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Department of Mechanical and Industrial Engineering

SYNOPSIS

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Interfacial Reconstruction of Taylor Bubble and Related Fluidic Behaviour in Vessel Emptying

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1. Introduction:

Slug bubble finds applications in different engineering devices and natural sciences, a few of which can be listed as nuclear reactor cooling, heat pipes, Stromboli volcanoes, airlift pumps, petroleum exploration, monolith chemical reactors, micro/nano-channels, heat exchangers, etc. The hydrodynamics of the slug bubble has a significant contribution in controlling the heat and mass transfer-related interfacial phenomenon. The interfacial dynamics of the slug bubble-like genesis, reorientation, pinch-off, coalescence play a paramount role in controlling the process parameters of the multiphase systems.

2. Literature review:

The interfacial evolution of the slug bubble under different conditions has been summarized in the next section highlighting the lacuna and objective of the thesis.

2.1 Transformation of a Taylor bubble to an annular bubble:

Many researchers have studied Taylor bubble and annular bubble dynamics individually experimentally (Campos et al., 1988; Nicklin et al., 1962), analytically (Kelessidisis and Dukler, 1990; Dumitrescu, 1943) and numerically (Tomiyama et al., 1993; Mitchell and Leonardi, 2020). The development of the annular bubble features like liquid bridge formation, sharpening of the nose, migration to one side of the annuli, etc. are of paramount interest in enhancing heat transfer in a double pipe heat exchanger (Pourhedayat et al., 2019) and mass transfer in a monolith reactor (Shin et al., 2017). Despite these efforts, the impetus has not been on the evolution of an asymmetric annular bubble from a symmetric Taylor bubble at the inception of annuli.

2.2 Flow pattern modulation by using passive techniques:

The flow pattern of liquid-gas flow inside the conduit affects the prevailing pressure drop and heat transfer enhancement. The modulation of the flow pattern by using a passive device like inserts has been a fertile area for research (James et al., 2006; Ambrose et al., 2017; Hoang et al., 2013). Chen et al. (2014) modified the phase distribution inside the vertical tube by employing a wire mesh annular insert resulting in the culmination of annular bubbles, which creates a thin film on the wall surface. Zhu et al. (2016) found different regimes of droplet breakup in expansion contraction geometry of injection nozzle (186 μm) and focusing orifice (210 μm). However, the modification of the flow pattern by using these inserts in two-phase flows has either been speculative or has not been given due attention.

2.3 Fluidic physics in an emptying bottle and the corresponding bubble dynamics:

Bottle emptying has intrigued many researchers and mathematicians alike due to its periodic pinch-off and oscillating discharge rate. Initial works of Whalley (1987), Tang and Kubie (1997), Tehrani et al. (1992) attempted to study the flooding and slugging at the bottle mouth by estimating the superficial velocities and flooding constant. Geiger et al. (2012) performed a three-dimensional simulation of an emptying bottle and optimized the emptying time for an inviscid fluid. Clanet and Searby (2004) modeled the emptying time by using the rise velocity of the Taylor bubble as postulated by Davis and Taylor (1950) in ideal bottles. Further, they employed a spring-mass analogy to model the time period of the minute interface oscillation originating from the compressibility of the gas inside the bottle. However, to date, none of the studies provides the relation between the bubble dynamics and the discharge rate of the bottle. Furthermore, different previous studies have not quantified the effect of fluid thermo-physical properties of the bottle emptying phenomenon at a different orientation.

2.4 Modeling bubble slug bubble interaction in a rectangular column:

The slip of the small bubble (SB) from the annular film of the slug/Taylor bubble (TB) is often encountered in the chemical reactors and has intrigued many researchers. Maxworthy (1986) first studied the interaction between the small bubble and the larger bubble in a Hele-Shaw cell. Tomiyama et al. (1993) studied the lateral migration of the bubble by using 2D VOF (Volume of Fluid) methodology in a linear shear field. Ervin and Tryggvason (1997) showed the effect of the shearing capillary number on the bubble trajectory in a linear shear field. Piedra et al. (2015) also utilized the front tracking technique coupled with the volume of fluid equations to model the terminal velocity, shape, and oscillating wake behavior of the bubble in two dimensions. Despite these advances, the slip of the SB from the annular film of TB has not been investigated in detail. The presence of the interface in the rectangular column is of paramount importance due to its role in heat transfer and mass transfer enhancement. Loss of the interface in the rectangular column due to bubble coalescence would affect the interfacial phenomenon and pressure drop.

3. Lacuna in literature and objectives of the present study:

A number of shortcomings have been found in the above literature review, which has been subsequently taken as the objectives for the current dissertation.

- The transformation of the Taylor bubble to an annular bubble at the inception of the annuli has not been studied to date.
  Objective 1: To experimentally and numerically simulate the transition of the slug bubble to an annular bubble with a concentric insert. The transition process of bubble shapes will be investigated around eccentric insert with fluids having different thermo-physical properties.

- There is a scarcity of investigations related to the modulation of the liquid-gas two phase flow pattern by using inserts/passive devices.
  Objective 2: To understand the modulation of the flow pattern of the slug bubble train by a perpendicular insert in a viscous medium. The stability of the cap bubbles to slug bubbles train will be investigated in detail.

- It has been observed from the literature review that not much work has been conducted to understand the bubble dynamics inside a discharging vessel/bottle having single inlet/outlet.

Objective 3: To experimentally investigate the discharge dynamics of a vessel closed from the top and study the subsequent bubble dynamics. The relation between bubble morphology, pinch-off frequency, and bottle discharge time will be investigated for different thermo-physical properties of the emptying fluid.

- Significant advances have been made in modeling the bubble dynamics inside a rectangular column; however, the impetus has not been on capturing the slip of the small bubble from the annular film of the slug bubble.
  Objective 4: To experimentally and numerically study the interaction dynamics between the small bubble and the slug bubble in a rectangular column. Sprint off and slip modes of bubble-bubble interactions will be studied.

4. List of contributions:

The present dissertation attempts to investigate various fluidic behavior related to the slug/Taylor bubble. Salient findings have been reported below.

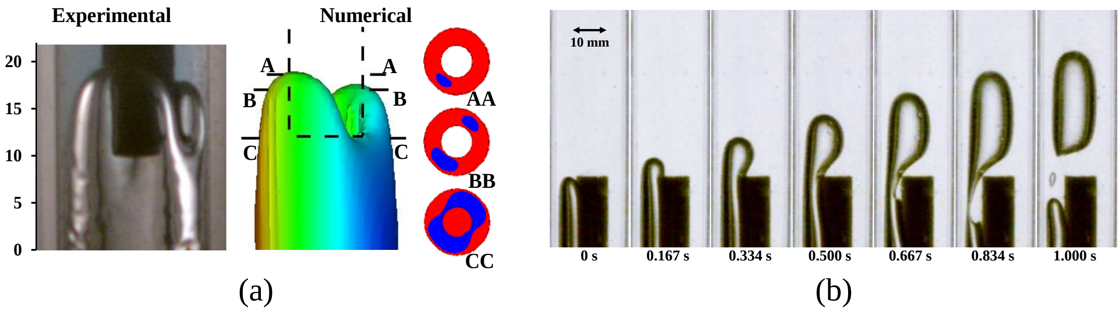


Fig. 4.1 (a) Comparison between the Volume of Fluid (VOF) simulation and experiments for the interfacial evolution of annular bubble and (b) pinch-off of the annular bubble at the exit of annuli.

4.1 Transformation of a Taylor bubble to an annular bubble:

The transformation of the Taylor bubble to the slug bubble takes place in six distinct stages, namely, plateau formation, doughnut shape orientation, and equipotential nucleation, preferential rise, retraction of lagging lobe, consumption of air thread formed, and the manifestation of an annular sectorial wrap.

- Bifurcating patterns in the growth of lobe heights and velocity history ascertains these stages behind genesis.
- A close similarity has been found between the interfacial reconstruction stages and Rayleigh-Taylor instability (RTI) in an annulus (Figure 4.1(a)).
- Nucleation, radial thinning, and equipotential growth have been described using the concept of one-dimensional wave propagation and linear RTI. The non-linear regime of RTI results in a preferential rise, which subsequently led to mushrooming of the leading lobe and the merging of the lagging lobe.

- The eccentricity of the insert reduces the rise velocity of the annular bubble for both low and high inverse viscosity number fluids.
- The effect of eccentricity on the rise velocity of the annular bubble has a minuscule effect (~ 1%), but the reacceleration process of the leading lobe is different, which has

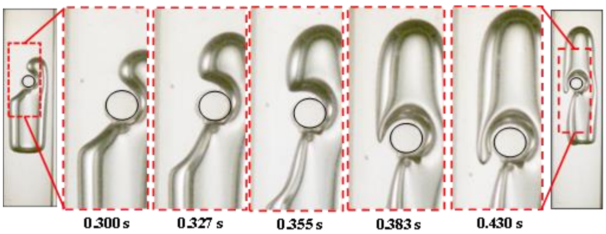
been quantified by axial velocity ratio, V/V_o. Low viscosity fluids like water have an axial velocity ratio $V/V_o > 1$ and on the other hand, higher viscosity fluid-like silicone oil has $V/V_o < 1$.

- The tip shape, annular bubble film thickness, δ_{AB} (Figure 4.1(b)), bubble length ratio, L_{TB}/L_{AB} for different $N_f = \rho\sqrt{gD^3}/\mu$ and eccentricities has also been investigated.

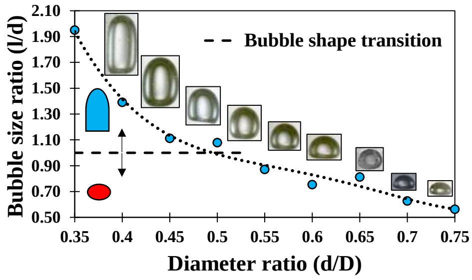
4.2 Flow pattern modulation by using a passive device:

The dynamics of a Taylor bubble bypassing a transverse circular insert in a viscous medium have been experimentally investigated in the present effort.

- The complete un-fragmented bypass (Figure 4.2(a)) is observed at lower insert to tube diameter ratio (d/D), whereas bypass through periodic pinch-off of daughters is identified as characteristic in case of larger blockage (d/D) in the flow path of the Taylor bubble.
- A competition between bubble bypass span, Δt_b and time required for pinch-off, Δt_p is proposed from analytical understanding for an explanation of both these contrasting bypass systems.
- Pinched-off bubbles are found to acquire a steady shape, which is quantified by its aspect ratio (a/b), faster as d/D increases. The pinch-off frequency initially increases up to d/D = 0.3 and eventually reduces above d/D = 0.35 due to the confinement of the bubble neck.
- The pinched-off bubble shape changes from the classical slug bubble (l/d>1) to cap-shaped bubble (l/d<1) at the diameter ratio, d/D ~ 0.5 (Figure 4.2(b)).
- The coalescence among the bubbles is observed for the cases in which the inter-slug distance, L_{IS} was smaller than wake length, L_W. The probability of coalescence among the bubbles was found to be maximum between d/D = 0.4 and 0.55.
- A scaling law for the temporal vanishing span of the longitudinal neck, $S_l \propto (t - t_0)^{0.55}$ has been proposed, which closely followed the experimental observations.



(a)



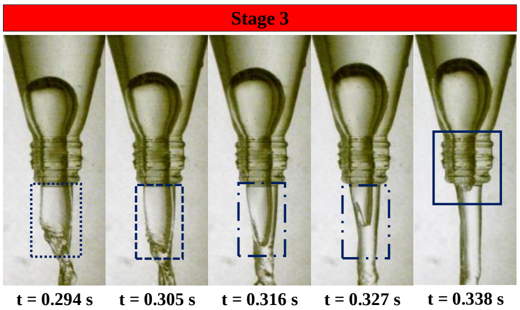
(b)

Fig. 4.2 (a) Unified bypass of the slug bubble across the perpendicular insert and (b) bubble size ratio after the pinch-off process.

4.3 Fluidic physics related to making and breaking of interface inside a bottle:

The bottle emptying process has been categorized into five different stages in order to quantify the complex emptying process (Figure 4.3(a)). The bubble nucleated from the bottle mouth during the bottle emptying process have been quantified in terms of voidage (ε), slug width (h_o), aspect ratio (a/b) and bubble pinch-off time (t_p).

- The bottle emptying time has been found to be reduced by two different mechanisms, i.e., by decreasing the size of each pinched-off bubble while increasing pinch-off frequency (Mode 1, water) and on the other hand by increasing the volume of each pinched-off bubble at a comparatively lower frequency (Mode 2, glycerol and silicon oil).
- A linear dependency has been deduced to establish a relationship of the bubble size and the velocity of the discharging fluid in terms of normalized Bond number and Froude number, which quantifies these two different emptying modes (Figure 4.3(b)).
- The asymptotic nature in the bottle emptying time and voidage, ε at the bottle mouth, is due to a change in the bottle emptying pattern from pure slugging to a stratified emptying pattern. Furthermore, a sudden reduction in the frontal radius of curvature, R_c near $\theta \sim 20^{\circ}$ provided concrete proof of the effect of inclination and the bottle geometry on the morphology of the bubble.



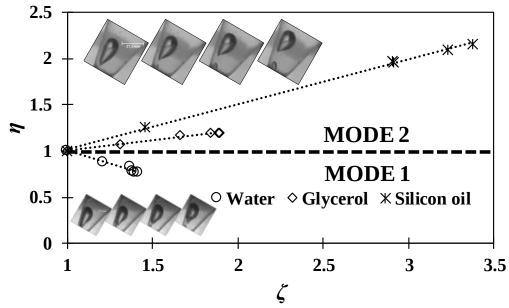


Fig. 4.3 (a) Bottle emptying stages in water having higher inverse viscosity number, $N_f = \rho\sqrt{gD^3}/\mu$ and (b) different modes of an emptying bottle plotted on non-dimensional Froude number, $\zeta = (Fr_f)/(Fr_f)_o$ and Bond number, $\eta = (Bo)/(Bo)_o$.

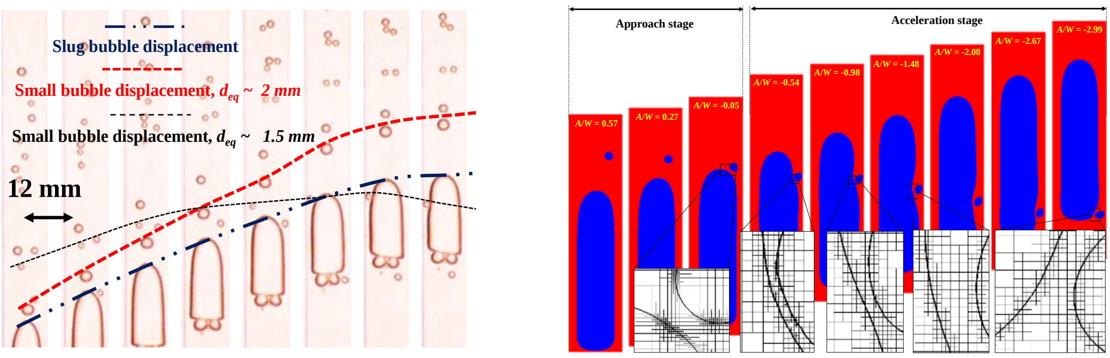
4.4 Modeling bubble slip phenomenon inside a rectangular column:

A combined experimental and numerical study has been performed to investigate the interaction of the small bubble and the slug bubble in a rectangular column with viscous fluids.

- The small bubble could either sprint away from the slug bubble or interact with the same as per their relative terminal velocity. The small bubble sprints away from the slug bubble at lower Morton numbers, $Mo = [(\rho_l - \rho_g)g\mu^4]/\rho_l^2\sigma^3$, in which case its terminal velocity is much higher as compared to that of the slug bubble (Sprint away regime; Figure 4.4(a)). However, the small bubble of the same size would interact with the slug bubble due to its lower terminal velocity (Bubble slip regime).
- A regime map based on the bubble size and the thermo-physical properties of the fluid has been proposed from the regime map differentiating bubble slip and sprint away regime. The small bubble maintains a constant terminal velocity ahead of the slug bubble nose and accelerates linearly into the annular film.
- The velocity field around the small bubble during bubble slip revealed the establishment of a continuous fluid channel in the entrapped film, which inhibits

coalescence. The entrapped film thickness initially reduces and becomes minimum but eventually thickens due to the gravitational feeding (Figure 4.4(b)).

- An ad-hoc pressure jump model revealed the cause of the repulsion of the slug bubble interface from the small bubble during the bubble acceleration stage. A modified lubrication model supported the hypothesis of the gravitational feeding of the entrapped film and experimental observations. The velocity at the interface of the small bubble and the slug bubble contributes to generate the pressure inside the entrapped film.



(a) (b)

Fig. 4.4 (a) Bubble sprint-off process at low $Mo = [(\rho_l - \rho_g)g\mu^4]/[\rho_l^2\sigma^3]$, and (b) bubble slip process of the small bubble in the annular film of the Taylor bubble by VOF simulation.

5. Organization of the thesis:

The present dissertation has been organized into five chapters. In the first chapter, a brief review of the different concepts related to the multiphase flows, thematic areas, and a specific literature review corresponding to the objective take in the dissertation have been presented.

Chapter 2 describes the fluidic physics behind the transformation of a slug bubble to an open annular one. Also, in this chapter, the concept of flow pattern modulation by using passive devices has been demonstrated in a stagnant viscous fluid. In the latter half, the effect of concentric and eccentric inserts on the interfacial evolution of the annular bubble has been studied experimentally.

Chapter 3 describes the interfacial dynamics during vessel emptying by changing the orientation of a commercial bottle and the thermophysical properties of the emptying fluid. Efforts have been made to establish a relation between the bubble pinch-off dynamics and its effect on bottle emptying time.

In Chapter 4, numerical and experimental efforts have been reported to understand the interaction between the small bubble and a slug bubble in a rectangular column. The phenomenon of a small bubble slip through the annular film of the Taylor bubble has been studied in this chapter. The observations have been described using a pressure jump model and a modified lubrication-based theory.

Finally, Chapter 5 summarizes all the observations made in the dissertation regarding gas-liquid flow involving the Taylor bubble. Further, the scope of future research on the current problems has also been highlighted.

List of publications in journals from dissertation work:

1. **Rohilla, L.** and Das, A.K., 2017. On transformation of a Taylor bubble to an asymmetric sectorial wrap in an-annuli. *Industrial & Engineering Chemistry Research*, *56*(48), pp.14384-14395. (Impact factor: 3.57).
2. **Rohilla, L.** and Das, A.K., 2018. Understanding of fluidic physics during bypass of a Taylor bubble around a transverse insert in a viscous medium. *Industrial & Engineering Chemistry Research*, *57*(40), pp.13539-13556. (Impact factor: 3.57).
3. **Rohilla, L.** and Das, A.K., 2019. Experimental study on the interfacial evolution of Taylor bubble at inception of an annulus. *Industrial & Engineering Chemistry Research*, *58*(6), pp.2356-2369. (Impact factor: 3.57).
4. **Rohilla, L.** and Das, A.K., 2020. Fluidics in an emptying bottle during breaking and making of interacting interfaces. *Physics of Fluids*, *32*(4), p.042102. (Impact factor: 3.514).
5. **Rohilla, L.** and Das, A.K., 2020. Modeling interaction between a Taylor bubble and small bubble in a rectangular column. *Physics of Fluids*, *32*(11), p.112106. (Impact factor: 3.514).

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