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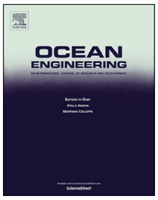

Numerical study of an individual Taylor bubble rising through stagnant liquids under laminar flow regime

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ABSTRACT

Slug flow is one of the main flow regimes encountered in multiphase flow systems especially in oil and gas production systems. In the present study, the rise of single Taylor bubble through vertical stagnant Newtonian liquid is investigated by performing complete dimensionless treatment followed by an order of magnitude analysis of the terms of equations of motion. Based on this analysis, it is concluded that Froude, Eötvös and Reynolds numbers are the sole physical parameters influencing the dimensionless slug flow equations. Using the guidelines of the order of magnitude analysis, computational fluid dynamics simulation is carried out to investigate the dynamics of Taylor bubbles in vertical pipe using the volume-of-fluid (VOF) method. Good agreement with previous experimental data and models available in the literature is established confirming that the density ratio, viscosity ratio and the initial ratio of bubble size to pipe diameter (L_{TB}/D) have minimal effect on the main hydrodynamic features of slug flow. Based on the developed results, correlations for the terminal velocity of the Taylor bubble and the dimensionless wall shear stress are proposed showing the significance of these main dimensionless parameters and support other important theoretical and experimental work available in the literature.

1. Introduction

Multiphase flows occur in a wide range of applications including natural processes, chemical processes, nuclear systems and petroleum industries. The petroleum industry is considered one of the most important applications of multiphase flow, as it could be encountered in different processes/stages such as: oil processing, oil and gas transport in pipelines, and sloshing in offshore separator devices.

For two-phase gas-liquid flow in pipes, different flow patterns can occur known as “flow pattern/flow regime”. These patterns depend on the flow rates, the geometry of the system, and inclination of the pipe (Morgado et al., 2016). Multiphase flow is classified according to the distribution of different phases building up the flow field, known as “flow regime/pattern”. Multiphase flow can be encountered in various flow patterns such as bubbly, slug, plug, annular and dispersed flow. Fluid flow investigation includes an important aspect which is the identification of the encountered flow pattern. For gas-liquid flow in pipes, one of the common and complex patterns encountered is known as “slug flow”. Slug flow is an intermitted flow between stratified and annular flow.

Flow intermittence is the main remarkable hydrodynamic characteristic causing the complex structure of slug flow which is composed of Taylor elongated bubble that occupies almost the whole cross-section of the pipe, and annular falling liquid film that might entrain many small bubbles, known as a “liquid slug”. Flooding of downstream processing facilities, severe pipe corrosion, structural instability of pipeline, and further induction of the reservoir flow oscillations, and a poor reservoir management are examples of the problems encountered as result of slugging in offshore oil and gas systems.

The prediction of the appropriate flow pattern regimes, the governing correlations, and the hydrodynamic characteristics of slug flow are essential for successful operation, simulation and optimization of any industrial applications encountering slug flow (Santos, 2007). According to the following authors, Computational fluid dynamics (CFD) has been proven to be a powerful, practical tool for the analysis and simulation of the hydrodynamic characteristics of slug flow in pipes. The main complex feature of gas-liquid slug flow is the deformable interface (Zheng and Che, 2007). The volume-of-fluid (VOF) method originally developed by Hirt and Nichols (1981) is often used to simulate complex multiphase

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Nomenclature

D	Pipe diameter (m)
g	Acceleration due to gravity (m s^{-2})
g_r	Acceleration due to gravity in radial direction (m s^{-2})
g_r^*	Dimensionless acceleration due to gravity in radial direction (–)
g_z	Acceleration due to gravity in axial direction (m s^{-2})
g_z^*	Dimensionless acceleration due to gravity in axial direction (–)
L	Pipe length (m)
L_{TB}	Length of the Taylor bubble (m)
L_W	Length of the wake (m)
p	Pressure (Pa)
p^*	Dimensionless pressure (–)
r	Radial direction (m)
r^*	Dimensionless radial direction (–)
r_1 and r_2	Local principal radii of curvature at the bubble surface as indicated by Mao and Dukler (1990) (m)
R	Pipe radius (m)
R_{TB}	Taylor bubble radius (m)
t	Time (s)
t^*	Dimensionless time (–)
u	Velocity (m s^{-1})
U_∞	Velocity of a Taylor bubble rising through stagnant liquid (m s^{-1})
U_L	Mean liquid velocity (m s^{-1})
U_{LF}	Velocity in the annular liquid film (m s^{-1})
U_{TB}	Taylor bubble velocity (m s^{-1})
v_r	Velocity component in radial direction (m s^{-1})
v_r^*	Dimensionless velocity component in radial direction (–)
v_z	Velocity component in axial direction (m s^{-1})
v_z^*	Dimensionless velocity component in axial direction (–)
v_θ	Velocity component in tangential direction (m s^{-1})
V_L	Relative liquid velocity to the bubble in moving reference frame (MRF) (m s^{-1})
V_W	Volume of the wake (m^3)
x or z	Axial coordinate in 2D coordinate system (m)
y or r	Radial coordinate in 2D coordinate system (m)
z^*	Dimensionless axial coordinate (–)

Greek letters

μ	Dynamic viscosity (Pa s)
ρ	Density (kg m^{-3})
σ	Surface tension (N m^{-1})
σ_r	Surface tension in radial direction (N m^{-1})
σ_r^*	Dimensionless surface tension in radial direction (–)
σ_z	Surface tension in axial direction (N m^{-1})
σ_z^*	Dimensionless surface tension in axial direction (–)
σ_θ	Surface tension in tangential direction (N m^{-1})
σ_θ^*	Dimensionless surface tension in tangential direction (–)
δ_{LF}	Liquid film thickness (m)
τ	Shear stress (Pa)
τ_W	Wall shear stress (Pa)
ν	Kinematic viscosity (m^2 s^{-1})
Γ_ρ	Density ratio, $\Gamma_\rho = \frac{\rho_L}{\rho_G}$
Γ_μ	Viscosity ratio, $\Gamma_\mu = \frac{\mu_L}{\mu_G}$

Dimensionless groups

Ar	Archimedes number, $Ar = \rho_L^2 g D^3/\mu_L^2$
Eo	Eötvös number, $Eo = \frac{g\rho_L D^2}{\sigma}$
Fr_{UTB}	Froude number, $Fr_{UTB} = \frac{U_{TB}}{\sqrt{gD}}$
M	Morton number, $M = \frac{\Delta\rho g \mu_L^4}{\rho_L^2\sigma^3}$
N_f	Inverse viscosity number, $N_f = \rho_L (gD^3)^{0.5}/\mu_L$
$Re_{U_{TB}}$ or Re_{U_∞}	Reynolds number based on the velocity of the Taylor bubble, $Re_{U_{TB}} = \frac{\rho_L U_{TB} D}{\mu_L}$
$Re_{U_{LF}}$	Reynolds number based on the velocity of the annular liquid film, $Re_{U_{LF}} = \rho_L U_{LF}\ \delta_{LF}/\mu_L$
Re_{V_L}	Reynolds number based on the mean velocity of the liquid, $Re_{V_L} = \rho_L V_L D/\mu_L$

List of acronyms

CFD	Computational fluid dynamics
FRF	Fixed frame of reference
MRF	Moving frame of reference
VOF	Volume-of-fluid

flows including slug flow, and is powerful in tracking the interface between fluids (Fabre and Liné, 1992; Razavi and Namin, 2011; Rahimi et al., 2013; Desamala et al., 2013; Desamala et al., 2014; Fabre and Liné (1992); Razavi and Namin, 2011; Rahimi et al., 2013; Desamala et al., 2013; Desamala et al., 2014).

The hydrodynamic characteristics of gas-liquid vertical slug flow include the final shape of the Taylor bubble, Taylor bubble rises velocity, liquid film thickness, liquid film velocity, wall shear stress distribution and wake shape. Despite the conduction of extensive work in the modelling process of gas-liquid slug flow, a need for correlations based on experimental data is still required. These correlations include slug characteristics such as: Taylor bubble velocity, slug frequency, slug length, slug liquid hold up, and slug unit velocity.

In literature, since the 1940s, a significant amount of research has been done to understand the complex principles of slug flow. Starting with Dumitrescu (1943) who investigates the rise of single Taylor bubble in the stagnant liquid by applying potential flow theory and concludes that the Taylor bubble rise velocity could be given by:

$$U_{TB} = 0.351\sqrt{gD} \tag{1}$$

Other analytical and/or experimental approaches are made later to modify the above correlation as discussed by Kang et al. (2010). A good review on the most commonly used correlations to estimate the Taylor bubble velocity is given by Morgado et al. (2016).

One of the main complex hydrodynamic features of slug flow is the wake flow pattern. Campos and De Carvalho (1988) performs an important photographic study to investigate the wake structure of Taylor bubbles rising in stagnant liquid using different pipe diameters and liquid viscosities. They conclude that the inverse viscosity number mainly influences the wake structure and they categorise the wake flow pattern into three main groups as follows:

- Type 1: Closed axisymmetric laminar wake for: $N_f < 500$.
- Type 2: Closed asymmetric transitional wake for: $500 < N_f < 1500$.
- Type 3: Opened turbulent wake with the recirculatory flow: $N_f > 1500$.

Araújo et al. (2012) discuss the importance of other experimental studies that investigate the main complex hydrodynamic nature of slug flow. They reach number of remarkable conclusions that helped in further understanding of the problem (Polonsky et al., 1999; Van hout et al., 2002; Clanet et al., 2004; Liberzon et al., 2006; Sousa et al., 2006; Direito et al., 2017; Polonsky et al., 1999; Van hout et al., 2002; Clanet et al., 2004; Liberzon et al., 2006; Sousa et al., 2006; Direito et al., 2017).