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Oscillations induced by bubble flow in a horizontal cylindrical vessel

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HIGHLIGHTS

- An interesting oscillation was observed in the horizontal cylindrical vessel.
- Circulating flow induced by the gas bubble flow was a cause of the oscillation.
- Height of the liquid surface had also an effect on the oscillatory phenomenon.
- Oscillation frequency was constant regardless of the operational conditions.

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ABSTRACT

Oscillations induced by bubble flow in a horizontal cylindrical vessel were experimentally investigated. These oscillations disturb the stable operation of complicated successive reactions and lead to the breakdown of the aeration system in the vessel. Therefore, they should be prevented. Understanding the generation mechanism of these oscillations could help improve the safety design of the reactor. A series of experiments were performed to examine the causes of the oscillations. The gas feed rate, height of the liquid surface, and length of the cylinder were varied as operational parameters. It was found that the oscillations occurred in the horizontal cylindrical vessel at specific conditions. In order to deepen the understanding of these oscillations, the operational conditions that maintained the stable state and the boundary conditions that caused the oscillations were investigated. The results provided two important suggestions. First, increasing the gas feed rate caused the oscillations. It was considered that the circulating flow induced by the gas bubble flow was a cause of the oscillations. Second, the height of the liquid surface influenced the oscillatory phenomenon. In particular, distance from the aeration tube to the liquid surface was important. The oscillation frequency was measured and it was constant regardless of the operational conditions, and it could be estimated based on the natural frequency of the vessel.

1. Introduction

A horizontal cylindrical vessel or horizontal bubble column reactor is a type of the industrially used bubble column where a cylindrical vessel is installed horizontally. In the standard type bubble column, gases and liquids are fed into the vessel in parallel and the flow regime is close to complete mixing. The flow regimes and bubble dynamics in bubble columns have been investigated extensively (e.g., see a review by Shah et al. (1982)). By contrast, in a horizontal cylindrical vessel, gases and liquids are fed into the vessel in perpendicular directions, and by separating the inside of the vessel with a baffle, its flow regime comes close to the plug flow regime. Fig. 1 shows the schematic diagram of a horizontal cylindrical vessel designed by Ciborowski et al. (1969). The inlet flow of the liquid phase and the gas flow from the bottom cross in the vessel. This multistage vessel has flexibility and the ease of controlling the residence time. Mechanical agitation has occasionally been used to break the bubbles and help in distribution (Joshi and Sharma, 1976). A horizontal cylindrical vessel can be applied for complicated successive reactions in which the desired products are intermediates in a sequence of reactions (Krzysztoforski et al., 1986).

The traditional commercial application of a horizontal cylindrical vessel is in the cyclohexane oxidation reactor. The cyclohexane oxidation process is the main source of cyclohexanol, cyclohexanone, caprolactam, and adipic acid, which are used in the manufacture of Nylon-6 and Nylon-6,6 on a large scale globally (Suresh et al., 2000). This process is relatively difficult since cyclohexanol and cyclohexanone are highly reactive intermediates in a chain reaction and could be easily oxidized to undesirable by-products. Thus, controlling the amount of oxygen is critical for the success

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Nomenclature

D	diameter of the cylinder (m)	H	height of the liquid surface (m)
f	oscillation frequency (Hz)	L	length of the cylinder (m)
F_G	gas feed rate (m^3/s)	n	number of oscillations observed (-)
g	acceleration due to gravity (m/s^2)	t	arbitrary time (s)
h	height of the liquid above the center of the cylinder (m)	λ	coefficient of frequency (-)

of the process (Tekie et al., 1997). A horizontal cylindrical vessel is used in many major commercial processes to control the gas residence time (Pohorecki et al., 2009). It is also used in the ethylbenzene oxidation reactor (Klusener et al., 2007). It is used widely in metallurgical industry (Burrows et al., 2012). The applications of a horizontal cylindrical vessel in bioreactors (including aeration tank in treatment of wastewater) and distillation equipment have also attracted attention. The horizontal cylindrical vessel is and will be important as a reactor or a separation device in industry.

Recently, an operational problem was reported for horizontal cylindrical vessels in some industrial situations. Oscillation of the liquid induced by the bubble flow was observed in a reactor. This oscillation disturbs the stable operation of the reactor. As stated above, a horizontal cylindrical vessel is used as the reactor for complicated successive reactions. This unexpected oscillation deteriorates the selectivity of the process. Moreover, this oscillation would cause damage to the aeration tube and breakdown of the aeration system in the vessel. Therefore, the oscillation should be prevented and its causes should be investigated.

The problems related to flow-induced oscillations have been extensively studied for the past 30–40 years. Systematic review books and handbooks explaining these problems have been published (Blevins, 1977, 1979). The problem is thought to be related to liquid sloshing. Ibrahim et al. (2001) have reviewed over 1000 articles concerning liquid sloshing. However, most of the research has been conducted on a rectangular container and the literature on a horizontal cylindrical vessel is rather limited. Recently, Karamanos et al. (2006) and Karamanos and Kouka (2016) investigated effects of sloshing on the earthquake design of horizontal cylindrical vessels. Papaspyrou et al. (2004) studied sloshing effects in a horizontal cylindrical vessel under longitudinal excitation. Dai and Xu (2006) developed a numerical approach to study dynamic liquid sloshing behaviors. Aus Der Wiesche (2007) investigated the sloshing dynamics of a viscos liquid in a horizontal cylindrical tank.

These previous studies have used numerical approaches to study liquid dynamics. There is a lack of experimental techniques to observe and evaluate the oscillatory phenomenon that occurs in a horizontal cylindrical vessel. Second, most of the previous investigations have paid attention to the oscillatory phenomena induced by the external motion of vessels. Some studies have investigated the self-induced sloshing in a rectangular or a cylindrical tank (Madarame and Iida, 1998; Saeki et al., 2001; Iguchi et al., 2004a, 2004b). The interaction between a liquid surface and liquid flow injected in a tank was examined in previous reports. On the other hand, this study investigates the oscillation induced by the internal gas bubble flow. It is a really interesting and novel problem in terms of dealing with the oscillatory phenomenon in gas-liquid two-phase flow, and it has rarely been studied previously.

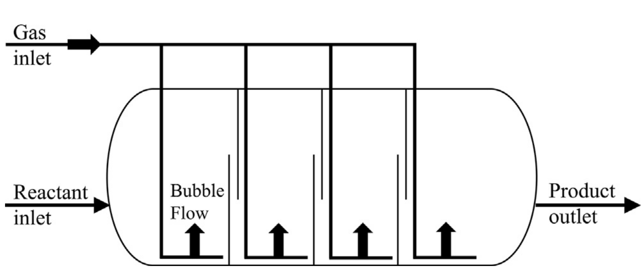

Fig. 1. Schematic diagram of a horizontal cylindrical vessel.

As is well known, Japan is one of the most earthquake-prone countries in the world. Measures against earthquake disasters are the main safety measures at chemical plants in Japan. Sloshing caused by oscillation of the structure due to an earthquake is started to be considered. Sloshing by the bubble flow as the oscillation source in the case of an earthquake should also be considered. The result of our study could help the stable operation of horizontal cylindrical vessels, and understanding the generation mechanism of sloshing by the bubble flow could be helpful for implementing safety measures for an emergency situation at chemical plants.

To understand this unique oscillatory phenomenon induced by the internal bubble flow, a laboratory-scale horizontal cylindrical vessel was made. First, it was confirmed whether the unique oscillatory phenomenon could be observed in this lab-scale experimental setup. Then, the operational conditions that caused the oscillation were examined. The effects of gas feed rate F_G and height of the liquid surface H were considered. The oscillation frequency induced by the bubble flow was measured, and its values were compared with the natural frequency of the vessel.

2. Material and methods

2.1. Experimental setups and procedure

A laboratory-scale horizontal cylindrical vessel was prepared from transparent acrylic. Fig. 2 shows the schematic of the vessel. The cylinder diameter D was 0.10 m. The cylinder length L was varied (0.16 m, 0.20 m, and 0.24 m) in order to observe the influence of the three-dimensional scale. An aeration tube made of sintered air stone (Sudo Co., Inc., S103-G) with diameter 1.5×10^{-2} m and length 0.15 m was located on the vertical central plane of the vessel 1.5×10^{-2} m from the bottom. The aeration tube was carefully installed and securely attached to exclude the effects of the aeration position and the vibration of the tube.

Fig. 3 shows the schematic diagram of the experimental setup. In this study, the horizontal cylindrical vessel was operated continuously with respect to the gas flow and batch-wise with respect to the liquid flow. Air was used as the gas phase and tap water was used as the liquid phase. Tap water was filled to a specific height H. Air was fed from a compressor (Hitachi Industrial Equipment Systems Co., Ltd., PO-0.75PTB). The gas feed was regulated by a valve and a manometer. The gas feed rate F_G was measured by a volumetric wet gas meter (Shinagawa Co., Ltd., W-NK-5). The phenomena happening in the vessel were recorded by a camera (Casio Computer Co., Ltd. EX-F1). The HD video mode (1280 × 720 pixels, 30 fps) was employed to observe the operational states in the vessel and to measure the oscillation frequency. The HS video mode