Chemical Engineering Science 97 (2013) 16–33

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Science

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

Flow of two consecutive Taylor bubbles through a vertical column of stagnant liquid—A CFD study about the influence of the leading bubble on the hydrodynamics of the trailing one

J.D.P. Araújo, J.M. Miranda, J.B.L.M. Campos *

Centro de Estudos de Fenómenos de Transporte, Departamento de Engenharia Química, Universidade do Porto, Faculdade de Engenharia, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

HIGHLIGHTS

- Behaviour of the trailing bubble nose reveals a sharpening-flattening mechanism.
- Liquid film thickness of the trailing bubble increases with the bubbles approach.
- Wake region of the trailing bubble becomes larger as the bubbles are approaching.
- Numerical data on U/U_{SB} is presented for a large set of flow conditions.
- Equations and fitting parameters describing the velocity ratio curves are proposed.

ARTICLE INFO

Article history:
Received 19 January 2013
Received in revised form
3 April 2013
Accepted 8 April 2013
Available online 16 April 2013

Keywords:
Hydrodynamics
Multiphase flow
Simulation
Fluid mechanics
Taylor bubble velocity
Bubble–bubble interaction

ABSTRACT

A detailed numerical study on the interaction between two consecutive Taylor bubbles rising through vertical columns of stagnant Newtonian liquids is reported in this work. The CFD method used is based on the VOF technique implemented in the commercial package ANSYS FLUENT. Simulations were made for a large set of flow conditions, within the laminar regime, covering a range of Morton number of 4.72×10^{-5}–104 and an interval of Eötvös number between 15 and 575. The changes in the shape of the bubbles interface were followed throughout the approach process, and the main hydrodynamic features characterizing the liquid film and the wake region of the trailing bubble were determined as the separation distance became smaller. Numerical data on the velocity ratio between the trailing and the leading bubble are presented, and two distinct regions are identified (acceleration and deceleration) in the corresponding evolution curves. The velocity ratio curves produced for several flow conditions were fitted to equations describing the acceleration and the deceleration behaviour of the trailing bubble. These equations together with the fitting parameters obtained here can be very useful to improve simulators of continuous slug flow.

1. Introduction

When gas and liquid flows simultaneously through a pipe, depending on the magnitude of the acting forces (inertia, buoyancy, surface tension and viscous), different phase distributions can occur, normally referred to as flow patterns. Slug flow is one of the most common gas–liquid flow patterns which take place over a wide range of flow conditions. In a vertical configuration, it is mainly characterized by a sequence of liquid slugs and elongated bullet-shaped bubbles, usually called Taylor bubbles, which occupy most of the available cross section of the channel. The liquid in the film confined by these bubbles and the pipe wall, accelerates as it moves downwards, achieving velocities much larger than the mean values in the bulk of the liquid slugs. If the bubble is long enough, the thickness of this film decreases until the gravitational forces are balanced by the shear forces (like in a free-falling liquid film). The flow in the liquid slugs can be divided into two main parts: immediately below the rear of the bubble, where, in the majority of flow conditions, there is the formation of a recirculation/mixing region, which in laminar regime has a shape of a toroidal vortex, also called wake region; the main body of the liquid slug where the flow is gradually recovering its original and undisturbed state.

Slug flow can be observed in a variety of industrial and natural applications, such as volcanic phenomena, transportation in gas and oil pipelines, membrane processes, chemical reactors, and

* Corresponding author. Tel.: +351 22 508 1692; fax: +351 22 508 1449.
E-mail addresses: daraujo@fe.up.pt (J.D.P. Araújo), jmiranda@fe.up.pt (J.M. Miranda), jmc@fe.up.pt (J.B.L.M. Campos).

0009-2509/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ces.2013.04.014

microflow systems (Brill and Mukherjee, 1999; Taha and Cui, 2002; James et al., 2004; Chinnov and Kabov, 2006; Pangarkar et al., 2008; Gupta et al., 2009). Particularly relevant, due to the higher velocities in the liquid film and the recirculation/mixing in the bubble wake, slug flow pattern can have a huge interest in processes involving the enhancement of heat and mass transfer properties (Mercier et al., 1997; Leung et al., 2010; Gupta et al., 2010; Asadolahi et al., 2011; Ratkovich et al., 2011; Talimi et al., 2012). However, for example, in corrosive environments, the velocity variations described above can be undesirable, not only for the increase in the transport of corrosive species towards metal surfaces, but also by the resulting high fluctuations in wall shear stresses that cracks or, at least, complicates the formation of protective films (Villarreal et al., 2006; Zheng and Che, 2006; Nešić, 2007).

For a fully-developed continuous slug flow, the length of the liquid slugs between any pair of consecutive bubbles remains constant and long enough, so that all the bubbles are not interacting with each other, and are rising at the same translational velocity. According to Nicklin et al. (1962), under these conditions, the translational velocity can be expressed as the superposition of the drift velocity (bubble velocity in stagnant liquid, U_{SB}) and the sum of liquid (U_L) and gas (U_G) superficial velocities:

$$U = U_{SB} + C(U_L + U_G) \tag{1}$$

where C is a parameter assumed to be the ratio between the maximum and the mean values of the liquid axial velocity profile, taken in the stabilized liquid ahead of the bubble nose, and so, it ranges from approximately 1.2 (for developed turbulent flows) to 2 (for developed laminar flows).

However, very large pipe lengths are necessary to achieve full development in continuous slug flow and, moreover, the occurrence of such a steady state is controversial, due to the pressure changes along the pipe and the consequent gas expansion inside the bubbles. In real systems, close to the pipe inlets, the bubbles are normally separated by small liquid slugs and thus, the influence of the wake region on the motion of the trailing bubbles cannot be avoided, which eventually leads to coalescence. Along the pipe inlet region, the developing mechanism of continuous slug flow is based on the fact that shorter liquid slugs are followed by faster travelling bubbles, and that they eventually merge forming larger individual units. The frequency of coalescence gradually decreases until, theoretically, this merging process ceases to happen.

The randomness, intermittence and unsteadiness evident in the developing slug flow pattern indicate the extremely complicated nature of the hydrodynamics involved. Due to these characteristics, a statistical approach is required to properly describe the evolution and distribution of the major flow parameters: length of the elongated bubbles; length of the liquid slugs; translational velocity of the bubbles and coalescence rate (or frequency).

Over the last years, the growing capabilities of data acquisition and processing, and the higher precision of measurement techniques, particularly the non-invasive ones, made possible the appearance of a considerable amount of research devoted to developing slug flow. Experimental studies were reported mainly for air–water systems, where the liquid slugs are fully turbulent, showing the effect of U_L and U_G in the major hydrodynamic features and, is some cases, also the influence of the pipe diameter and inclination (van Hout et al., 2001, 2002b, 2003; ; Xia et al., 2009; Mayor et al., 2008a). Only in the works of Mayor et al. (2007a, 2008b), where different aqueous solutions of glycerol were used as test fluids, can be found data for liquid slugs in the fully laminar or in a mixed scenario (laminar flow in the main body of the liquid together with turbulent wake regions). Some predictive models for the hydrodynamic parameters were also reported, and the corresponding simulation data compared reasonably well with experimental results (Barnea and Taitel, 1993; van Hout et al., 2001; Mayor et al., 2007a, 2007b, 2008b; Xia et al., 2009). These models require the input of information about the bubble translational velocity as a function of the length of the liquid slug above it. Together with this fact, the idea that coalescence mechanisms are governed by the degree of interaction between consecutive bubbles is in agreement with all the referenced studies about continuous slug flow. Therefore, it is very important to attain a detailed knowledge about the hydrodynamics of fundamental systems, such as individual or a pair of consecutive Taylor bubbles.

Applying a dimensional analysis to the problem of an isolated Taylor bubble rising in vertical slug flow, the description can be reduced to three dimensionless groups:

- Eötvös number, representing the ratio between surface tension and gravitational effects, $Eo = g(\rho_L - \rho_G)D^2/\sigma$;
- Morton number, also called the property group, $M = g\mu_L^4(\rho_L - \rho_G)/\rho_L^2\sigma^3$;
- Froude number, defining the ratio of inertial and gravitational forces, $Fr = U_{SB}/\sqrt{gD(\rho_L - \rho_G)/\rho_L}$.

where ρ_L and ρ_G are the liquid and gas density, respectively, D the tube diameter, σ the surface tension, and the μ_L the dynamic viscosity of the liquid. Other relevant dimensionless group, that can be derived from the above, is the inverse viscosity number, $N_f = \rho_L\sqrt{gD^3}/\mu_L = (Eo^3/M)^{1/4}$.

Since the middle of the last century, a substantial amount of research has been dedicated to the flow of individual Taylor bubbles in vertical tubes (Dumitrescu, 1943; Davies and Taylor, 1950; Goldsmith and Mason, 1962; White and Beardmore, 1962; Collins et al., 1978; Bendiksen, 1985; Mao and Duckler, 1991). Particularly relevant to the subject of bubble–bubble interaction is the information gathered in studies more focused in the wake region. Campos and Guedes de Carvalho (1988a) performed a photographic study of the wakes of Taylor bubbles rising through stagnant liquids, varying the liquid viscosity and the tube diameter. Three different kinds of wakes were reported, depending on the inverse viscosity number: laminar and closed axisymmetric wakes for N_f below 500; a transitional regime when $500 < N_f < 1500$; and open wakes with a clear turbulent behaviour and liquid shedding, for N_f higher than 1500. The same authors presented an experimental study about the mixing produced by the wake of Taylor bubbles, and compared the data with two different models (Campos and Guedes de Carvalho, 1988b). Also for a single rising bubble through a vertical column of stagnant liquid, van Hout et al. (2002a) used the Particle Image Velocimetry (PIV) to measure the velocity fields in front of the bubble, in the liquid film, and in the wake region. The system consisted of air–water, and the flow conditions were defined solely by a Reynolds number (based on U_{SB}) of 4350. Nogueira et al. (2006) used a non-intrusive methodology combining PIV and pulsed shadow techniques (PST) to characterize the hydrodynamics of the flow in the wake region of Taylor bubbles, rising through stagnant and co-currently flowing Newtonian liquids (viscosities in the range of 1×10^{-3}–1.5 Pa s), inside a vertical tube with 32 mm internal diameter. Shemer et al. (2007a) extended part of the work of van Hout et al. (2002a), that related to the wake region, to other flow conditions. These different conditions were made by variations in the tube diameter (0.014–0.044 m) and in the water co-current superficial velocity (0–1 m/s).

The first research regarding the coalescence mechanism of a consecutive pair of Taylor bubbles in vertical tubes was carried out by Moissis and Griffith (1962). Pinto and Campos (1996) reported