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Study of the interactions between rising air bubbles and vortex core of swirling water flow around vertical axis

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HIGHLIGHTS

- The precessional amplitude of the vortex core depends on the bubble flow rate.
- The bubbles reduce the water velocity in the lower horizontal cross-sections.
- The shape of the vortex funnel formed at the water surface is affected by the bubbles.

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ABSTRACT

The interactions between rising air bubbles and the vortex core of swirling water flows in a cylindrical tank are experimentally investigated. A stirring disc mounted at the center of the tank bottom is rotated to produce swirling water flows around the central (vertical) axis of the tank, and small air bubbles are successively released from tubules mounted near the stirring disc. The bubbles rise helically in the swirling water flow because of the buoyancy force, and some bubbles are entrained into the vortex core. The precessional amplitude of the vortex core is enhanced by the bubbles when the bubble flow rate Q_g is very low. But it decreases with increasing Q_g when Q_g is larger than a certain value. In the horizontal cross-sections near the stirring disc, the bubbles make the water flow field nonaxisymmetric and reduce the water velocity. The water velocity variation due to the bubbles affects the shape of the vortex funnel formed at the water surface.

1. Introduction

Swirling flows are widely used in various industrial applications, such as cyclone separators, atomizers, furnaces and combustors. They are also useful to handle gas-liquid bubbly mixtures. Applications to bubble motion control and bubble generation have been reported. Tanaka et al. (2001) experimentally visualized a swirling water flow entraining small air bubbles in a circular pipe and discussed a bubble removal method using the pressure gradient induced in the pipe cross-section because of the centrifugal force. Kurokawa and Ohtaki (1995) measured the velocity distribution of a swirling air-water bubbly flow in a pipe. On the basis of the measurement, they clarified the separation of the bubbles and water and explored the high-efficiency separation method. Erdal and Shirazi (2004) measured the water velocity of a gas-liquid two-phase flow in a cylindrical cyclone and performed a numerical simulation of the flow. Gomez et al. (2004) also measured the water velocity distribution in a cyclonic separator for gas-liquid two-phase mixtures and developed velocity field correlations. Tabei et al. (2007) paid attention to the bubble micronization caused by the shear force of swirling water flow and proposed a method generating micro-bubbles with the use of a swirling water jet. Since the bubble motion control and bubble generation by using swirling water flows utilize the concentration of the bubbles in the vortex core, knowledge of the interactions between a vortex core of a swirling flow and the entrained bubbles is essential to develop the high-efficiency devices.

The interactions between gas bubbles and swirling water flows have been investigated. Magaud et al. (2003) experimentally and numerically studied the motion of a bubble in a swirling water flow inside a circular pipe. Escalera et al. (2006) observed the motion of cavitation bubbles in a vortex core appearing in a draft tube of a Francis turbine and proposed a detection method of the cavitation based on the measured pressure. Uchiyama and Sasaki (2014) experimentally investigated the interactions between rising air bubbles and a swirling water flow imposed around the central

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(vertical) axis of a bubble plume. They clarified the decrease in the swirling water velocity due to the bubbles. Though the above-mentioned studies explored the swirling bubbly flows, the behavior of the vortex core has not been fully elucidated.

The objective of this study is to experimentally investigate the impact of rising air bubbles on swirling water flows around the vertical axis. The experiment, performed in a cylindrical tank, clarifies the bubble motion, the behavior of the vortex core, and the shape of the vortex funnel formed at the water surface.

2. Experiment

2.1. Experimental setup

Fig. 1 shows a schematic of the experimental setup. A cylindrical tank, made of transparent acrylic resin to enable flow visualization, is used for the experiment. The diameter D_1 is 300 mm, and the height is 455 mm. The top of the tank is open to the atmosphere, and the tank is installed in a rectangular tank made of transparent acrylic resin. The width and depth of the rectangular tank are 350 mm, respectively. To accurately visualize the bubbles and water flow in the cylindrical tank, the effect of refractive index at the cylindrical tank wall is eliminated by filling the gap between the two tanks with water. The origin of coordinates is set at the center of the tank bottom. The $x-y$ plane is horizontal, and the z-axis is considered to be vertical.

A cylindrical casing, the top of which is open to the water, is mounted on the bottom of the cylindrical tank, as shown in Fig. 2. The inner and outer diameters are 62 mm and 70 mm, respectively, and the height is 20 mm. On the outer wall, two tubules having inner diameter of 0.5 mm are attached, and each of the tubules is connected to an air pump through a flow meter. Air bubbles, which are successively released from the tubules into the water, rise as a result of buoyancy force. A cylindrical stirring disc with diameter D_0 of 60 mm and height of 13 mm is installed in the cylindrical casing. It has a cross-shaped thin vane on the top. The stirring disc, including a magnet, is rotated around the central (vertical) axis of the tank by a magnetic force imposed by a magnetic stirrer. The rotation produces swirling water flows in the tank.

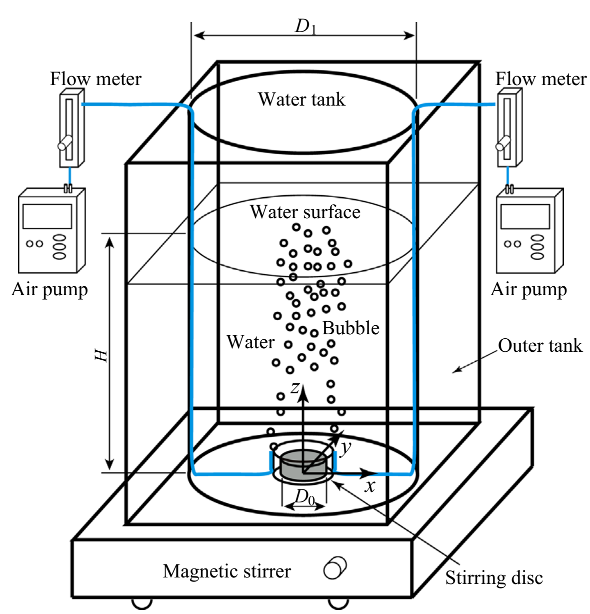

Fig. 1. Experimental setup.

2.2. Experimental method and conditions

The water depth H is 300 mm. The water velocity in the horizontal cross-sections of the tank is measured by a PIV system. Nylon particles (mean diameter: 80 μm, specific weight: 1.02) are used as tracers for the PIV system. Particle images, produced on a horizontal laser light sheet (power: 100 mW, wavelength: 532 nm, thickness: 1 mm), are acquired by a high-speed camera. The frame rate, shutter speed, view area, and spatial resolution of the camera

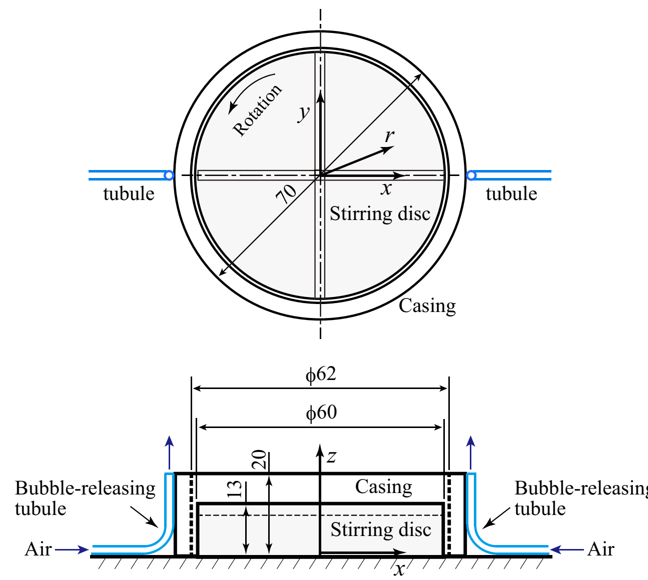

Fig. 2. Stirring disc and bubble-releasing tubules.

Table 1
Experimental conditions.

Diameter of stirring disc, D_0 (mm)	60
Diameter of cylindrical tank, D_1 (mm)	300
Water depth, H (mm)	300
Rotational frequency of stirring disc, N (rpm)	398
Angular velocity of stirring disc, ω (rad/s)	41.7
Volumetric flow rate of released bubbles, Q_g (cm^3/s)	0–10

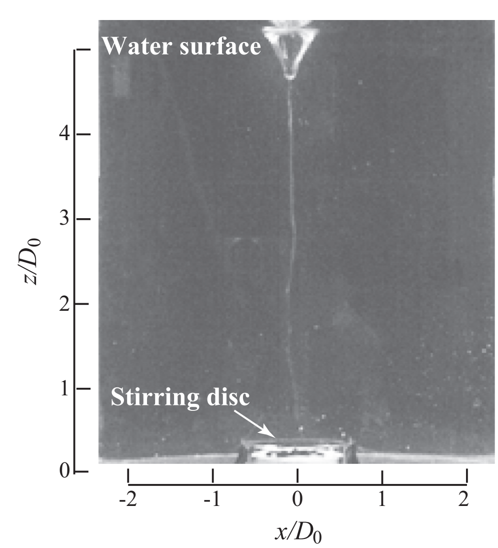

Fig. 3. Vortex core and vortex funnel formed at water surface at bubble-free condition ($Q_g = 0$).