International Journal of Multiphase Flow 37 (2011) 888–897

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Co-current flow effects on a rising Taylor bubble

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ARTICLE INFO

Article history:
Received 11 November 2010
Received in revised form 13 April 2011
Accepted 21 April 2011
Available online 28 April 2011

Keywords:
Taylor bubble
Archimedes number
Co-current
Upward
Downward
Velocity ratio
Front tracking
Wake
Vortex rings
Thin film
Wall shear stress

ABSTRACT

The effects of co-current flows on a rising Taylor bubble are systematically investigated by a front tracking method coupled with a finite difference scheme based on a projection approach. Both the upward (the co-current flows the same direction as the buoyancy force) and the downward (the co-current moves in the opposite direction of the buoyancy force) co-currents are examined. It is found that the upward co-current tends to elongate the bubble, while the downward co-current makes the bubble fatter and shorter. For large N_f (the inverse viscosity number), the upward co-current also elongates the skirted tail and makes the tail oscillate, while the downward co-current shortens the tail and even changes a dimpled bottom to a round shape. The upward co-current promotes the separation at the tail, while the downward co-current suppresses the separation. The terminal velocity of the Taylor bubble rising in a moving flow is a linear combination of the mean velocity (U_C) of the co-current and the terminal velocity (U_0) of the bubble rising in the stagnant liquid, and the constant is around 2 which agrees with the literature. The wake length is linearly proportional to the velocity ratio (U_C/U_0). The co-currents affect the distribution of the wall shear stresses near the bubble, but not the maximum.

1. Introduction

The dynamics of Taylor bubbles rising through vertical tubes filled with another viscous fluids has been an interesting subject for decades due to their wide existence in many engineering applications and real life, such as: nuclear reactors, oil–gas pipelines, steam boilers, heat exchangers, and blood flows. Taylor bubbles usually have a rounded leading edge, a long cylindrical middle part, and a trailing edge with either rounded, or flattened, or dimpled shape. The length of Taylor bubbles can be as long as several diameters of the tube, and they almost fully occupy the cross-section of the tube, and thus a thin film appears between the bubbles and the tube inner walls.

The literature on Taylor gas-bubbles rising in initially stagnant fluids is abundant and the pioneer research was performed by Dumitrescu (1943) and Davies and Taylor (1950). They theoretically found that the rising velocity of a Taylor bubble in the inviscid limit is: $U_0 = \alpha\sqrt{gD}$, where g is gravitational acceleration, D denotes the tube diameter, and the value of the coefficient α is around 0.33–0.35. This correlation has been confirmed by experimental observations (Campos and Guedes de Carvalho, 1988; Polonsky et al., 1999). The motion of Taylor bubbles was reviewed by Clift et al. (1978) and Fabre and Liné (1992) in great detail. The dynamics of the Taylor gas bubble rising in a stagnant viscous fluid is governed by a group of non-dimensional numbers, namely: the Eötvös number (Eo), the Archimedes number (Ar) or the inverse viscosity number (N_f), the Reynolds number (Re_T), the Weber number (We_T), the Froude number (Fr), the density ratio (η), and the viscosity ratio (λ), and these numbers are defined as:

$$\mathrm{Eo} = \frac{(\rho_s - \rho_b)gD^2}{\sigma}; \quad \mathrm{Ar} = N_f^2 = \frac{\rho_s(\rho_s - \rho_b)gD^3}{\mu_l^2}; \quad \mathrm{Re}_T = \frac{\rho_s U_0 D}{\mu_s};$$
$$\mathrm{We}_T = \frac{\rho_s U_0^2 D}{\sigma}; \quad \mathrm{Fr} = \frac{U_0}{(gD)^{1/2}}; \quad \eta = \frac{\rho_s}{\rho_b}; \quad \lambda = \frac{\mu_s}{\mu_b}.$$

In these definitions, the viscosities and the densities of the suspending fluid and the bubble are denoted by μ_s and μ_b, ρ_s and ρ_b, respectively; g is the gravitational acceleration; σ stands for the surface tension coefficient and is assumed constant; U_0 is the terminal velocity of the bubble. Recently, universal correlations for the rising velocity of Taylor bubbles in stagnant fluids contained in circular tubes were proposed by Viana et al. (2003) by analyzing hundreds experimental data from the literature. Using a viscous potential flow model, Mandal et al. (2007) demonstrated that the rising velocity of liquid Taylor bubbles is also related to the shape of the nose. Besides the terminal velocity, the fluid field and the bubble shape are also of great interest of research (Campos and Guedes de Carvalho, 1988; van Hout et al., 2002; Bugg and Saad, 2002; Nogueira et al., 2006a; Nogueira et al., 2006b).

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doi:10.1016/j.ijmultiphaseflow.2011.04.004

In cases where the suspending fluid initially flows instead of being stagnant, the dynamics of Taylor bubbles is more complex, while the literature is rather limited. Nicklin et al. (1962) proposed that the terminal velocity of a Taylor bubble rising in a moving fluid (U_B) is a linear combination of the mean velocity of the co-current (U_C) and the rising velocity in the stagnant liquid (U_0), i.e.

$$U_B = CU_C + U_0 = CU_C + \alpha\sqrt{gD} \quad (1)$$

where U_C denotes the mean velocity of the co-current flow, and C is a constant. It was found that C takes value around 1.2 for turbulent flows, and for laminar it is around 2 (Nicklin et al., 1962; Collins et al., 1978; Grace and Clift, 1979; Bendiksen, 1985). Polonsky et al. (1999) experimentally studied the relation, and they found that the value of C is depended on the co-current velocity. Nogueira et al. (2006a,b) performed experiments on the detailed velocity field around a Taylor bubble rising through vertical tubes filled with upward flowing Newtonian liquids, and they demonstrated that the wake length increases linearly with a Reynolds number based on the superficial liquid velocity relative to the bubble. Pinto et al. (2000) investigated the transition in the Taylor bubble velocity in vertical upward co-currenting liquids, and they reported that the coefficient C is a function of the Reynolds number, the Weber number, and U_C/U_0.

Numerical modeling serves an alternative to explore the dynamics of Taylor bubbles in initially stagnant fluids, for example (Mao and Dukler, 1991; Bugg et al., 1998; Ndinisa et al., 2005; Taha and Cui, 2006; Akbar and Ghiaasiaan, 2006). For Taylor bubbles with co-currents, Lu and Prosperetti (2009) simulated Taylor bubbles rising in a vertical tube filled with stagnant, upward or downward flowing liquids by a finite volume method coupled with marker points to track the interface.

The objective of this work is to systematically investigate the co-current (including both upward and downward flows) effects on a rising Taylor bubble. A front tracking scheme coupled with finite difference method is employed as this scheme has been extensively validated for the simulations for bubble rising (Mukundakrishnan et al., 2007) and especially for a Taylor bubble rising in a stagnant fluid (Kang et al., 2010). In the front tracking scheme, the two-fluid flow (including the gas inside the bubble and the suspending liquid) is solved, and thus both the velocity fields inside and outside the bubble can be revealed. The effects of the co-currents on the terminal velocity and the overall shape of the bubble are studied. The detailed investigations of the shape in the nose and tail regions, the velocity inside bubble and in the thin film region, and the wall shear stresses are presented. Correlations between the bubble rising velocity and the mean velocity of the suspending flow are obtained and compared with the published results. A correlation between the wake length and the co-current velocity is also proposed.

2. Problem setup and numerical methods

Fig. 1 displays the computational domain and the initial bubble shape for the simulations. The problem is assumed rotational symmetry (or axi-symmetry), and the axis of the symmetry is denoted by the dash-dot-dot line. Therefore, all the simulations are performed in a cylinder coordinate system (r,z). The cylindrical tube has an inner radius of R_0 = 1.6 cm and a length of $30R_0$, and the side wall of the tube is denoted by the thick line. The density and viscosity of the bubble are ρ_b and μ_b, and ρ_s and μ_s for the suspending fluid. The two fluids are assumed incompressible and immiscible. The gravitational force is downward. The initial bubble has a shape of a cylinder with two hemispheres at the two ends. The radius of the middle section is r_0, which is $0.84R_0$, and the length of the initial bubble is $4r_0$. As both the upward and downward co-currents

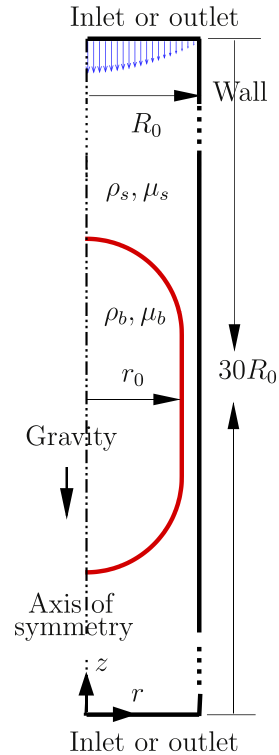

Fig. 1. Sketch of a Taylor bubble (the red thick line) rising in a cylindrical tube filled with a co-current fluid. The co-current either flows downwards or upwards with a parabolic velocity distribution. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are of the interest of study, the bottom and top of the simulation domain can either be outlet or inlet. The velocity profile at the inlet of the co-current is parabolic, i.e. $u_z^{inlet} = U_C(1 - r^2)$ with r being non-dimensional radius, to mimic the fully-developed pressure-driven Poiseuille flow in a cylindrical tube. As the suspending fluid is moving, one extra governing non-dimensional number is introduced, i.e. the velocity ratio (U_C/U_0). Then, the Reynolds number (Re_{U_B}) and Webber number (We_{U_B}) are based on the terminal velocity of the Taylor bubble in the moving fluid, U_B.

The numerical scheme solves the Navier–Stokes equations by a finite difference method with a projection scheme (Bell and Marcus, 1992), and the flow is assumed to be laminar. The interface is located by the front tracking scheme (see Tryggvason et al. (2001) for a great review of the method and Esmaeeli and Tryggvason (1998, 1999, 2005) for the applications). The detail of the current implementation of the method for bubble rising including the validations can be found in Kang et al. (2010), Mukundakrishnan et al. (2007), and here only a brief summary is given. In the projection approach, first, an intermediate velocity is obtained by a semi-viscous procedure in which a one-time-step lagged pressure is used. This intermediate velocity, of course, does not satisfy the continuity equation. Therefore, the intermediate velocity field is then projected onto discretely divergence-free vector fields. The Crank–Nicholson method is employed for the time integration. The interface (or front) moves in a trapezoidal mode by the velocity interpolated from the neighboring fixed grids. The surface tension forces which are calculated on the interface and then are distributed to the surrounding grids using a δ function (Griffith and Peskin, 2005) in a density-weighted manner. The viscosity is calculated by a harmonic mean method, and similar schemes can be found in Gunsing (2004) and Prosperetti and Tryggvason (2007). The numerical method has been extensively validated against a number of experiments for a bubble and a Taylor bubble