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Hydrodynamics of slug flow in a vertical narrow rectangular channel under laminar flow condition

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ABSTRACT

The hydrodynamics of gas–liquid two-phase slug flow in a vertical narrow rectangular channel with the cross section of 2.2 mm × 43 mm is investigated using a high speed video camera system. Simultaneous measurements of velocity and duration of Taylor bubble and liquid slug made it possible to determine the length distributions of the liquid slug and Taylor bubble. Taylor bubble velocity is dependent on the length of the liquid slug ahead, and an empirical correlation is proposed based on the experimental data. The length distributions of Taylor bubbles and liquid slugs are positively skewed (log-normal distribution) at all measuring positions for all flow conditions. A modified model based on that for circular tubes is adapted to predict the length distributions in the present narrow rectangular channel. In general, the experimental data is well predicted by the modified model.

1. Introduction

Slug flow is often encountered in many practical applications such as distillation columns, gas absorption units, nuclear reactors, oil–gas pipelines, and steam boilers. The complicated structure of slug flow can be described as a series of slug units, each of which consists of a Taylor bubble with a liquid film around it and a portion of liquid slug behind the Taylor bubble. The evolution of slug flow along a pipeline strongly depends on the relative velocities between the continuous Taylor bubbles. With short separations, trailing Taylor bubbles accelerate and eventually merge with the leading ones (Moissis and Griffith, 1962; Pinto et al., 1998; Aladjem Talvy et al., 2000; Araújo et al., 2013). During the merging process, both the liquid slug and the Taylor bubble increase in length. It is assumed that this process terminates once the liquid velocity profiles at the back of the liquid slug become fully developed and all Taylor bubbles move at the same velocity (Shemer, 2003).

The two-phase slug flow in a narrow rectangular channel is encountered in many important applications, such as high performance micro-electronics, supercomputers, high heat-flux compact heat exchangers and research nuclear reactors with plate type fuels (Satitchaicharoen and Wongwises, 2004). It has been the subject of increased research interest in the past few decades (Griffith, 1963; Maneri and Zuber, 1974; Sadatomi et al., 1982; Mishima et al., 1993; Clanet et al., 2004; Ide et al., 2007; Sowinski et al., 2009; Bhusan et al., 2009; Wang et al., 2013a,b, 2014a,b). However, the majority of the studies are confined to slug flow in circular tubes, a few works deal with the slug flow in narrow rectangular channels.

Several experimental and theoretical works have been reported on the velocity of Taylor bubbles in circular tubes (Dumitrescu, 1943; Davies and Taylor, 1950; Bretherton, 1961; Nicklin et al., 1962; Moissis and Griffith, 1962; White and Beardmore, 1962; Wallis, 1969; Bendiksen and Zuber, 1984; Shemer and Barnea, 1987; Pinto et al., 1998; van Hout et al., 2002; Viana et al., 2003; Zheng and Che, 2006). Nicklin et al. (1962) proposed Eq. (1) to predict the velocity of a single Taylor bubble (V_T) in a moving liquid. It is generally assumed that V_T is a superposition of the drift velocity of a single Taylor bubble in a stagnant liquid (V_0), and a contribution due to the mean liquid velocity (V_m). Eq. (1) has later been applied for predicting the Taylor bubble velocity in continuous slug flow by most researchers, whereas substituting the mean liquid velocity (V_m) by the mixture velocity (j_{TP}), the sum of the liquid and gas superficial velocities (j_L)and (j_G). Then, Eq. (2) results.

$$V_T = C_0 V_m + V_0 \tag{1}$$

$$V_T = C_0 J_{TP} + V_0 \tag{2}$$

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Nomenclature

$B_i(t)$	Instantaneous position of the bottom of the i-th liquid slug (m)
C_0	Distribution parameter
Eo	Eotvos number
D	Diameter (m)
D_e	Equi-periphery diameter (m)
D_h	Hydraulic diameter (m)
$F_i(t)$	Instantaneous position of the front of the i-th liquid slug (m)
F_{scale}	Scale factor
G_{TP}	Two-phase mixture mass velocity (kg/(m^2·s))
g	Gravitational acceleration (m/s^2)
h_1, h_2	Distances relative to images bottom edge (pixel)
j_G	Gas superficial velocity (m/s)
j_G^*	Dimensionless gas superficial velocity
j_L	Liquid superficial velocity (m/s)
j_L^*	Dimensionless liquid superficial velocity
j_{TP}	Two-phase superficial velocity (m/s)
L_S	Liquid slug length (m)
$L_{Si}(t)$	Instantaneous length of i-th liquid slug (m)
L_T	Taylor bubble length (m)
$L_{Ti}(t)$	Instantaneous length of i-th Taylor bubble (m)
N_1	Frame of Taylor bubble nose arriving at h_1
N_2	Frame of Taylor bubble nose arriving at h_2
N_3	Frame of Taylor bubble bottom arriving at h_1
N_4	Frame of trailing Taylor bubble nose arriving at h_1
Re_{TP}	Reynolds numbers based on two-phase superficial velocity
Re_{V_S}	Reynolds numbers based on liquid slug velocity relative to Taylor bubble
s	Gap of rectangular channel (m)
V_0	Drift velocity (m/s)
$V_{Fi}(t)$	Instantaneous velocity of the front of the i-th liquid slug (m/s)
V_{max}	Maximum local velocity (m/s)
V_m	Mean liquid velocity (m/s)
V_T	Taylor bubble velocity (m/s)
$V_{Ti}(t)$	Instantaneous velocity of the front of the i-th Taylor Bubble (m/s)
$V_{T\infty}$	Taylor bubble velocity in undisturbed region (m/s)
w	Width of rectangular channel (m)
x	Axial distance from the inlet (m)

Greek letters

α	Average void fraction
α_T	Average void fraction of Taylor bubble region
δ_{fd}	Thickness of narrow side liquid film at the bottom of Taylor bubble (mm)
δ_m	Average liquid film thickness of the narrow side of Taylor bubble region (mm)
μ_L	Liquid phase viscosity (Pa·s)
μ_{TP}	Two-phase viscosity proposed by McAdams et al. (1942) (Pa·s)
ζ	Parameter defined in Eq. (26)
σ	Surface tension (N/s)
π	Circumference ratio
ρ_L	Liquid density (kg/m^3)
ρ_G	Gas density (kg/m^3)
$\Delta\rho$	Density difference between liquid and gas phases (kg/m^3)
τ	Time interval between two frames
ω	Parameter defined in Eq. (26)

Subscripts

G	Gas phase
L	Liquid phase
TP	Two-phase

The value of C_0 is based upon the assumption that the velocity of the Taylor bubble follows the maximum local velocity (V_{max}) in the front of its nose tip, and thus, $C_0 = V_{max}/V_m$ (Nicklin et al., 1962; Bendiksen and Zuber, 1984; Shemer and Barnea, 1987). The value of C_0 therefore equals approximately 1.2 for fully developed turbulent flow and 2.0 for fully developed laminar flow. For the inertia-controlled region when viscosity and surface tension can be neglected (Eotvos number $Eo = g(\rho_L - \rho_G)D^2/\sigma > 70$ and $\rho_L^2 g D^3/\mu_L^2 > 3 \times 10^5$), White and Beardmore (1962) recommended that the drift velocity V_0 for the vertical tube can be expressed by following equation proposed by Dumitrescu (1943).

$$V_0 = 0.35\sqrt{\Delta\rho g D/\rho_L} \tag{3}$$

where the tube diameter D is taken as the characteristic length, g is the gravitational acceleration, μ_L is the liquid phase viscosity, σ is the surface tension, $\Delta\rho$ is the density difference between the two phases, ρ_G and ρ_L are the gas and liquid density, respectively.

Velocities and characteristic lengths of the Taylor bubble and liquid slug, void fractions in both regions of the slug bubble and liquid slug as well as the drift velocity are required for most classical models of the slug flow in circular tubes (Fabre and Line, 1997). The knowledge of the mean values of the characteristic lengths of Taylor bubble and liquid slug is, however, insufficient for truthful modeling, and the statistical parameters are also required. For circular tubes, experimental investigations on the length distributions of liquid slugs and Taylor bubbles have been carried out for horizontal, inclined and vertical flows (Bernicot and Drouffe, 1989; Barnea and Taitel, 1993; Cook and Behnia, 2000; van Hout et al., 2001, 2003; Shemer, 2003; Zheng and Che, 2006; Mayor et al., 2007a, 2008a,b; Wang et al., 2006; Wang et al., 2009; Xia et al., 2009). The liquid slug length distribution can be described by positively skewed distributions, such as the log-normal, the gamma, or the inverse Gaussian (Dhulesia et al., 1991; Nydal et al., 1992; van Hout et al., 2001, 2003; Shemer, 2003).

Modeling of the evolution of slug flow was undertaken by Bernicot and Drouffe (1989) for the horizontal case and by Barnea and Taitel (1993) for all inclination angles. The latter model was verified against experimental data by Cook and Behnia (2000) and Wang et al. (2006) for the horizontal and slightly inclined cases, by van Hout et al. (2003) for inclined cases, and by Mayor et al. (2007b), Xia et al. (2009) and van Hout et al. (2001) for the vertical cases. All the above models are for the gas–liquid slug flow in the turbulent regime. Predictions by these models compared reasonably well with the experimental data. The dependence of the Taylor bubble velocity on the liquid slug length ahead of it, $V_T = f\,(L_S)$, should be provided as an input relation to the Barnea and Taitel model. Several researchers proposed the relationship of $V_T = f\,(L_S)$ based on fitting experimental data. Moissis and Griffith (1962) expressed the function as follows:

$$\frac{V_T}{V_{T\infty}} = 1 + 8\exp\left(-1.06\frac{L_S}{D}\right) \tag{4}$$

where $V_{T\infty}$ is the velocity of the Taylor bubble in the undisturbed condition in which the trailing Taylor bubble is undisturbed by the leading one.