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Taylor flow in intermediate diameter channels: Simulation and hydrodynamic models

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ABSTRACT

The two-phase Taylor flow pattern has been studied extensively. However, limited information is available for flows in intermediate diameter channels ($5 \lesssim \mathrm{Bo} \lesssim 40$, or $6\ \mathrm{mm} \lesssim D \lesssim 27\ \mathrm{mm}$ for ambient gas–water flows), as found in air-lift and bubble pumps. Previous investigations have primarily evaluated Taylor flow models in terms of overall pressure drop, which incorporates hydrostatic and multiple hydrodynamic components. Thus, individual sub-models and sources of error could not be directly assessed. In this investigation, volume-of-fluid (VOF) based Taylor flow simulations are performed over a wide range of laminar and turbulent conditions in the intermediate Bond number regime ($5 < \mathrm{Bo} < 20$, $250 < \mathrm{N_f} < 1000$, and $20 < \mathrm{Re}_j < 8100$). Results are applied to individually evaluate hydrodynamic submodels for bubble-region frictional pressure drop gradient ($\nabla p_{\mathrm{f,b}}$), slug frictional pressure drop gradient ($\nabla p_{\mathrm{f,s}}$), and flow transition pressure loss ($\Delta p_{\mathrm{trans}}$). Based on these results, recommendations are provided for selection of hydrodynamic sub-models. These hydrodynamic closure models are integrated with kinematic flow models to yield a complete intermediate Bond number Taylor flow formulation for which all submodels were independently validated. The resulting model achieves improved accuracy for predicting experimental liquid flow rates compared with previous Taylor flow models (81% of cases within 50% of measured flows rates).

1. Introduction

1.1. Background

The vertical-upward Taylor flow pattern is a quasi-periodic two-phase flow pattern [32] that occurs over a broad range of flow scales (μm- to cm-scale channel diameters). In Taylor flow, elongated large diameter (Taylor) bubbles are separated by full-channel cross-section liquid *slugs*. Thin annular liquid films drain downward around the rising bubbles. This flow pattern is encountered in a variety of geometries and applications including miniaturized heat and mass exchangers [33], monolithic catalytic reactors [73], fuel cells [6], petrochemical extraction equipment [29], and gas-lift and bubble pumps [62].

The Taylor flow pattern has been extensively studied at the capillary/microchannel ($\mathrm{Bo} = (\rho_{\mathrm{L}} - \rho_{\mathrm{G}})gD^2/\sigma \lesssim 5$ [43]; [61]) and large diameter number ($\mathrm{Bo} \gtrsim 40$ [78]) limits. The present study focuses on Taylor flow in the intermediate Bond number regime, which has been comparatively poorly characterized. These operating conditions span a transition regime in which forces due to buoyancy, inertia, surface tension, and viscosity are all significant. Additionally, for many fluids (e.g., air–water at ambient temperature and pressure), the intermediate Bond number Taylor flow regime also spans the transition from laminar to turbulent flow, further complicating analysis.

The Taylor flow pattern is often idealized as being composed of repeating *unit cells* (Fig. 1), which can be analytically modeled in a piecewise and mechanistic fashion. This approach has been applied in the high Bond number limit (*e.g.*, for large diameter channels) by Fernandes et al. [29], Sylvester [69], and Taitel and Barnea [71]. Similar approaches have also been developed for capillary and microchannel Taylor flow [33,73]. Such models generally describe the flow pattern with two coupled systems of equations for *kinematic* (flow rates and fluid structure dimensions) and *hydrodynamic* (momentum balances) closure.

The kinematic specification of Taylor flow can be formulated by first applying continuity balances between representative liquid-slug and Taylor-bubble cross-sections.

$$U_{\mathrm{s}} = \alpha_{\mathrm{b}} U_{\mathrm{b}} + (1 - \alpha_{\mathrm{b}}) U_{\mathrm{f}} \tag{1}$$

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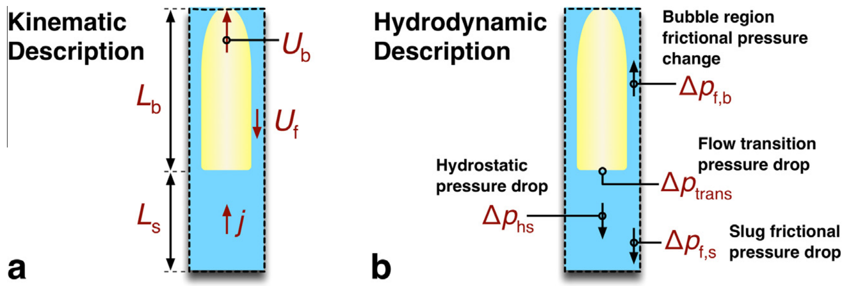

Fig. 1. Repeating unit cell model for Taylor flow: a. Kinematic and b. Hydrodynamic descriptions.

Here, U_s is the average slug velocity, α_b is the fraction of the bubble-region channel cross-section occupied by the gas-phase (assuming prismatic bubble shape), U_b is the average bubble velocity, and U_f is the average liquid film velocity. The total volumetric flow rate must be conserved across each channel cross-section for incompressible flow; therefore, the slug velocity (U_s) must equal the total superficial velocity (j).

$$U_s = j = j_L + j_G \tag{2}$$

Here, the phase superficial velocities (j_L, j_G) are defined as the phase volumetric flow rates divided by the channel flow area ($j_L = V_L/A$, $j_G = V_G/A$). Similarly, by averaging over the whole unit cell, the bubble velocity can be related to the gas superficial velocity.

$$j_G = U_b \alpha_b \beta \tag{3}$$

Here, β is the ratio of the bubble length to the total unit-cell length ($\beta = L_b/(L_b + L_s)$). In the case of negligible gas volume fraction in the liquid slug, as has been found for intermediate Bond number Taylor flow [63], the total void fraction (α, gas-phase volume fraction) is thus:

$$\alpha = \alpha_b \beta \tag{4}$$

For a circular cross-section channel, the liquid film thickness and bubble diameter are:

$$\delta_f = \frac{D}{2}(1 - \alpha_b^2) \tag{5}$$

$$D_b = D - 2\delta_f \tag{6}$$

Eqs. 1–6 summarize the continuity constraints for the idealized repeating unit-cell description of Taylor flow. Kinematic closure is usually obtained by specifying constitutive relations for bubble velocity (U_b), liquid film velocity (U_f) or thickness (δ_f), and bubble or liquid slug length (L_b, L_s). Sets of kinematic closure models for intermediate Bond number Taylor flows have been proposed by Reinemann et al. [62], de Cachard and Delhaye [25], and Rattner and Garimella [61].

The hydrodynamic description of Taylor flow can be formulated by applying a momentum balance over the fluid in the unit cell. Here, incompressible flow is assumed.

$$-\frac{dp}{dz} = [\alpha\rho_G + (1-\alpha)\rho_L]g + \beta\nabla p_{f,b} + (1-\beta)\nabla p_{f,s} + \frac{\Delta p_{trans}}{L_b + L_s} \tag{7}$$

dp/dz is the total average pressure gradient in the flow direction (upward). The first term on the right hand side of Eq. (7) represents the hydrostatic pressure drop (∇p_{hs}). $\nabla p_{f,b}$ and $\nabla p_{f,s}$ represent the frictional pressure change gradients in the Taylor bubble and liquid slug regions, respectively. Finally, Δp_{trans} represents the irreversible pressure drop (pressure loss) due to flow transitions between the Taylor bubble and liquid slug regions. Reversible pressure changes also occur due to liquid acceleration and deceleration in the bubble-to-slug transitions, but there is no net effect over a unit cell. Representative pressure change contributions from these terms are presented schematically in Fig. 2. Here, the dynamic pressure field (p_d) is defined as $p - p_{hs}$. Hydrodynamic closure is obtained by specifying constitutive relations for $\nabla p_{f,b}$, $\nabla p_{f,s}$, and Δp_{trans}. The objective of this investigation is to assess hydrodynamic closure models for Taylor flow in the intermediate Bond number regime.

Taylor flow is generally predicted to occur at low-to-moderate flow rates, for which fluid velocities are not sufficient to disrupt large scale flow structures (*i.e.*, Taylor bubbles and liquid slugs) and cause transition to the annular [72] or churn [41] flow patterns. Under such conditions, hydrodynamic pressure drops are relatively minor (~10–20%) compared to hydrostatic pressure drops. Thus, large errors in frictional and transition pressure drop predictions can often be tolerated in applications where gas and liquid flow rates are specified. In such cases, general purpose flow-regime-independent two-phase flow hydrodynamic pressure drop correlations could be employed, such as those of Chisholm [20], Friedel [30], Müller-Steinhagen and Heck [53], and Mishima and Hibiki [52] (for microchannels).

In contrast, for air-lift- and bubble-pump applications, where gas flow rates and total pressure drops are specified, relatively small errors in hydrodynamic pressure drop prediction can lead to dramatic changes in liquid pumping rates – the primary quantity of interest. The high sensitivity of liquid flow rate to pressure drop, wherein relatively small $(\partial(\partial p_d/\partial z)/\partial j_L)_{j_G}$ indicates large $(\partial j_L/\partial(\partial p_d/\partial z))_{j_G}$, has been reported in previous studies [26,66]. In fact, for many of the conditions considered in the present investigation, net hydrodynamic pressure forces actually act *in the flow direction*. This occurs because upward wall shear stress in the relatively long draining liquid-film regions exceeds downward shear stress in the shorter liquid slugs and transition pressure loss. This

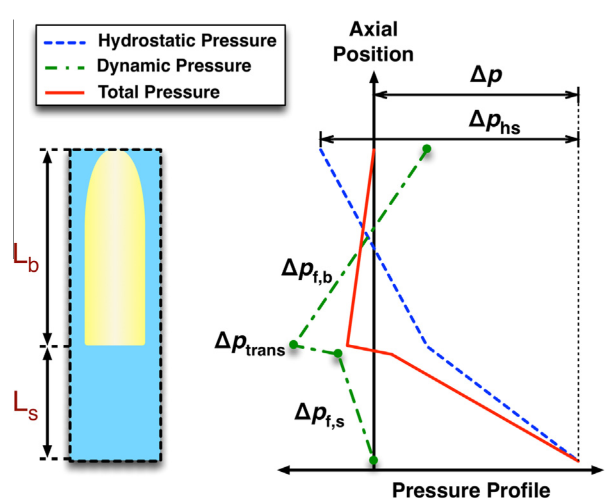

Fig. 2. Hydrostatic, dynamic, and total pressure profiles in a Taylor-flow unit cell.