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Review

Review on vertical gas–liquid slug flow

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ABSTRACT

Vertical slug flow is characterized by the rise of long bullet-shaped gas bubbles with a diameter almost matching that of the tube - Taylor bubbles. Liquid slugs separate consecutive Taylor bubbles, which may interact and coalesce if the distance between them is small. Slug flow has numerous industrial applications, being also observed on physiological and geological systems. In spite of the contribution of the development of non-intrusive experimental techniques to a deeper understanding of slug flow features, the complexity of this flow pattern requires the combined use of numerical approaches to overcome some of the optical problems reported in experimental methods, and other limitations related to the flow aperiodic behavior.

The need to systematize the large amount of data published on the subject and to understand the limitations of the techniques employed constitutes the motivation for this review. In the present work, literature on vertical gas–liquid slug flow, with Newtonian fluids, from 1943 to 2015, covering theoretical, experimental and numerical approaches, is reviewed. Focus is given to single and trains of Taylor bubbles rising through stagnant and co-current liquids.

It should be emphasized, however, that further research still needs to be conducted in some particular areas, namely the hydrodynamics of the liquid film surrounding the Taylor bubbles, the interaction between consecutive bubbles, and a more detailed approach to the flow of Taylor bubbles through co-current liquids.

1. Introduction

When gas and liquid flow simultaneously in a tube, several types of spatial distribution of both phases – flow patterns - may occur depending on the set of fluid properties, flow rates, and on the geometry and inclination of the tube. Realizing the importance of accurately predicting the transition conditions between flow patterns, several authors proposed classifications for upward flow of gas-liquid mixtures in vertical pipes (Barnea, 1987; Hewitt, 1970; Taitel et al., 1980; Taitel and Dukler, 1976). Five main types of gas–liquid flow patterns are usually identified: bubbly, slug, semi-annular, annular, and mist (Fig. 1).

In vertical gas–liquid flow, feeding gas at low flow rates at the bottom of a pipe causes a random distribution of small discrete bubbles through the liquid continuous phase. This behavior, observed both for stagnant and flowing liquid, is designated by bubbly flow (Barnea, 1987; Hewitt, 1970; Moissis and Griffith, 1962; Taha and Cui, 2006; Taitel et al., 1980; Taitel and Dukler, 1976). The increase of the gas flow rate and, consequently, the concentration of small bubbles, promotes coalescence between them, yielding larger bubbles. Named Taylor bubbles after Geoffrey Taylor, a British physicist and mathematician notable for his pioneer work on slug flow (Davies and Taylor, 1950), these large gas bubbles are characterized by their bullet shape: a round-shaped nose followed by a cylindrical main body. Isolated Taylor bubbles rise almost uniformly in vertical pipes, occupying nearly the entire cross-section of the tube. On its turn, continuous slug flow or bubble train flow is characterized by an almost-periodic rise of Taylor bubbles separated by liquid slugs that may contain small, dispersed bubbles in it. Between a Taylor bubble and the tube wall, the liquid flows downwards as a thin falling film. As it reaches the bottom of the bubble, the annular film enters the liquid slug behind it as an expanding jet, with the possibility of creating a recirculation region known as the bubble wake, depending on the flow conditions. Both the shape of the bubble trailing edge and the wake flow pattern depend on the fluid properties and tube geometry, besides flow conditions. If the separation distance between two Taylor bubbles is small enough, the motion and shape of the trailing bubble get largely affected by the flow in the wake of the leading one: the nose becomes distorted and wavy, its velocity increases, and

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Nomenclature

a^2	Specific cohesion m^2
$\dot{b}$	Dimensionless film thickness for turbulent flow
C	Ratio between the centreline and the mean liquid velocities
D	Internal diameter of the tube m
g	Acceleration due to gravity $m\,s^{-2}$
l	Distance between consecutive Taylor bubbles m
l_e	Entrance length m
l_{min}	Minimum separation length for which there is no interaction m
l_s	Length of the liquid slug m
l_{TB}	Length of the Taylor bubble m
l_W	Length of the wake m
r	Radial coordinate m
$\dot{r}$	Distance from the central axis of the tube normalised by its radius m
R	Internal radius of the tube m
R_N	Radius of curvature at the nose of the bubble m
R_{TB}	Taylor bubble radius m
u	Velocity $m\,s^{-1}$
$u*$	Friction velocity $m\,s^{-1}$
U_∞	Velocity of a Taylor bubble rising through stagnant liquid $m\,s^{-1}$
U_C	Maximum or centerline liquid velocity $m\,s^{-1}$
U_F	Velocity in the annular liquid film $m\,s^{-1}$
U_G	Superficial velocity of the gas phase $m\,s^{-1}$
U_l	Velocity of the leading bubble $m\,s^{-1}$
U_L	Mean liquid velocity $m\,s^{-1}$
U_t	Velocity of the trailing bubble $m\,s^{-1}$
U_{TB}	Taylor bubble velocity $m\,s^{-1}$
V_L	Relative liquid velocity in a MFR m^3
V_{TB}	Volume of the Taylor bubble m^3
V_W	Volume of the wake m^3
$\dot{x}$	Axial distance normalised by the tube radius
z	Axial coordinate m
$Z*$	Distance from the nose where the liquid film is fully developed m
Z_A	Interaction distance above the nose of the bubble m

Greek Letters

$\dot{\gamma}$	Deformation rate s^{-1}
δ	Annular liquid film thickness m
μ	Dynamic viscosity Pa s
ρ	Density $kg\,m^3$
σ	Surface tension $N\,m^{-1}$
τ	Shear stress Pa
τ_W	Wall shear stress Pa
υ	Kinematic viscosity $m^2\,s^{-1}$

Dimensionless groups

Ar	Archimedes number
Eo	Eötvös number
Fr	Froude number
M	Morton number
N_f	Inverse viscosity number
Ps	Poiseuille number
Re	Reynolds number
Re_F	Reynolds number based on the velocity of the annular liquid film
Re_{TB}	Reynolds number based on the velocity of the Taylor bubble
Re_{U_L}	Reynolds number based on the mean velocity of the liquid
Re_{V_L}	Reynolds number based on the relative velocity of the liquid in a MFR
We_{U_∞}	Weber number based on the velocity of a Taylor bubble rising through stagnant liquid

List of acronyms

CFD	Computational fluid dynamics
FFR	Fixed frame of reference
MFR	Moving frame of reference
PIV	Particle image velocimetry
PST	Pulsed shadow technique
SFS	Slug flow simulator
VOF	Volume-of-fluid

coalescence between bubbles will occur. In Fig. 2, images of a single Taylor bubble (a) and of two consecutive Taylor bubbles (b) obtained from computational slug flow simulations illustrate the flow details just described.

Coalescence between Taylor bubbles can also result from increasing gas flow rates, leading eventually to the development of semi-annular and annular flow. Semi-annular flow can be seen as an intermediate stage between slug and annular flow, where shorter liquid slugs separate bubbles of increased length. As a consequence of a further increase of the gas flow rate, complete destruction of the liquid slugs occurs and annular flow emerges, *i.e.*, the gas phase becomes a continuum, flowing in the core section of the tube, surrounded by the liquid flowing as a film in the annular space between the gas phase and the tube wall (Hewitt, 1970; Moissis and Griffith, 1962; Taha and Cui, 2006). For even higher gas flow rates, the liquid becomes dispersed within the continuous gas phase in a mist flow.

From the five flow patterns referred, slug flow is usually on the spotlight due to its numerous practical applications. In industrial plants, gas-liquid slug flow is present in vapor-liquid absorbers, vapor generators, reboilers, buoyancy-driven fermenters, vaporizers, and during crystallization (Yun and Shen, 2003), filtration (Mayer et al., 2006) and membrane processes (Bellara et al., 1997; Cui et al., 2003; Ghosh and Cui, 1999; Li et al., 1997; Taha and Cui, 2002). This flow pattern is also observed in emergency core cooling of nuclear reactors, in oil extraction from wells, transportation in pipelines of hydrocarbons, and in geothermal and thermal power plants (Bugg et al., 1998; Fabre and Liné, 1992; Fernandes et al., 1983; Lu and Prosperetti, 2008; Mao and Dukler, 1991; Taha and Cui, 2006).

Gas bubbles are often used to promote mixing and mass transfer in several types of reactors (Bi, 1999; Braak et al., 2011; Campos and Carvalho, 1988b; Elperin and Fominykh, 1997), and slug flow has been described as an excellent alternative to mechanical induced agitation. Terrier et al. (2007) described a new bubble column disposable bioreactor, where Taylor bubbles promote mixing and aeration. According to the authors, the Slug Bubble Bioreactor allowed for an easy scale-up by using the desired number of multiple units, being compact, efficient, robust, easy to operate aseptically, flexible and cost effective.

Examples of slug flow are also observed on physiological and geological systems. At the capillaries, red blood cells behave similarly to Taylor bubbles due to the stress-induced deformation of their shape (Kang et al., 2010). In gas embolism, caused by the presence of gas bubbles within the cardiovascular system - a situation that can lead to a patient's death -, the bubbles are, in fact, Taylor bubbles. Slug flow is also a common phenomenon in volcanology, where large gas bubbles rise through basaltic magma during volcanic eruptions, often resulting in Strombolian eruptions,