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Modeling of bubble shape in horizontal and inclined tubes

Gu Hanyang [a,*], Guo Liejin [b]

[a] School of Nuclear Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] State Key Laboratory of Multiphase Flow, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

An experimental and theoretical study on the bubble shape of intermittent flow in the horizontal and inclined pipes has been carried out. The experiment results show that the bubble shape depends on the Froude number, bubble length and pipe inclination. The bubble with staircase pattern tail is observed at low Froude numbers, which is corresponding to plug flow. A model for the prediction of the bubble shape in horizontal and inclined pipes is proposed. The model is able to predict the bubble shape, flow pattern transition between plug and slug flow regimes as well as nose-tail inversion phenomenon observed in the downwardly inclined pipe. Validation shows the model can well predict the bubble shapes in horizontal and inclined pipes. The model discloses that the transition between plug and slug flow regimes occurs within a region. The Froude number range for plug flow regime in the downwardly inclined pipe is much wider than that in the horizontal or upwardly inclined pipe. The assumption of fully developed liquid film under the long bubbles tends to under-estimate the liquid fraction in this part of the slug structure, especially, for the intermittent flow in the upwardly inclined pipe with high Froude numbers.

1. Introduction

Intermittent flows are frequently encountered in many two-phase flow engineering applications, such as power generation units, nuclear industry, two phase pipelines and other process industries. The intermittent flow can be viewed by the succession of aerated liquid pistons followed by elongated gas bubbles which are not periodic in time and space. The unsteady and nondeterministic nature of the intermittent flow makes the modeling complicated.

The first comprehensive model to predict the intermittent hydrodynamic parameters was developed by Dukler and Hubbard (1975) based on the unit cell concept by neglecting its nondeterministic nature and considering the alternating liquid pistons and gas bubbles in an orderly periodic way. More researchers, such as Nicholson et al. (1978), Kokal and Stanislav (1989), Taitel and Barnea (1990) improved the steady state slug flow models by employing the unit cell concept. It is assumed that liquid slugs and gas bubbles have constant lengths. The gas volume fraction in the bubble region is usually determined based on the assumption that the liquid film has a constant thickness like that in a fully developed stratified flow. In fact the slug structure is never periodic. The bubble and slug lengths are widely distributed around the average values. Many experimental works by Grenier (1997), Cook et al. (2000), Shemer (2003) provided a statistical description of slug flow. Slug-tracking method was widely employed to predict the evolution of the slug structure (Taitel et al., 1998; Cook et al., 2000). Most slug tracking models assume that all bubbles are fully developed with a uniform liquid film thickness. From various experiments carried out in horizontal and near horizontal intermittent flows, the liquid film thickness in any section of the bubble region changed with the distance to the bubble nose (Fagundes et al., 1999). The assumption of fully developed liquid film in bubble region tends to overestimate the hold-up in bubble region.

For horizontal and near horizontal pipes, the liquid film region has an interface separating the elongated gas bubble at the upper section of the pipe from the liquid film at the lower section due to the gravity force. The elongated bubble is characterized as three regions: the front nose, the body and the tail (Fagundes et al., 1999; Roitberg et al., 2008; Barnea et al., 2013). Fragunde et al. (1999) used capacitance wire probes to detect the passage of the gas–liquid interface of long bubbles at the centerline of a horizontal pipe. The shape of long isolated bubbles was experimentally presented. The bubble obtained from the experiment was divided into four regions: the nose, the body, the hydraulic jump at the back

* Corresponding author.
E-mail address: guhanyang@sjtu.edu.cn (G. Hanyang).

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and the tail. More recently, the remarkable experimental study was performed by Roitberg et al. (2008). The 3D structure of an elongated bubble in a downwardly intermittent flow was reconstructed using a wire-mesh sensor. The ensemble-averaged shapes of the bubble nose, bubble body and bubble tail were determined. Benjamin (1968) obtained the drift velocity of an isolated bubble flowing in a horizontal pipe and its profile by employing the inviscid theory. With the same theory, Alves et al. (1993) extended Benjamin's works to inclined and vertical pipes, taking into consideration surface tension forces. Fagundes Netto et al. (1999) also employed Benjamin's model to get bubble's nose shape and further developed a liquid film model including the bubble's nose, body hydraulic jump and tail region. Many models were developed based on one-dimensional, steady-state, separated phases to capture the liquid film in bubble body region in horizontal and near horizontal gas–liquid intermittent flows (Dukler and Hubbard, 1975; Nicholson et al., 1978; Kokal and Stanislay, 1989; Taitel and Barnea, 1990; Cook and Behnia, 1997; Fagundes Netto et al., 1999). An analysis of the liquid film models was performed by Marzza et al. (2010). It was found that the usual slug flow codes using equilibrium height of film assumption tended to significantly overestimate the gas fraction in the bubble region.

Moreover, intermittent flows in horizontal and inclined pipes are usually classified by two subregimes: the plug flow, in which liquid slugs do not entrain gas, and the slug flow, in which slugs entrain many small gas bubbles. Although these two subregimes have similar appearance, their fluid dynamic characteristics in such areas as pressure drops and slug velocity are distinctively different. Many studies have been performed to define the transition from a plug flow to a slug flow in a horizontal pipe. There is a history of uncertainty over the correct location of the plug to slug boundary as it can be seen from the examination of different flow maps and transition criteria. To date, it still remains unclear whether the transition occurs at a constant superficial gas velocity or at a constant mixture superficial velocity. Barnea and Brauner (1985) proposed a theoretical model assuming that gas bubbles were entrained into the liquid slug when turbulence overcame gravity, and the transition from a plug flow to a slug flow depended on the mixture superficial velocity. More recently, Bontozoglu and Hanratty (1990) and Fan et al. (1993) proposed different mechanisms of slug flow initiation according to different superficial gas velocities. Visualization experiment was carried out by Ruder and Hanratty (1990) to study the gas entrainment at the back of the bubble in a horizontal intermittent flow. It was found that the liquid slug behind the bubble was free of bubbles when staircase-like shape tail was present, however, the level jump at the bubble back reached the top the pipe and the entrainment of small bubbles were observed. Thereafter, Ruder and Hanratty (1990) used this bubble shape characteristic to define the transition between the plug flow and slug flow regimes. The later studies of Fagundes et al. (1999) and Fossa (2001) verified this conclusion. Hence, the knowledge of the shape of the bubble region in intermittent flows is very important to improve the knowledge of the flow structure and flow pattern transition. Recently, CFD model has been used to simulate the bubble in intermittent flows (Taha et al., 2006; Asadolahi et al., 2011). The CFD results provided insightful information on the structure of the intermittent flow. But the CFD modeling was difficult to be implemented into slug tracking code. Fagundes et al. (1999) was proposed a theoretical one-dimensional model to predict the bubble shape in horizontal pipes. In his model, the bubble was divided into four regions: the nose, the body, the hydraulic jump at the back and the tail. The bubble shape and flow pattern transition between the plug and slug flow were predicted by the model. However, the model by Fagundes et al. (1999) was limited to a horizontal intermittent flow.

The present study is aimed at detailed experimental and simulated investigation of the shape of single elongated bubble in horizontal and inclined intermittent flows. The effect parameters on bubble shapes, such as bubble length, Froude number, pipe inclination are studies experimentally. A theoretical model based on the model by Fagundes et al. (1999) is developed. The developed model can well predict the bubble shapes for horizontal and inclined intermittent flows when compared with the experimental results. Based on the validated model, the characteristics of the elongated bubble in intermittent flows are analyzed, including the flow pattern transition between plug and slug flow regimes as well as nose-tail inversion phenomenon.

2. Experiment facility and measuring technique

The evolution of intermittent flows along a pipeline strongly depends on the separation distances between the elongated bubbles. At small separation distances, trailing elongated bubbles accelerate and eventually merge with the leading ones. During the merging process, both the liquid slug and the elongated bubble lengths increase. This process is assumed to terminate until the liquid velocity profiles at the back of the liquid slug are fully developed and all elongated bubbles propagate at the same translational velocity with steady bubble shapes. This work is focused on the elongated bubbles with steady shapes in the fully developed intermittent flows.

Fig. 1 showed two bubble shapes in the fully developed intermittent flow in horizontal pipes at the same mixture velocity. The good agreement of two bubble shapes indicated that the bubble shape only depended on the air-liquid mixture velocity, which agreed with the observation of Grenier et al. (1997) and Woods et al. (1996). Thereby, the bubble shape in the intermittent flow was studied by injecting isolated bubbles into the pipe at a constant liquid flow rate to ensure a better control on the bubble length and to avoid the overlap of different phenomena induced by a train of bubbles in this study. The bubble shape of isolated bubble injected depended on the liquid velocity. From dimensional analysis, the dimensionless number Froude based on liquid superficial velocity U_{sl} was defined by:

$$Fr = \frac{U_{sl}}{\sqrt{gD}}$$

where g is gravity and D the pipe diameter.

The experiment was performed in an air–water two phase flow test system, as shown in Fig. 2. Air and water were used as the test fluids in this study. The water was measured by a mass flow meter with a precision high up to 0.1%. Water was introduced into the inlet of the test section and formed a continuous liquid flow, and finally circulated to a water tank via a separator. The air, supplied from a compressor, was introduced into the pressure regulator.

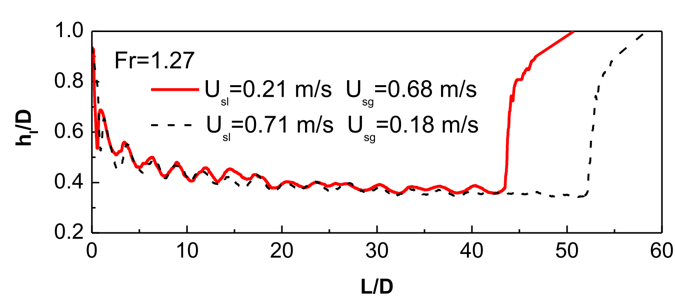

Fig. 1. Shape of two bubbles at the same mixture velocity.