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Interaction between two consecutive axisymmetric Taylor drops flowing in a heavier liquid in a vertical tube

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A B S T R A C T

A study regarding the interaction between two consecutive Taylor drops flowing in a heavier liquid in a vertical tube is reported. Under certain conditions, due to the wake of the leading drop, the trailing drop accelerates, leading to coalescence of the two drops. This study was developed using a numerical model based in the Volume of Fluid method in an axisymmetric geometry. The simulations reported in the present work had to fulfill two conditions: axisymmetry (due to the numerical model) and a high enough drop Reynolds number (which is related to the disturbances in the wake of an isolated drop, and thus to the tendency to drop interaction). Relevant dimensionless numbers are used to assess the effect of the acting forces. Detailed flow patterns and drop shapes are provided. Furthermore, the approaching velocity acquired by the trailing drop is analyzed and velocity profiles between the leading and the trailing drop are also reported. In general, the trailing drop shows an accelerating region, followed by a deceleration near the leading drop. The increase of Eotvos number promotes higher accelerations, while the increase in Morton number and viscosity ratio has the opposite effect. By comparison to literature gas-liquid studies, it was also found that interfacial forces promote the shape stability of the drops.

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1. Introduction

One of the foremost multiphase flow patterns is slug flow. Slug flow can be summarized as a flow pattern in which the dispersed phase forms long and large bullet-shaped drops or bubbles (Taylor bubbles or drops (Davies and Taylor, 1950; Govier and Aziz, 1972; Mandal et al., 2008)), flowing surrounded by the continuous phase (Fabre and Line, 1992). Earlier studies on slug flow concern gas-liquid phases (Davies and Taylor, 1950; Moissis and Griffith, 1962; Nicklin et al., 1962; White and Beardmore, 1962). Slug flow can occur in macro (gravity effects) (Mydlarz-Gabryk et al., 2014) or in micro tubes (no gravity) (Aoki et al., 2011; Jovanović et al., 2011). Slug flow can also appear in three phase flows, with a dominant liquid phase, and two other phases in drops and bubbles (Oddie et al., 2003; Liu et al., 2014).

The present work deals with vertical liquid-liquid slug flow with gravity effects.

Gas-liquid slug flow (Davies and Taylor, 1950; Nicklin et al., 1962; Morgado et al., 2016) is a well-known flow pattern, impelled by its importance in industrial applications, such as: vapor liquid absorbers, core cooling of nuclear reactors, reboilers and buoyance driven fermenters. On the other hand, the interest in liquid-liquid slug flow is more recent and driven by its potential applications, for example, in the petroleum industry (Hasan and Kabir, 1990; Bannwart et al., 2004; Mandal et al., 2010; Zhang et al., 2012).

Unlike gas-liquid, liquid-liquid slug flow is still a pattern not well known. In order to gain a deeper knowledge of liquid-liquid slug flow, one must study the phenomenon step by step. The simpler approach is to analyze the flow of a single Taylor drop (dispersed phase) rising in a stagnant heavier liquid (continuous phase) in a vertical tube (Brown and Govier, 1961; Govier et al., 1961; Zukoski, 1966; Direito et al., 2016). The Taylor drop, in such conditions, reaches its terminal velocity (V_T), while the heavier liquid is forced, by the drop upward flow, to flow downwards (referential attached to the drop) in the narrow space between the drop and the wall, creating a thin annular film. Three regions of the continuous phase are of interest: the region above the drop ("I" in Fig. 1), the film region ("II") and the region below the drop ("III").

Concerning an isolated Taylor drop rising in a stagnant liquid, Mandal et al. (2007); 2008); 2009) studied the shape and velocity. Hayashi et al. (2011) presented experimental drop shapes as well as a dimensional analysis and data from numerical simulations. Kurimoto et al. (2013) also presented a correlation to predict the terminal velocity of Taylor drops rising in vertical tubes.

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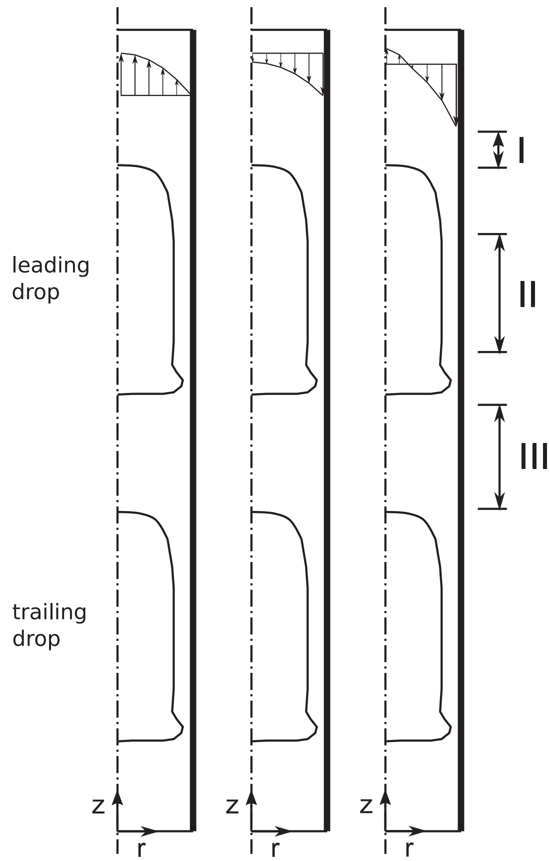

Fig. 1. Axisymmetric domain with two drops. Velocity profiles: earth reference frame (left), leading drop nose reference frame for drops faster than undisturbed continuous phase (middle) and leading drop nose reference frame for drops slower than portions of undisturbed continuous phase (right). Marked region above the drop (I), leading drop continuous phase film (II) and leading drop wake (III).

The aim of the present work is to analyze the flow behavior, drop shape and velocity when a trailing drop approaches a leading one flowing at its terminal velocity. The data was obtained by conducting numerical simulations (Computational Fluid Dynamics – CFD) using a two-dimensional axisymmetric model (Direito et al., 2016) and using, as starting point, previous simulations and experimental data regarding isolated Taylor drops flowing in stagnant (Direito et al., 2016) and co-current (Direito et al., 2017a) heavier liquid.

2. Physical background

In many applications, slug flow occurs in co-current flow. The behavior of single Taylor drops in liquid-liquid co-current flow was analyzed in a previous work (Direito et al., 2017a).

However in continuous liquid-liquid slug flow, consecutive Taylor drops interact with each other, leading to drop coalescence and the formation of longer drops. It is therefore relevant to describe the continuous liquid-liquid slug flow reformulating the terms previously stated for single Taylor drops (Direito et al., 2016). A dimensional analysis can be performed on the phenomena (Hayashi et al., 2011), in which it is important to consider the density ratio

$$\rho^* = \frac{\rho_D}{\rho_C}, \tag{1}$$

as well as the viscosity ratio

$$\mu^* = \frac{\mu_D}{\mu_C}, \tag{2}$$

where ρ is the density and μ the viscosity. The subscripts “D” and “C” refer to the dispersed and continuous phases. The density difference, $\Delta\rho = \rho_C - \rho_D$, also appears in some dimensionless numbers. Note also that the density ratio is always smaller than 1, as the present work deals with rising drops.

The ratio between inertial and gravity forces is represented by the Froude number, which is the dimensionless number usually used to quantify the drop terminal velocity:

$$\mathrm{Fr} = \frac{V_T}{\sqrt{\Delta\rho\, gD/\rho_C}}. \tag{3}$$

The ratio between buoyancy and interfacial forces is of foremost importance and is represented by the Eötvös number:

$$\mathrm{Eo} = \frac{\Delta\rho\, gD^2}{\sigma}, \tag{4}$$

with σ standing for the interfacial tension between the continuous and the dispersed phase.

Morton number balances gravitational, viscous and surface tension forces:

$$\mathrm{M} = \frac{\Delta\rho\, g\mu_C^4}{\rho_C^2\sigma^3}. \tag{5}$$

The combined analysis of Morton, Eötvös and viscosity ratio numbers is an important tool to inspect the flow behavior. When Eötvös number is high, i.e. low interfacial tension, and the viscosity ratio is low enough, the liquid-liquid isolated drop flow should resemble the flow of a gas Taylor bubble rising in a liquid in a macro tube. Such behavior is explained by the predominance of the gravity effect, i.e., by the large density difference. For low Eötvös, Morton number is required to quantify the importance of the viscous forces. Low Eötvös and high Morton numbers implicate a high viscosity of the continuous phase. If the viscosity ratio is high, such combination should be observed when, at the macro-scale, both fluids have close densities (viscous effects predominance). For low Eötvös and Morton numbers and low viscosity ratio, the flow should resemble that of a gas Taylor bubble flowing in a liquid contained in a micro tube (interfacial tension predominance) (Rocha et al., 2017).

In order to avoid confusion between the terminal velocity and the drop velocity in continuous co-current flow, the terminology V_{TC} will be used for the co-current drop velocity and V_T for the terminal velocity. Notice the following relationship between both (Fabre and Line, 1992; Nicklin et al., 1962):

$$V_{TC} = V_T + CU_C, \tag{6}$$

where C is a constant that depends on the flow properties (Direito et al., 2017a) and U_C is the superficial velocity of the continuous phase when the superficial velocity of the dispersed phase is zero as is the case of the present study. Furthermore, the ratio between the superficial velocity and the drop terminal velocity can be used:

$$u^* = \frac{U_C}{V_T}. \tag{7}$$

If Eq. (6) is divided by V_T:

$$\frac{V_{TC}}{V_T} = 1 + Cu^*. \tag{8}$$

Even though the presented dimensionless numbers suffice (Eqs. (1)–(5)) for the characterization of the problem, it is also useful to consider the ratio between inertial and viscous forces in the continuous phase regarding the disturbance caused by the drop passage in the continuous liquid which is represented by the drop Reynolds number,

$$\mathrm{Re}_D = \frac{\rho_C V_{TC} D}{\mu_C}, \tag{9}$$