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Effects of interfacial shear condition and trailing-corner radius on the wake vortex of a bubble

Boonchai Lertnuwat*, Asi Bunyajitradulya

Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Phaya Thai Road, Wang Mai, Pathum Wan, Bangkok 10330, Thailand

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Abstract

Comparative effects between the interfacial shear condition and the trailing-corner radius (ϕ) on the wake vortex of a bubble are studied. In the investigation, the standard k–ε model is employed, and the two types of bubble: solid and gaseous, have different interfacial boundary condition. Namely, for solid bubbles the no-slip condition is imposed, resulting in a non-zero interfacial shear condition, while for gaseous bubbles the free-slip condition is imposed, yielding a zero interfacial shear condition. The flow condition is set for a slug flow with the bubble drifting at a terminal velocity corresponding to the Reynolds number of 35,000. The results show that, the flow can be roughly divided into two flow regimes: the small- and large-ϕ regimes. In the small-ϕ regime, the trailing-corner radius plays a dominant role and the difference in the interfacial shear condition has little effects on the wake vortex, causing the wake vortices of the two bubble types to be similar in shape, size, and circulation. In contrast, in the large-ϕ regime, the interfacial shear condition can manifest and affect flow separation and the wake vortex, causing significant differences between the wake vortices from the two bubble types. Namely, as ϕ is increased towards the large-ϕ regime, the wake vortex of the solid bubble changes relatively little while that of the gaseous bubble significantly decreases in size. At small-ϕ the circulations around the wake vortex of both types of bubble are almost identical initially. However, as ϕ is increased towards the large-ϕ regime, the circulation of the gaseous bubble decreases with increasing ϕ at a more pronounced rate than that of the solid bubble. These results show that it is the absence of interfacial shear in the large-ϕ regime that causes the wake vortex to be more sensitive to the trailing-corner radius.

1. Introduction

It has long been observed that there are many different flow regimes in gas–liquid flows. One of them is the slug flow, which has been the focus of many past researches because of its many practical applications, such as in oil and gas wells, boilers, chemical and nuclear reactors, to mention but a few. The characteristic of slug flows depends on many parameters such as the pipe size and superficial fluid velocity (Das and Pattanayak, 1994; Mi et al., 2001; Sun et al., 2004). A prominent characteristic in one regime of a slug flow in a pipe is the alternate distribution of liquid slugs and elongated bullet-shaped gaseous bubbles, called the Taylor bubbles (Fig. 1). The liquid flow around the Taylor bubble is divided into three regions, i.e., the bubble nose, falling film and bubble bottom as illustrated in Fig. 1. The Taylor bubble and its interaction with the liquid flow around it play an important role in this flow regime and have attracted many investigations. For example, Bugg and Saad (2002), Hout et al. (2002), and Shemer (2003) studied flow field around a Taylor bubble, while Polonsky et al. (1999) focused on the flow field in the region of bubble head.

While many researchers have investigated flows around a single Taylor bubble, some have focused on the interaction between two Taylor bubbles. Kawaji et al. (1997) studied the effect of the lateral motion of a Taylor bubble on its acceleration. In order to control the lateral position of the bubble, they employed a solid model of a Taylor bubble in place of a gaseous one. The experiments showed significant reduction in the drag force as well as the acceleration of the solid bubble when it was moved eccentrically. Another similar study with solid bubbles was also

* Corresponding author. Fax: +66 2 2522889.
E-mail address: Boonchai.L@Chula.ac.th (B. Lertnuwat).

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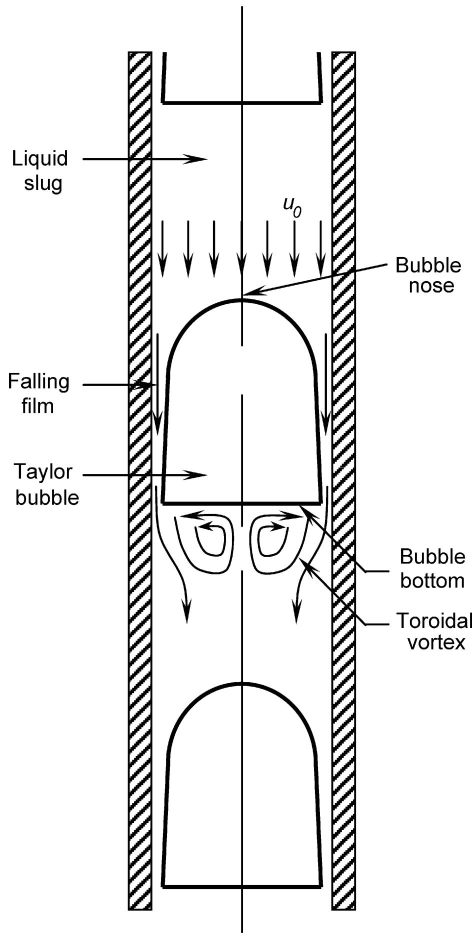

Fig. 1. The schematic diagram of a slug flow.

conducted by Tudose and Kawaji (1999). In this study, both a single Taylor bubble and a Taylor bubble in the wake of a leading Taylor bubble were investigated on the acceleration mechanism. They found a significant reduction in the drag force on the solid bubble when it was laterally displaced from the tube axis or when the nose of the bubble was deformed. Using a one-dimensional model, the acceleration of a trailing Taylor bubble in a gas–liquid slug flow was attributed to the reduction in the drag force, caused by the lateral displacement and the nose shape.

Naturally, these studies raised a question of the flow characteristics of a solid bubble in comparison to those of a gaseous bubble. Specifically, the flow characteristics of these two types of bubble were not initially expected to be similar since their interfacial boundary condition differed quite significantly. Namely, the no-slip condition – a non-zero interfacial shear condition – prevailed for a solid bubble while the free-slip condition – a zero interfacial shear condition – prevailed for a gaseous bubble. Nonetheless, their results suggested that differences in these interfacial shear conditions did not appear to cause a major alteration on the structure of the wake. In this regard, Sotiriadis and Thorpe (2005) also arrived at a similar conclusion in their experiments on velocity fields behind a bluff body and a ventilated cavity in a pipe flow. Namely, they found that the axial locations of the vortex center and the end of the re-circulation region of the ventilated cavity were almost identical to those of the bluff body. As a result, they concluded that the induced flow beneath the bluff body is similar to that of the ventilated cavity and, thus, suggested that the bluff body provided a convenient experimental substitute for the study of the flow pattern beneath the ventilated cavity.

Given that the interfacial shear conditions in these two flows are significantly different, the fact that they induce similar wake vortex suggests that there may be some other flow parameters that play competitive and important role in these flows. This raises the obvious questions of what these parameters are, and of when or under which conditions the interfacial shear condition no longer exhibits the dominant role on wake vortex. In summary, what are the additional governing parameters and what are their roles for the vortex wake in the framework of two different interfacial shear conditions?

The objectives of this investigation are thus to gain further insights into the effects of the interfacial shear conditions as well as the flow physics by identifying the additional governing parameters in the context of different interfacial shear conditions and, if such parameters exist and exhibit a competitive role, by identifying possible different flow regimes that they compete over. As it will be subsequently shown, one of the immediate parameters is the trailing-corner radius. The results have, among others, direct implications on the limitation of the use of solid bubbles in place of gaseous ones. In the investigation, a standard k–ε model is used, and the two types of bubble have different interfacial shear condition.

2. Problem set and numerical algorithm

The computer code, "CAFFA.F", given in Ferziger and Peric (2002), is further developed to simulate a vertically up-rising Taylor bubble in stagnant water. The implicit pressure-correction method on the finite volume framework with the second order spatial accuracy is employed in this code.

The computational domain is attached to the bubble. That is, the bubble is stationary while water flows towards the bubble at a terminal velocity (u_0). The bubble geometry is divided into three parts. The first part starts from the bubble nose and ends at the point A as shown in Fig. 2(a). The shape of bubble in this part produces an approximately constant pressure on the bubble surface when the free-shear interfacial boundary condition is imposed. This shape is achieved by trial-and-error. Even though Dumitresku has derived a mathematical model for predicting the shape of Taylor bubble, the predicted shape of Taylor bubbles by this existing model is not suitable when it is exploited in many CFD schemes (Clarke and Issa, 1997; Mao and Dukler, 1990, 1991). The second part of bubble geometry is the trailing corner between points A and B, composing of a quarter circular arc with radius ϕ, hereafter referred to as the trailing-corner radius. The third part is the flat bottom between point B and the center of bubble bottom. As reported by many publications (Cheng et al., 1998; Kytomaa and Brennen, 1991; Sun et al., 2002), the slug flow can occur in pipes with diameter ranging approximately from 10 to 100 mm. For the present work,