR to remove the gaseous fission production with a high efficiency.

The practical efficiency for a bubble generator depends greatly on the size and distribution of the generated bubbles. Figuring out the influence factors becomes the key issue in the process of developing bubble generators with high efficiency (Kress and Keyes, 1973). One of the earliest frameworks was carried out by Gabbard (1972) who designed a conical venturi-type bubble generator for the xenon removal system of a molten-salt breeder reactor. Gas bubbles are injected into a high velocity liquid flow in the throat section and immediately afterwards are broken up into smaller bubbles in the diverging section. The experimental results showed that the volume averaged bubble size was under -0.8 power law dependence on the liquid Reynolds number (Re_L), and 0.6 power dependence on the surface tension. Recent experimental studies with similar generators showed the exponents of Re_L in above mentioned relationship was recommended of -1.3 by Tang et al. (2014) and -1.0 by Yin et al. (2015). This difference was probably arisen from more factors (Kress and Keyes, 1973). Experiments on a venturi-type generator with a rectangular cross section by Gordiychuk et al. (2016) indicated that besides the liquid Reynolds number, the gas Reynolds number and volume fraction also influenced the microbubble size distribution. Bubble size distribution was predicted under the log-normal distribution law, which is a common way to correlate the measured results of the microbubble sizes (Crowe et al., 2012; Thang and Davis, 1979). However, as a simple case of air-water flow under the constant temperature, the influence of surface tension was not taken into account in this correlation.

For the case of the venturi-type bubble generator, the high velocity in the throat and the pressure recovery processes in the diverging part play an important role in the bubble generation with a high number density (Thang and Davis, 1979; Fujiwara et al., 2007). Once entering these conditions, a relative large bubble often experiences a complex transportation process involving expansion, deformation and breakup. In order to clarify this process, Fujiwara et al. (2007) observed bubbles behaviors in a small venturi-type generator with a gas-water mixture inlet. They found that bubbles were deformed by the strong turbulent flow in the throat, and afterwards in the diverging section, they were split up due to the great pressure difference between the top and bottom of them. The bubbles were actually broken up by the liquid columns behind them. Uesawa et al. (2011) measured the fluctuation of void fraction in a similar venturi-type generator to that of Fujiwara et al. They found that the void fraction achieved a peak resulted from the bubble expansion, and then decreased drastically right after the bubbles being collapsed. Later on, they (Uesawa et al., 2012) found that the Mach number (Ma) of the flow was larger than 1 between the throat and the breakup point, and whereas lower than 1 at the upstream of throat and downstream of breakup point.

As explained by Fujiwara et al. (2007) and Uesawa et al. (2012) about the mechanism of bubble breakup or collapse in a venturi-type generator, it was the recovered pressure in the diverging section broke the bubble balance. In fact, under such circumstances, other forces like drag force, lift force, added mass force and turbulent dispersion force, etc., will also strongly effect the movement, deformation and breakup of a bubble in motion (Uesawa et al., 2012; Kuo, 1978; Soubiran and Sherwood, 2000; Sherwood, 2000). Kuo (1978) and Sherwood (2000) established a force balance model for bubbly flow in nozzles and for a deforming bubble in a venturi tube, respectively.

By far, both theoretical and experimental work need more experimental data to analyze the interaction between dispersed particles and continuous phase. For modeling the bubbly flow in a venturi-type bubble generator, the difficulty is the lack of understanding of the more complex bubble behaviors than that in a straight tube. Current work focuses on the bubble behaviors, especially the deformation, movement velocity and collapse of individual bubbles in a venturi-type bubble generator in details for a better understanding the transportation process of bubbles in a continuous liquid stream with high speed. Thus an optimum design of a venturi-type bubble generator for a MSBR might be possible by a simulation work combined with the experimental results. The phenomenological results obtained by this visualized study will also help researchers and engineers well understand the performance and principles of a venturi-structure equipment in the applications of bubble generation, wet dust collection, flow rate measurement, etc.

2. Experimental measurements

2.1. Experimental system

The bubble breakup process in a venturi-type generator was observed using of air and water as the working fluids. The experimental system is mainly composed of a water supply circuit and a gas supply circuit as well as a measurement system, as shown in Fig. 1. Water is driven by a centrifugal pump and air is supplied by an air compressor. The air is injected into the high velocity liquid flow in the throat section. A high speed camera of FASTCAM SA5 with speed of 10,000 fps is used for recording the bubble transportation process in the generator for further post processing. Water flow rate covers the range of 15.0 m^3/h to 20.6 m^3/h, generating an absolute velocity of 8.5–11.7 m/s in the throat, and the air flow rate varies from 0.2 L/h to 1.2 L/h. The both are measured by a turbine flowmeter and a mass flowmeter with accuracy of 0.5% and 1%, respectively.

Fig. 2 presents the configuration and the dimension of the bubble generator, it is actually a venturi tube composed of three main sections: a convergent entrance, a throat and a divergent outlet. Twelve small air feed holes of 1.5 mm in diameter are drilled through the wall of the throat for injecting air into the stream. Three pressure sensors with accuracy of 0.04% were mounted at the inlet, throat and outlet of the venturi tube, respectively, to measure the local pressures inside the three sections. The camera is faced to the diverging outlet in order to reduce the effect of the refraction during recording the bubble motion.

The experiments in current work were carried out under the room temperature around 20 °C. The variation of bubbles in shape and size occurred mainly in the entrance of the diverging section within a short distance and time, during which the local static pressure had a small change no more than 0.01 atm. Consequently, the effect of temperature and static pressure was neglected herein.

2.2. Imaging processing

2.2.1. Image analysis algorithm

Digital Image Analysis (DIA) is one of the most convenient non-