Proceeding of Global Summit and Expo on Fluid Dynamics & Aerodynamics

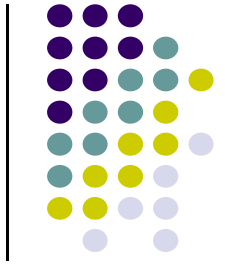
Numerical Study of Hydrodynamic Characteristics of Gas–Liquid Slug Flow in Vertical Pipe

Enass Massoud

- *PhD Student:*
  Department of Naval Architecture, Ocean and Marine Engineering (NAOME), University of Strathclyde, Glasgow, United Kingdom.
- *Teaching Assistant:*
  Mechanical Engineering Department, Arab Academy for Science, Technology & Maritime Transport (AASTMT), Alexandria, Egypt.
- enass-zakaria-shafik-massoud@strath.ac.uk

August 2016

Presentation Overview



1. Introduction.
2. Aim of the study.
3. Model development;
    a) Governing equations.
    b) Model geometry and boundary conditions.
    c) Solution strategy and convergence criterion.
4. Results and discussions;
    a) Taylor bubble shape.
    b) Taylor bubble rise velocity.
    c) Liquid film.
    d) Wake flow structure.
    e) Wall shear stress distribution.
5. Conclusions.
6. Recommendations for future work.

1. Introduction

a. What is Multiphase Flow?

- A multiphase flow is defined as any fluid system in which there is interaction between two or more phases (gas, solid and liquid) where the interface between the phases is influenced by their motion.

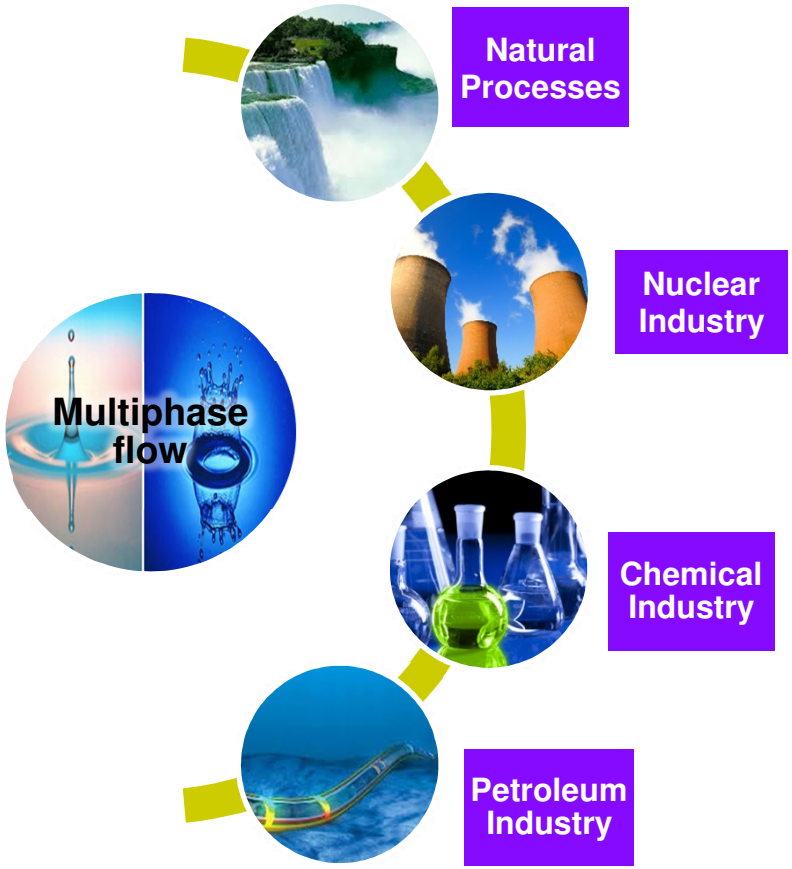


1=http://goo.gl/a69rhf, 2=http://goo.gl/F82TK5, 3=http://goo.gl/rSphqM,
4 =http://goo.gl/I14xlI, 5=http://goo.gl/JJqOD3,6=http://goo.gl/O5uc2X

1. Introduction

a. What is Multiphase Flow?

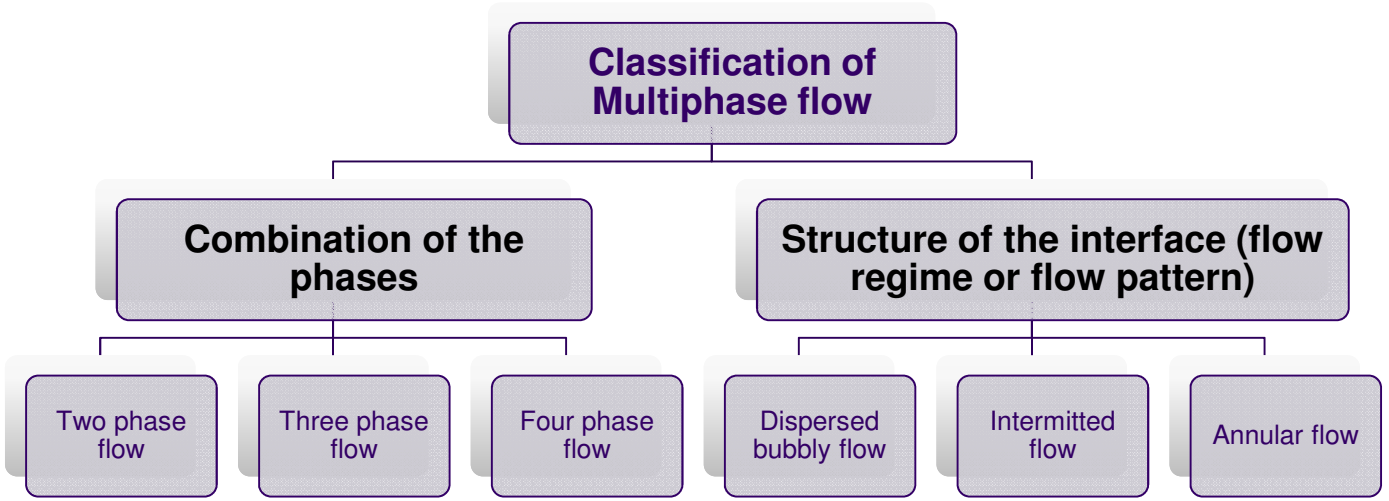
- The multiphase flow is involved in natural, technologically processes and industrial applications including nuclear, chemical and petroleum industries.



1. Introduction

b. Classifications of Multiphase Flow?

- Multiphase flow can be classified according to;



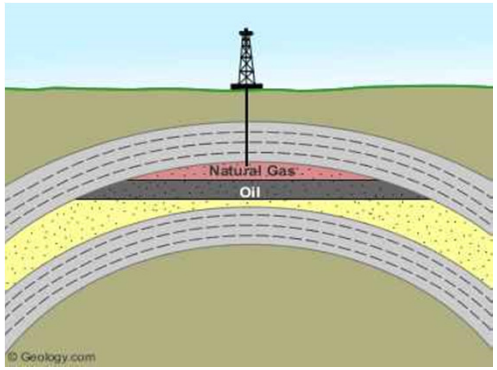
1. Introduction

b. Classifications of Multiphase Flow?

1) Two Phase Flow

Gas-liquid flows:

- It is found widely in a whole range of industrial applications;
  - ***Pipeline systems for the transport of oil-gas mixtures***,
  - Evaporators,
  - Boilers,
  - Condensers,



Liquid-liquid flows:

- ***Flow of oil-water mixtures in pipelines.***

Liquid-solid flows:

- Liquid-solid suspensions in; crystallization systems, food-mineral transportation, oil processing and nuclear waste management.

1. Introduction

b. Classifications of Multiphase Flow?

1) Two Phase Flow

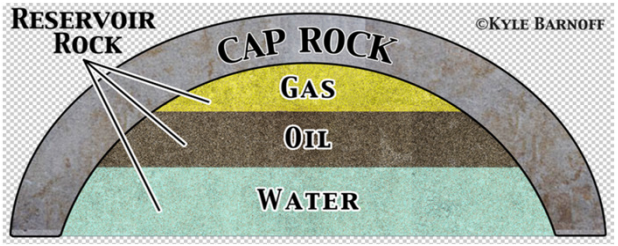
Gas-solid flows:

- Flows of solids suspended in gases are important in;
  - Pulverized fuel combustion,
  - Fluidized beds.

2) Three Phase Flow

Gas-liquid-liquid flows:

- ***Gas-oil-water flows in oil recovery systems.***



Gas-liquid-solid flows:

- Two Phase Fluidized bed.

Solid-liquid-liquid flows:

- Presence of sand or solid particles in ***oil-water mixtures in pipelines.***

1. Introduction

b. Classifications of Multiphase Flow?

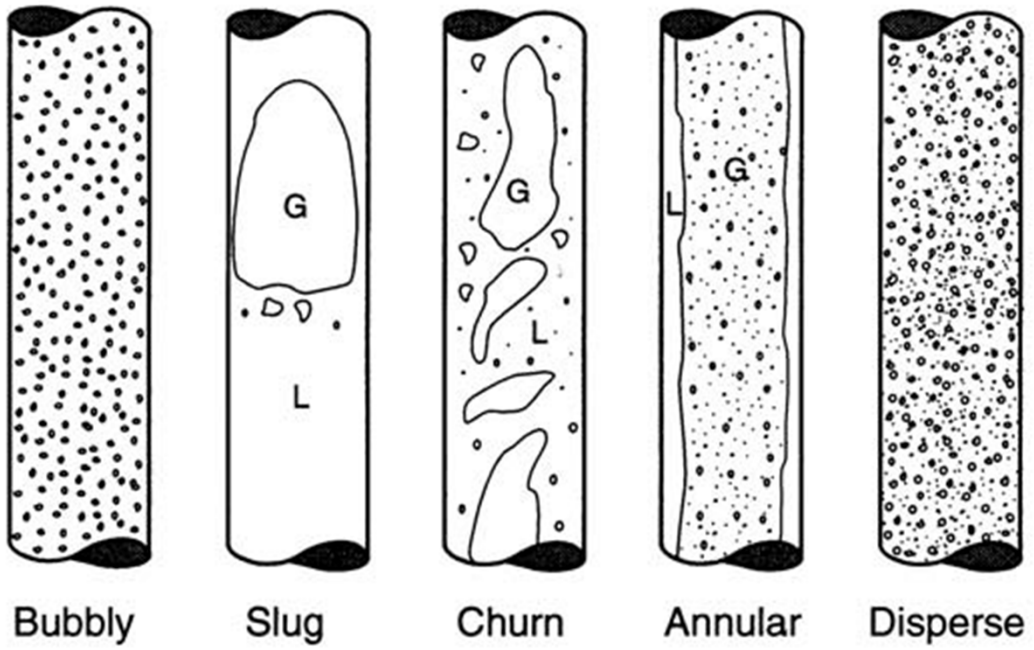
3) Four Phase Flow

- The three phase flow is often encountered as a mixture of gas, oil and water.
- The presence of sand or other particle may result into four phase flow (G-L-L-S).

1. Introduction

b. Classifications of Multiphase Flow?

Gas-Liquid flow regimes in vertical pipes

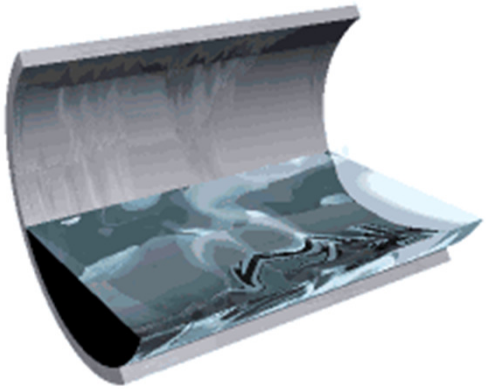


Sketches of flow regimes for two-phase flow in a vertical pipe

Weisman (1983)

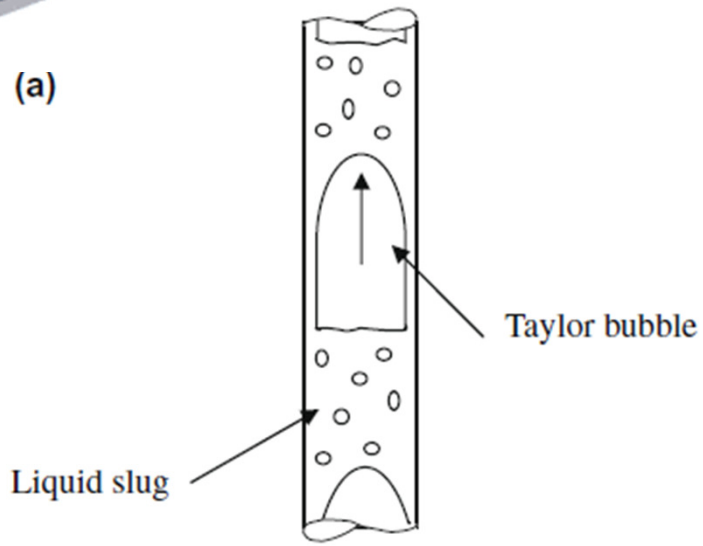
1. Introduction

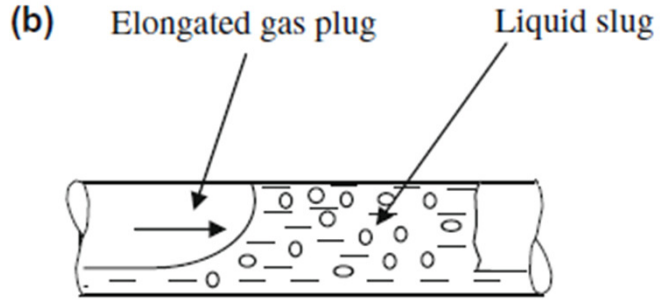
c. Slug Flow



- A slug unit cell (fundamental unit) consists of an elongated bullet shaped bubbles that fills almost the entire pipeline cross section, known as Taylor Bubble, a liquid film flowing downwards between the bubble interface and pipe wall, known as liquid slug.

- The body of the slug is liquid. But in cases of high gas flow rates, some gases diffuse into the liquid slug and is referred to as Aerated Slug.



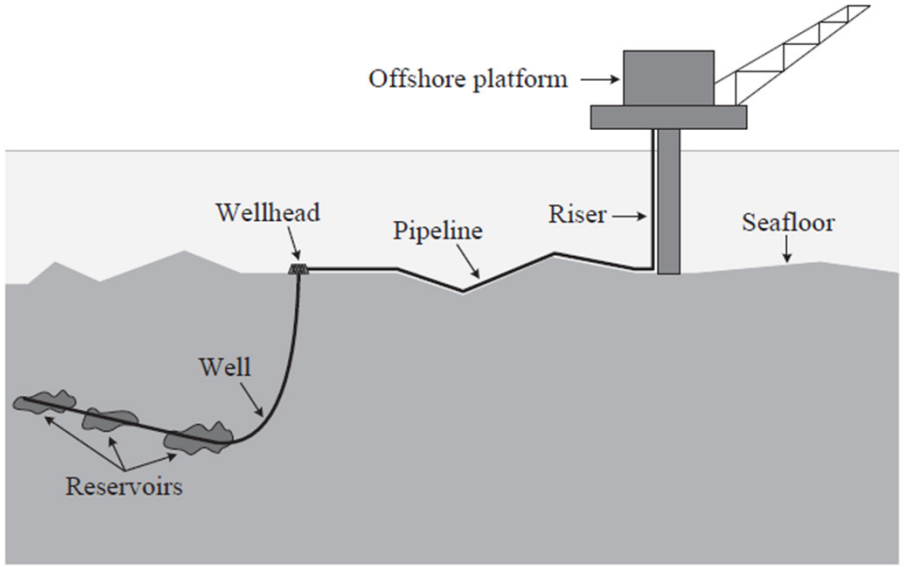


Mandal et al. (2010)

1. Introduction

c. Slug Flow

- Severe slugging may appear for low gas and liquid flow rates when a section with downward inclination angle (pipeline) is followed by another section with an upward inclination (riser). This configuration is common in offshore petroleum production systems.

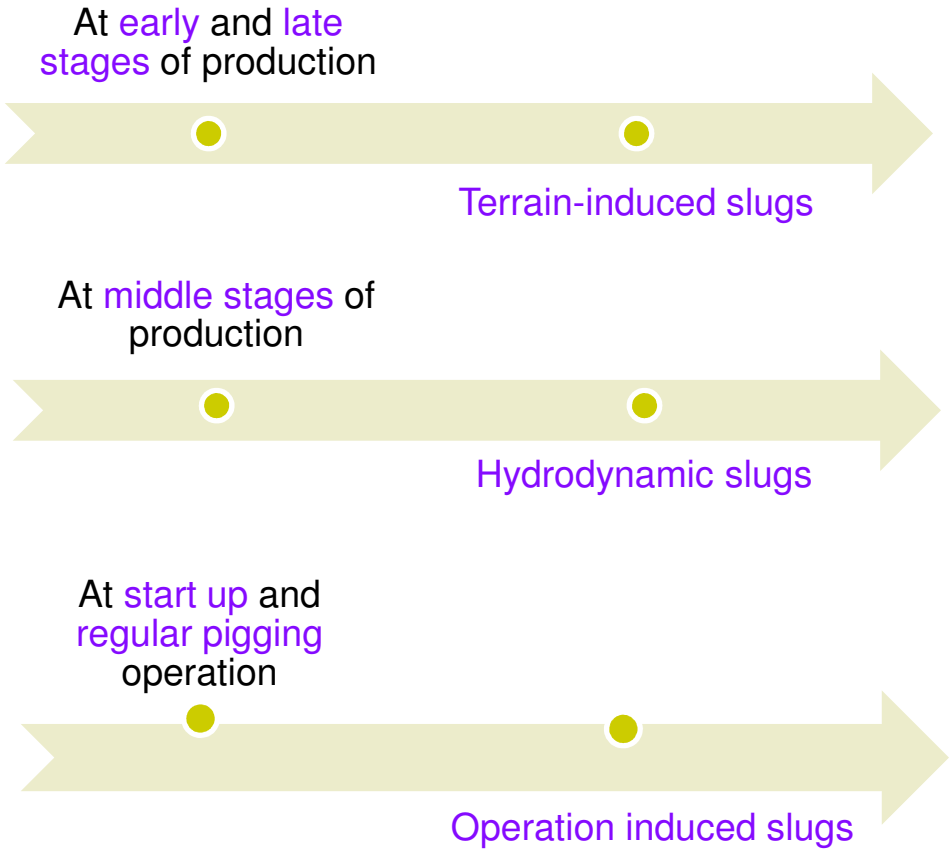


Malekzadeh, R. (2012)

1. Introduction

c. Slug Flow

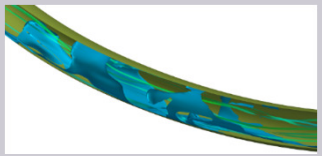
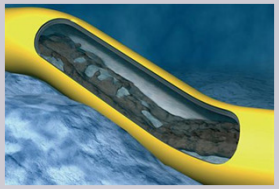
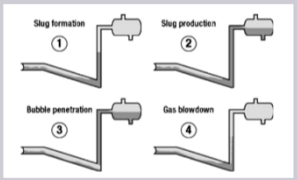
- According to Xing et al. (2014), the liquid slugs generated in the Oil and Gas multiphase flowlines can be classified based on their *initiation mechanism* into;



1. Introduction

c. Slug Flow

Causes

Hydrodynamic Slugging	Terrain-Induced Slugging	Riser-Based Slugging	Operation-Induced Slugging
			
http://petronet-resources.co.uk.websitebuilder.prositehosting.co.uk/ascomp	https://www.software.slb.com/products/olga/olga-pipeline-management/slug-tracking	Mokhatab, S., & Towler, B. F. (2007).	http://www.pipelinebundle.com/ser_pigging.htm

Effects

Higher pressure drop for flow	Could cause platform trips and plant shutdown	Reduces capacity of separation and compression units	Enhance corrosion, erosion and fatigue in pipelines

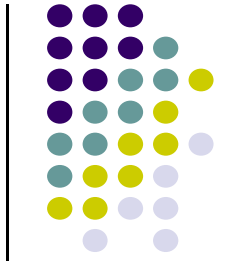
5. Slug Flow in Subsea Oil & Gas Production System



v. Slug flow problems-Why model slug flow?

- Flooding of downstream processing facilities.
- Reservoir flow oscillations and poor management.
- Severe pipe corrosion and structural instability of pipeline.
- The slug induces unsteady loading on pipeline and also on the receiving devices, such as separators. This causes design problems and hence lower the system efficiency and size.
- Instabilities in liquid control system of separators due to high sudden flow rates which may lead to complete shut down.
- Production loss due to the slug induced high average back pressure.

Presentation Overview



1. Introduction.
2. **Aim of the study.**
3. Model development;
    a) Governing equations.
    b) Model geometry and boundary conditions.
    c) Solution strategy and convergence criterion.
4. Results and discussions;
    a) Taylor bubble shape.
    b) Taylor bubble rise velocity.
    c) Liquid film.
    d) Wake flow structure.
    e) Wall shear stress distribution.
5. Conclusions.
6. Recommendations for future work.

2. Aim of the study

- A dimensionless analysis for two-phase gas-liquid vertical slug flow can be covered by applying Pi Buckingham theorem.
- The hydrodynamic characteristics of the slug flow can be governed by the main forces, namely, viscous, inertial, and interfacial forces.
- Eötvös number: the ratio between gravitational forces, and surface tension forces.

$$Eo = \rho_L * g * D^2/\sigma$$

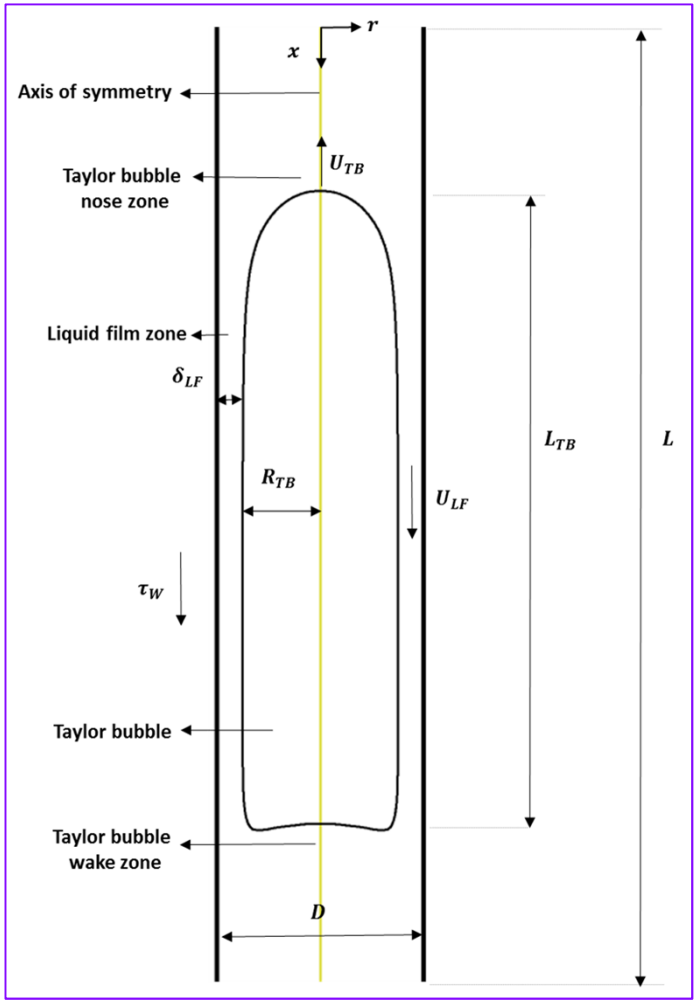
- Froude number: the ratio between the inertia and gravitational forces

$$Fr_{TB} = U_{TB}/\sqrt{g * D}$$

- Inverse viscosity number: the ratio between Eötvös number and Morton number

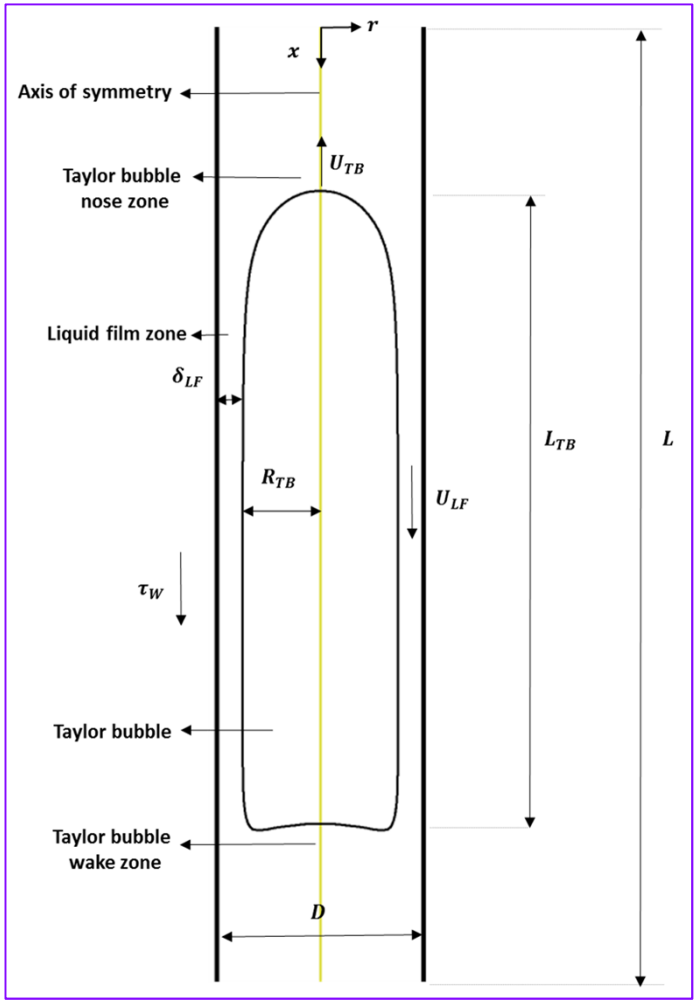
$$M = g\,{\mu_L}^4(\rho_L - \rho_G)/{\rho_L}^2\,\sigma^3$$

$$N_f = \rho_L * (g * D^3)^{0.5}/\mu_L$$

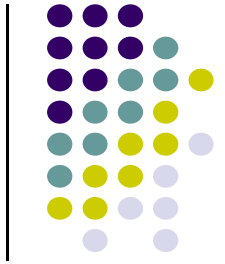


2. Aim of the study

- The main aim of the present investigation is to study the hydrodynamics characteristics of single Taylor bubble rising in a stagnant Newtonian liquid using the volume-of-fluid (VOF) methodology implemented in the computational dynamic software package, ANSYS Fluent (Release 15.0).
- The results accounts for; Taylor bubble shape, Taylor bubble rise velocity (U_{TB}), liquid film (U_{LF}, δ_{LF}), wake flow structure, and wall shear stress distribution (τ_W).
- The simulation has been performed for 2D, unsteady, laminar flow with constant fluid properties.
- The two phases were assumed as incompressible, viscous, immiscible, and not penetrating each other.



Presentation Overview

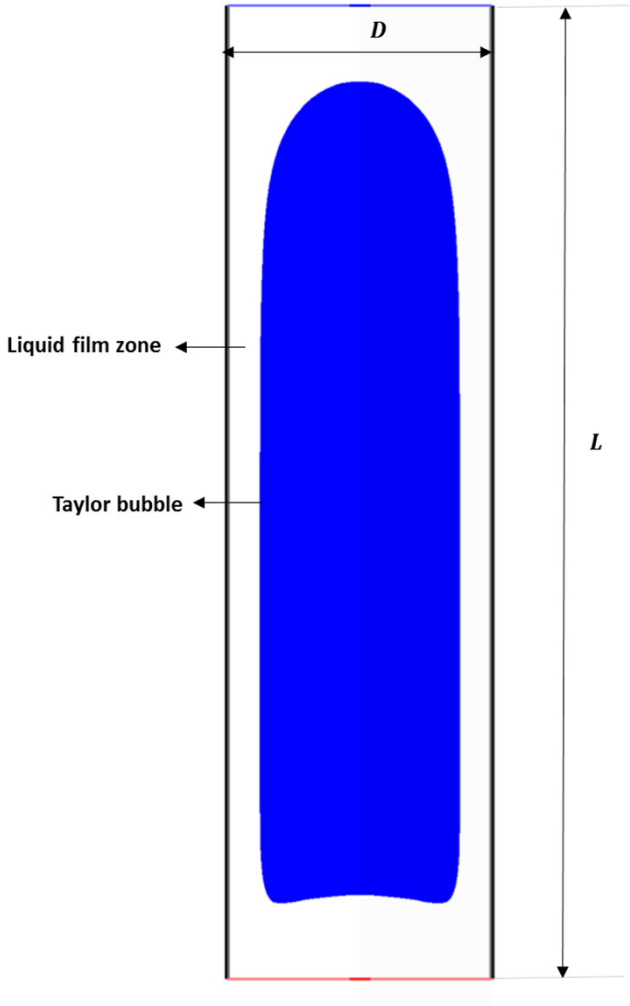


1. Introduction.
2. Aim of the study
3. **Model development;**
   a) Governing equations.
   b) Model geometry and boundary conditions.
   c) Solution strategy and convergence criterion.
4. Results and discussions;
   a) Taylor bubble shape.
   b) Taylor bubble rise velocity.
   c) Liquid film.
   d) Wake flow structure.
   e) Wall shear stress distribution.
5. Conclusions.
6. Recommendations for future work.

3. Model Development

a. Governing Equations

- The simulation domain is a vertical pipe of diameter, D, and length, L.
- The flow consists of single Taylor bubble rising in stagnant fluid.
- The volume-of-fluid (VOF) method is used to track/capture the sharp interfaces between two immiscible fluids (free surface flow).
- This model solves a single set of Naiver Stokes equations (NSE) that is shared by the two fluids, and the volume fraction of each of the fluids in each computational cell throughout the domain.



3. Model Development

a. Governing Equations

1. Reynolds Average Continuity Equation

$$\frac{\partial \boldsymbol{\rho}}{\partial t} + \nabla.(\boldsymbol{\rho} U) = \sum_{q=1}^{n} S_q$$

- ρ : volume-fraction-averaged density
- U : time average velocity which is computed by solving the momentum equation for the mixture (not individual components).
- n : number of the phases (for the present two phase flow, n=2).
- S_q : mass source (set to zero in the present case)

2. Reynolds Average Momentum Equation

$$\frac{\partial (\boldsymbol{\rho} U)}{\partial t} + \nabla.(\boldsymbol{\rho} UU) = -\nabla P + \nabla.[\boldsymbol{\mu}(\nabla U + \nabla U^T)] + (\boldsymbol{\rho} g) + F$$

- P: pressure in the domain,
- μ : volume-fraction-averaged viscosity of the flowing fluid,
- g : acceleration due to gravity,
- F : body force.

3. Model Development

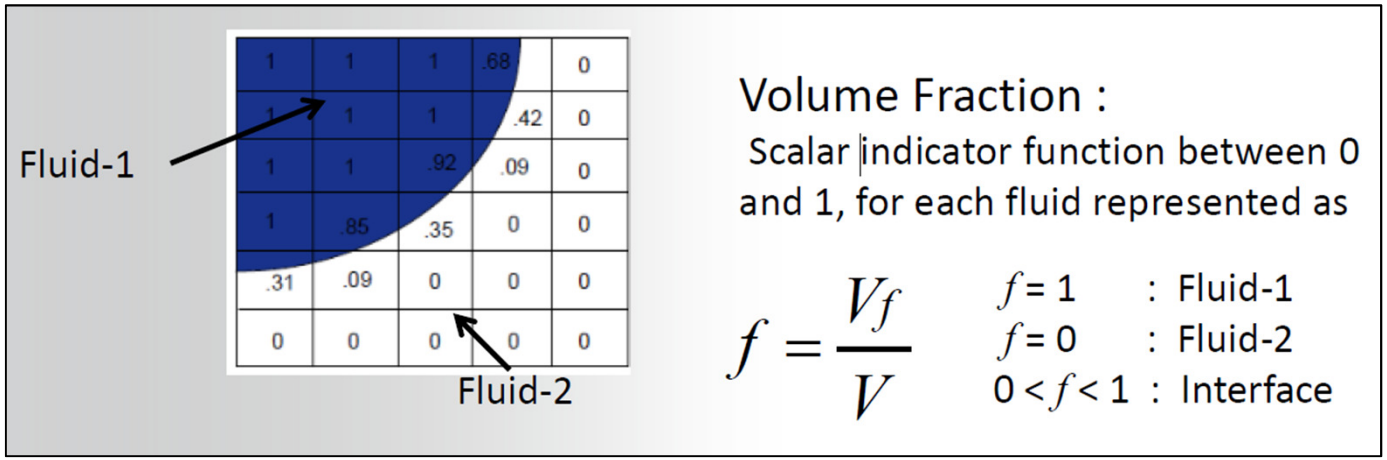
A. Governing Equations

- The NSE's are unaltered. The fact that two or more fluids (or phases) are present is accounted for by the introduction of additional scalar variables: the volume fraction averaged properties

$$\boldsymbol{\rho} = \sum_{q=1}^{n} \rho_q \alpha_q = \alpha_L \rho_L + \alpha_G \rho_G = \alpha_L \rho_L + (1 - \alpha_L)\rho_G$$

$$\boldsymbol{\mu} = \sum_{q=1}^{n} \mu_q \alpha_q = \alpha_L \mu_L + \alpha_G \mu_G = \alpha_L \mu_L + (1 - \alpha_L)\mu_G$$

In a control volume, the volume



3. Model Development

a. Governing Equations

3. Volume fraction equation

- Tracking the interface between the two phases is achieved by the treatment of the volume fraction of the q^{th} fluid, α_q through solving a separate continuity equation, given by;

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q\rho_q) + \nabla.(\alpha_q\rho_q U_q)\right] = S_{\alpha q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})$$

  - $S_{\alpha q}$: mass source term,
  - $\dot{m}_{pq}$: mass transfer from phase p to phase q,
  - $\dot{m}_{qp}$: mass transfer from phase q to phase p.

3. Model Development

b. Model Geometry and Boundary Conditions

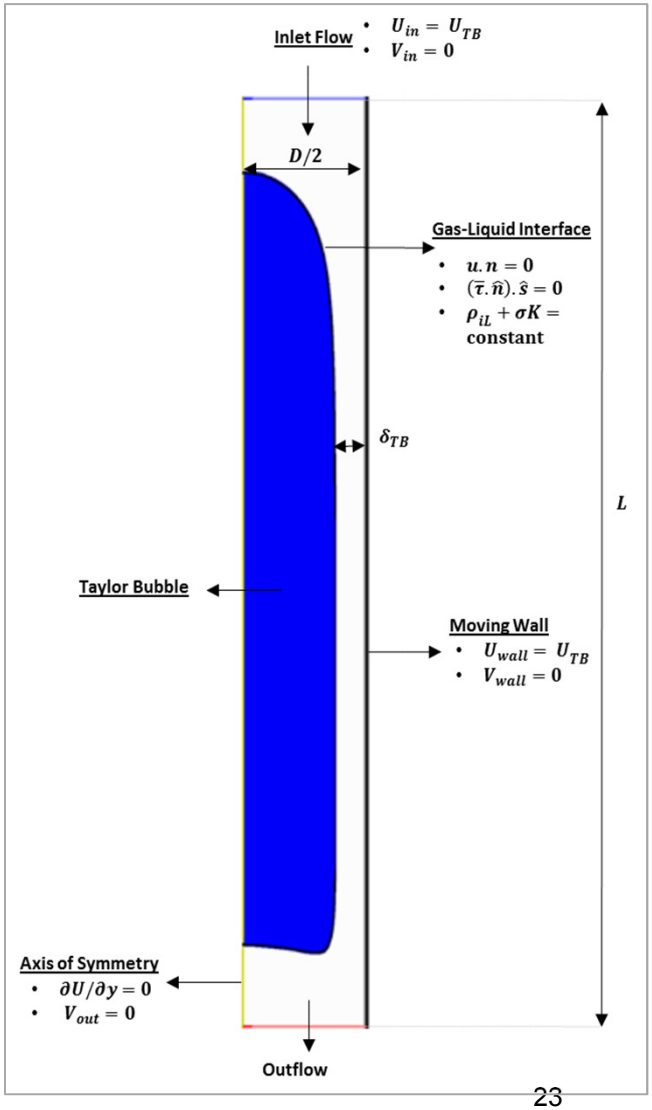
- The initial guess of Taylor bubble velocity, U_{TB}, is estimated according to Wallis (1969) correlation;

$$Fr = \frac{U_{TB}}{\sqrt{g * D}} = 0.345 \left(1 - e^{\frac{-0.01 N_f}{0.345}}\right)\left(1 - e^{\frac{3.37 - Eo}{m}}\right)$$

where;

$$m = \begin{cases} 25, & N_f < 18 \\ 69 N_f^{-0.35}, & 18 < N_f < 250 \\ 10, & N_f > 250 \end{cases}$$

- The simulation is performed by



velocity equal to that of the bubble.

- The initial guess of the liquid film thickness,δ_{LF}, is estimated using Brown (1965) equation;

$$\delta_{LF} = \left[\frac{3 * \nu}{2 * g * (R - \delta_{LF})} * U_{TB} * (R - \delta_{LF})^2\right]^{1/3}$$

FRF and MRF

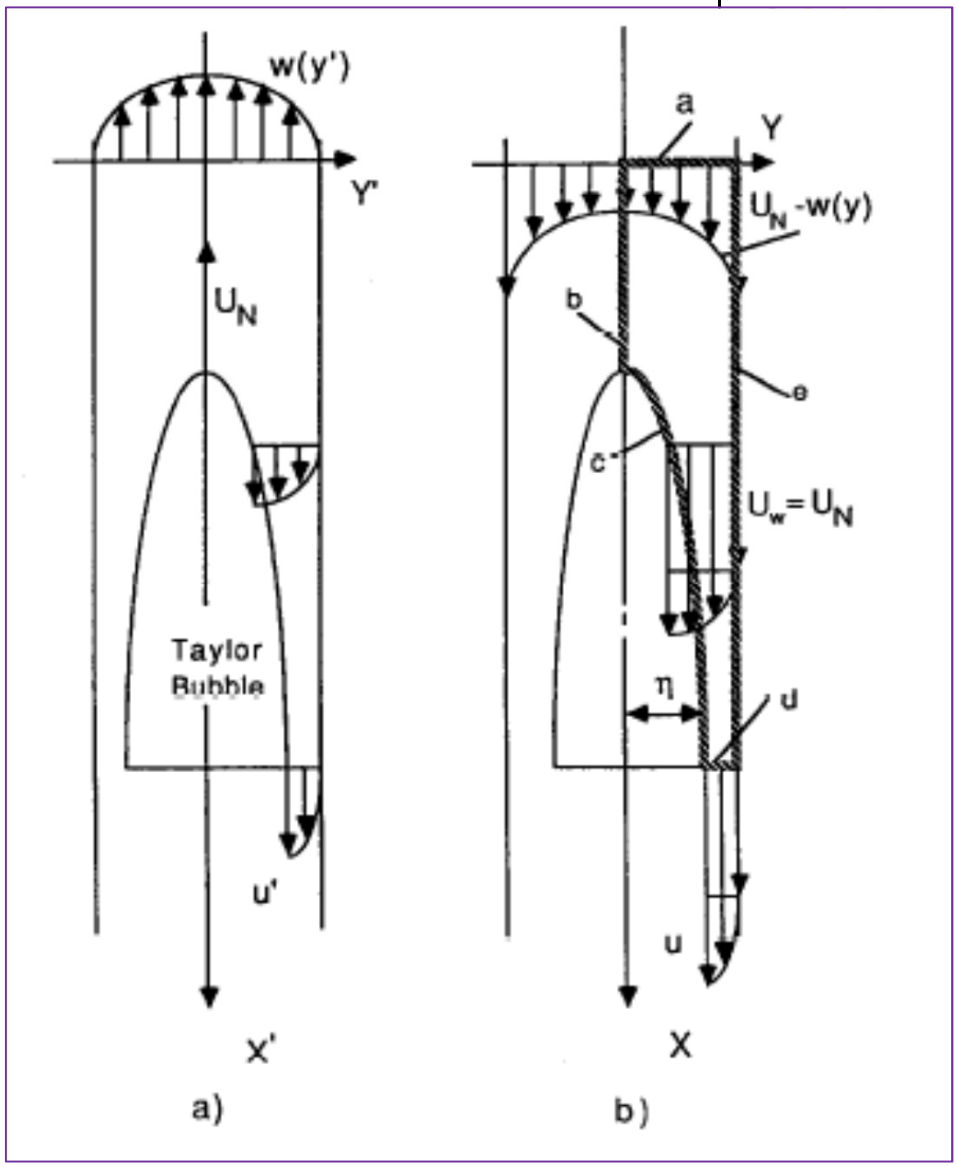
- Consider single TB rising up with velocity, U_N, relative to the stationary walls. The transformation coordinate from FRF to MRF are;

$$x = \grave{x} - U_N t$$

$$y = \grave{y}$$

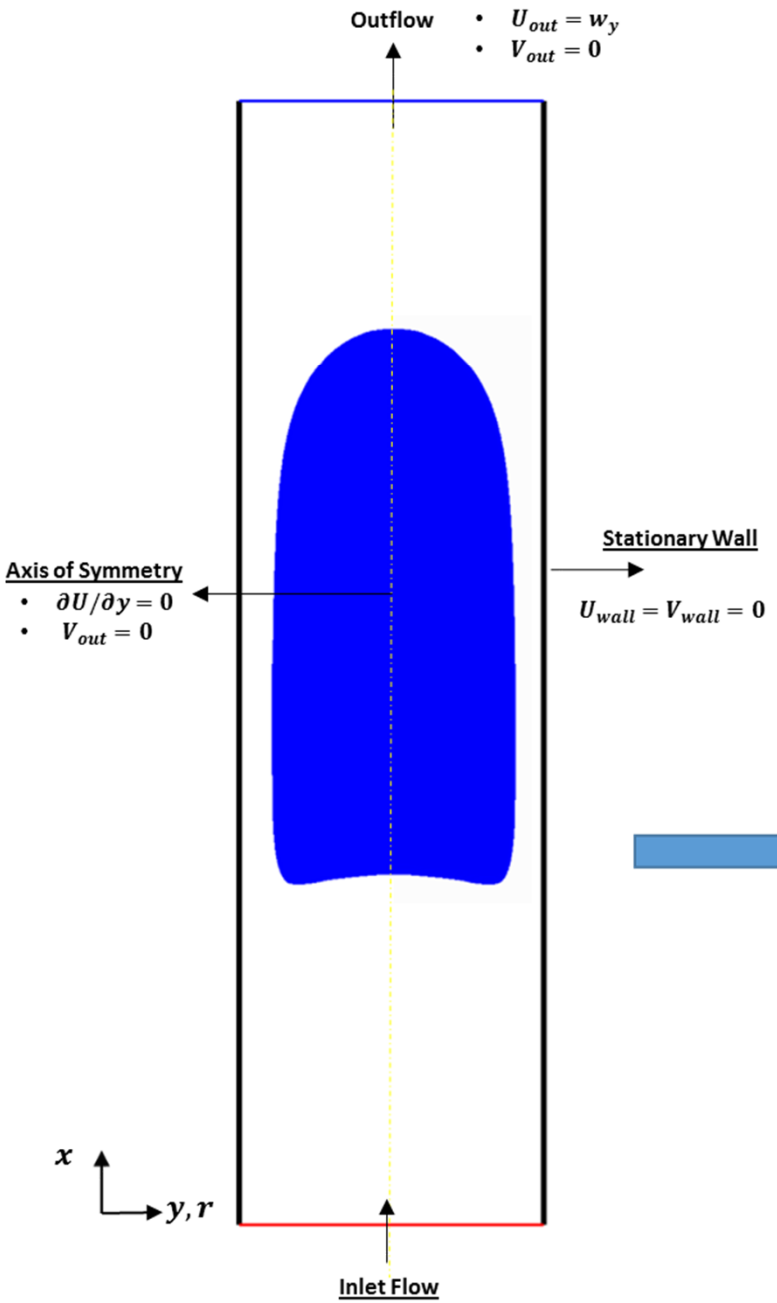
- The TB becomes stationary if a new velocity variable, u , is assigned as follow;

$$u = \grave{u} + U_N$$

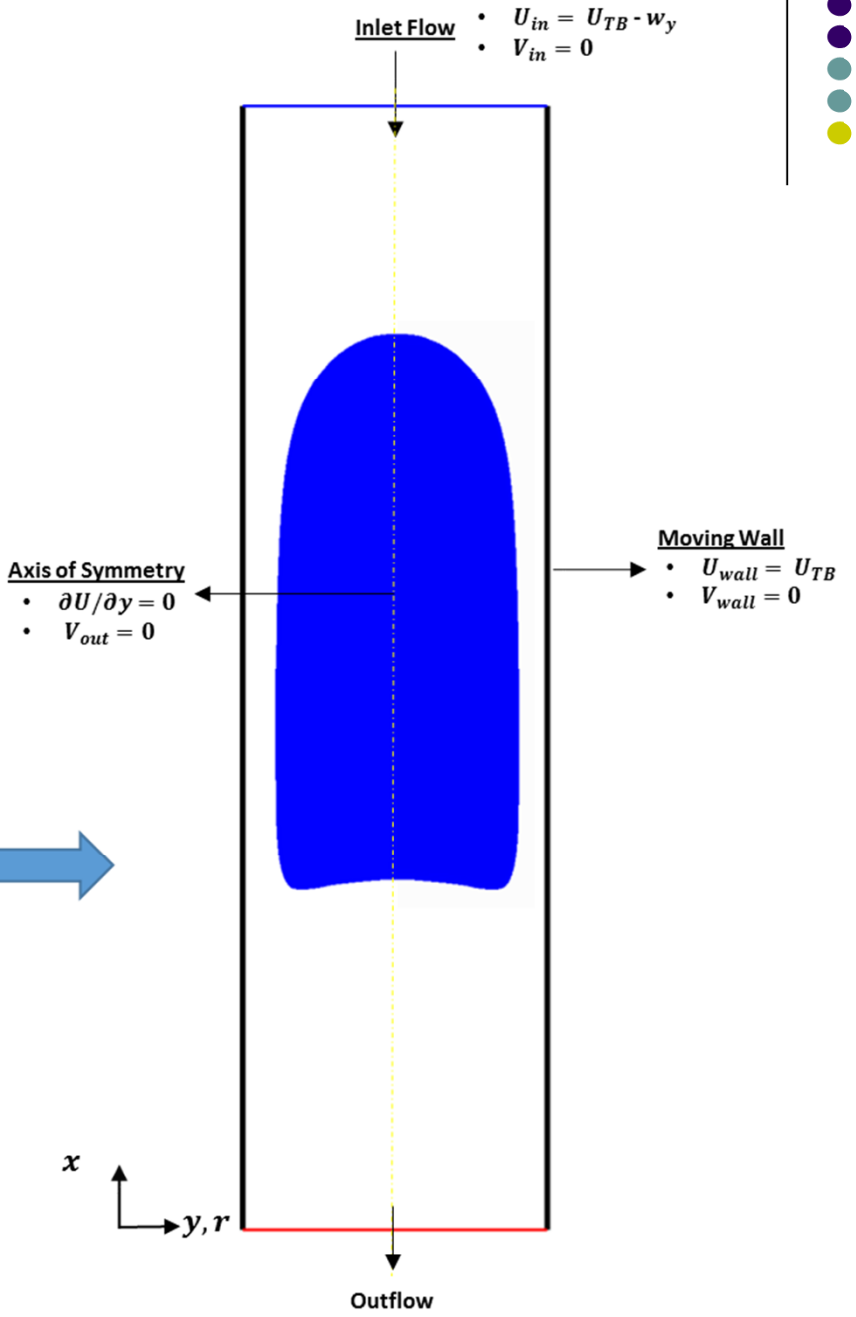


Mao and Dukler (1990)

Fixed Reference Frame (FRF)



Moving Reference Frame (MRF)



G-L Interface BC

- The pressure variation in the gas phase is assumed to be constant.
- The boundary conditions at the gas-liquid interface are given by;

1. The kinematic condition,
   b) The normal stress balance assuming full slip at the interface is applied;

$$\rho_{iL} + \sigma K = constant$$

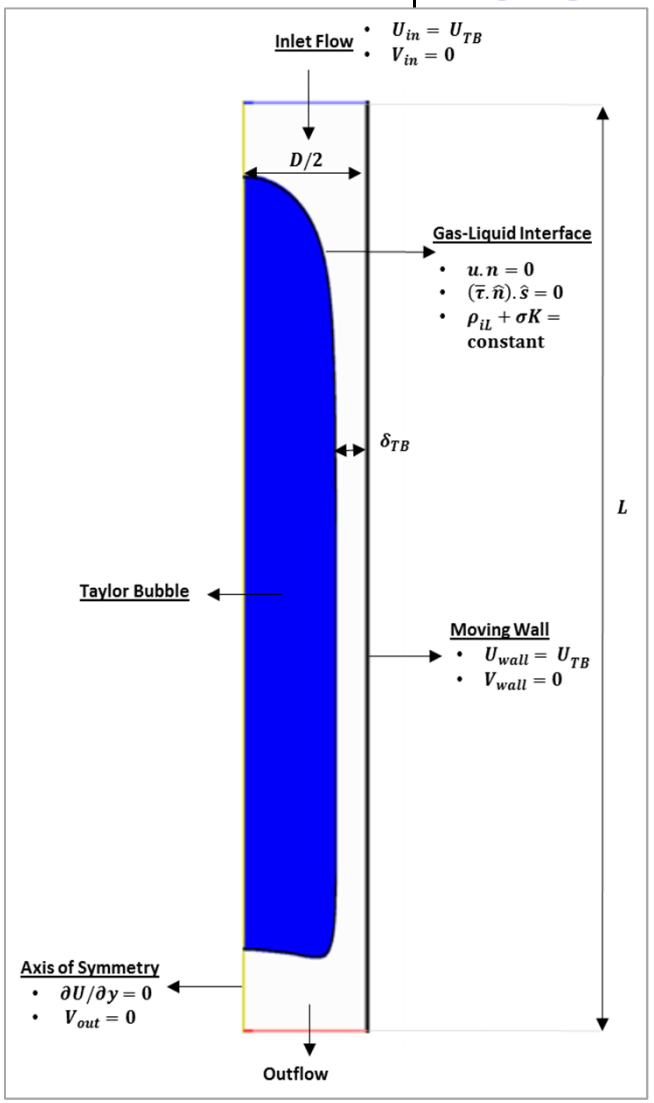
$$u.n = 0$$

Where; τ, $\hat{n}$, $\hat{s}$, σ, ρiL and K are the shear stress, unit normal vector at the interface, unit tangential vector at the interface, surface tension, liquid phase side pressure, and curvature of the interface, respectively.

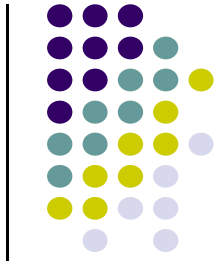
2. The dynamic boundary condition, which is also known by stress jump condition can be divided into two separate boundary conditions;

- According to Mao and Dukler (1990) the
  a) the tangential stress balance assuming zero interfacial shear stress along the interface,
  curvature of the interface is expressed in terms of radii of the curvature of the bubble surface, as follows;

$$K = \frac{1}{r1} + \frac{1}{r2}$$



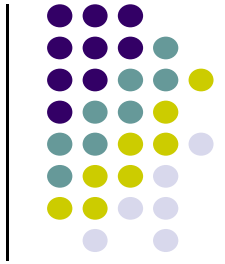
3. Model Development



c. Solution Strategy and Convergence Criterion

1. Transient solver and a time step size of 0.0001s was employed.
2. The simulation was carried out using the explicit VOF model.
3. A simple scheme for the pressure-velocity coupling is considered.
4. A spatial discretization scheme used are as follows;
   - Green Gauss Cell Based for Gradient.
   - PRESTO for Pressure.
   - Compressive for Volume fraction.
   - Quick scheme for Momentum.
   - First order implicit for transient formulation
5. The scaled absolute values of the residual of the calculated values of mass, velocity in x and y directions were monitored and convergence criterion was set to 10^{-3} for each time step.
6. Results were obtained using the Engineering and Physical Sciences Research Council (EPSRC) funded ARCHIE-WeSt high performance computer (www.archie-west.ac.uk).

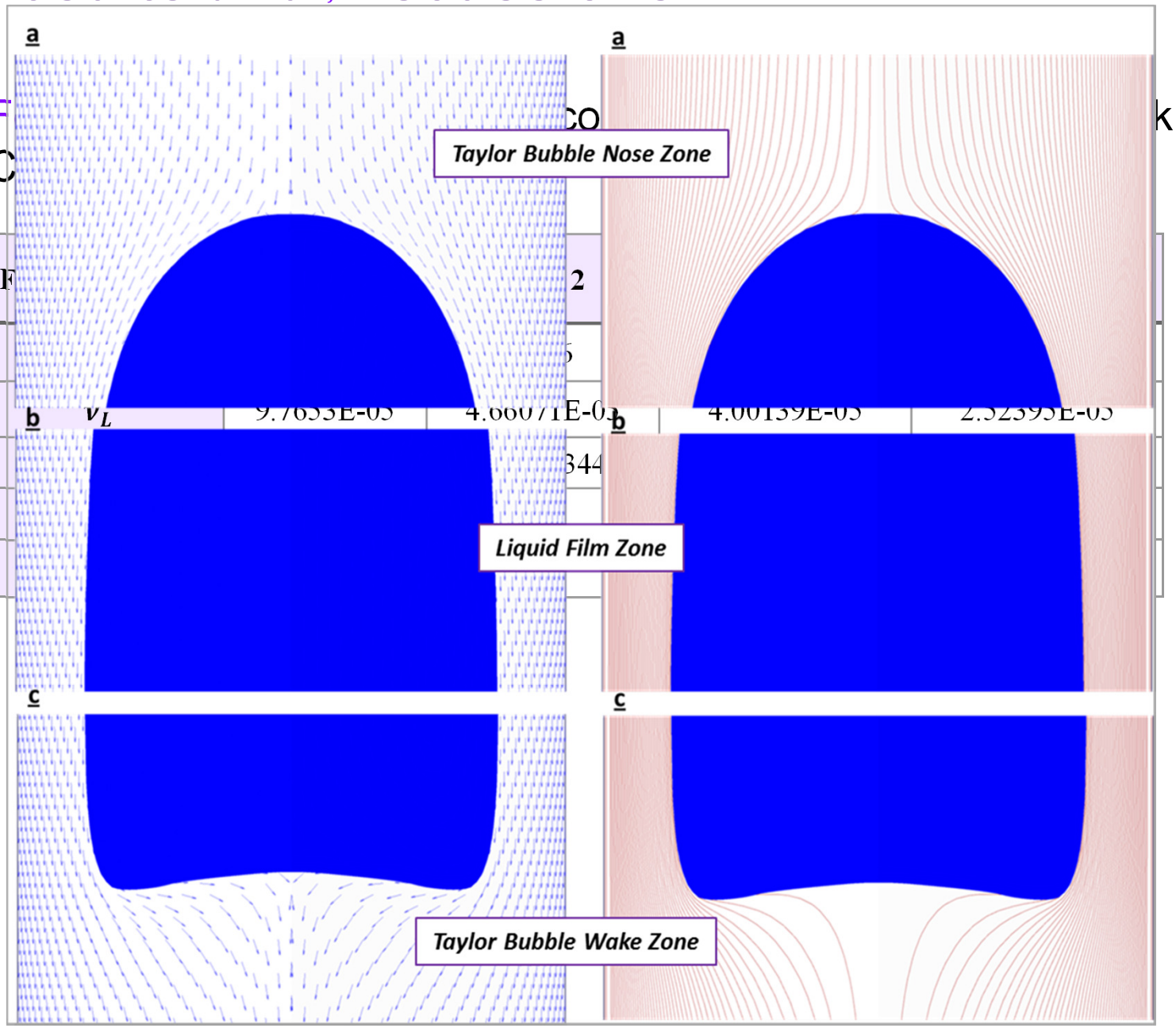
Presentation Overview



1. Introduction.
2. Aim of the study.
3. Model development;
   a) Governing equations.
   b) Model geometry and boundary conditions.
   c) Solution strategy and convergence criterion.
4. **Results and discussions**;
   a) Taylor bubble shape.
   b) Taylor bubble rise velocity.
   c) Liquid film.
   d) Wake flow structure.
   e) Wall shear stress distribution.
5. Conclusions.
6. Recommendations for future work.

4. Results and Discussions

Velocity fields and streamlines of gas-liquid slug flow in vertical pipe of 19mm diameter, and 209 mm length, N_f=84, Ar_f=6.289, and Re_f=66.3 using MRF

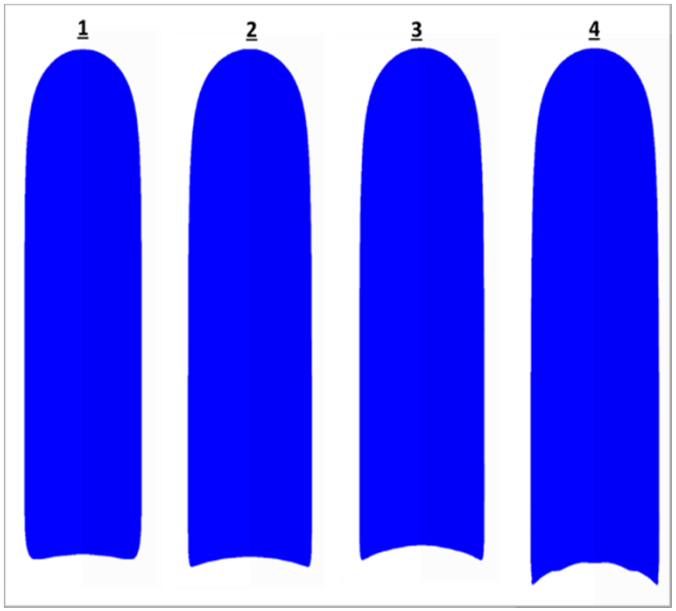


4. Results and Discussions

a. Taylor Bubble Shape

- Effect of inverse viscosity number N_f on Taylor bubble shape.
- The simulated results are in good agreement with;

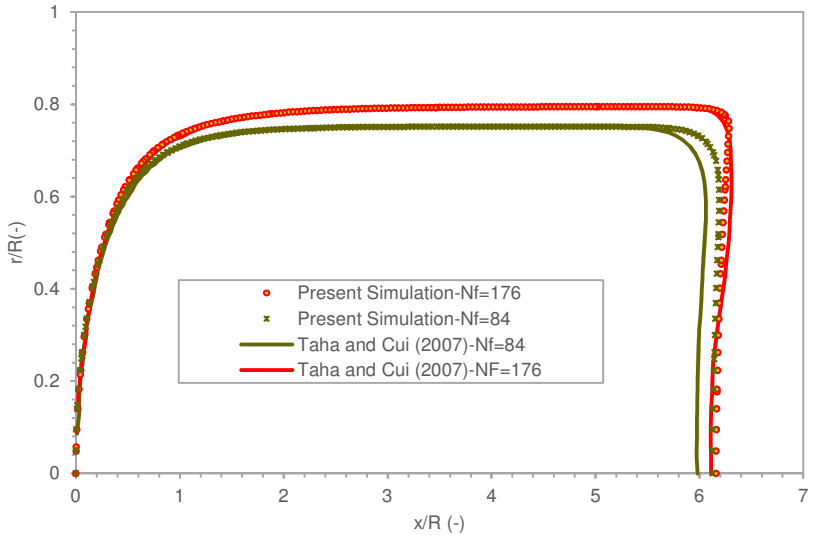
1. the experimental observations of Goldsmith and Mason (1962); in highly viscous flow (viscosity dominated flow) the Taylor bubble has spheroid shape where the top end of bubble is prolate, and the bottom end is oblate. While, in low viscosity flow the flattening or concaving shape of Taylor bubble bottom end is observed.
2. the numerical work of Araújo et al. (2012), Taha and Cui (2006), and Zheng et al. (2007).



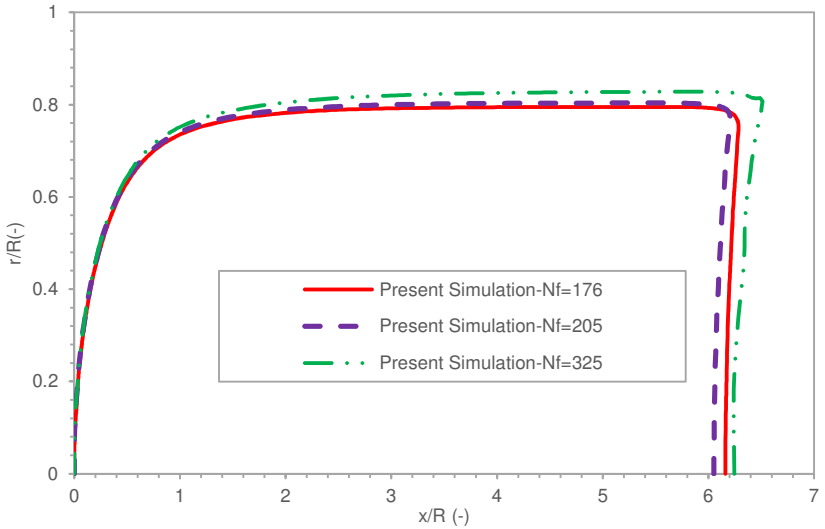
(1) N_f=84, (2) N_f=176, (3) N_f=205, and (4) N_f=325

4. Results and Discussions

a. Taylor Bubble Shape



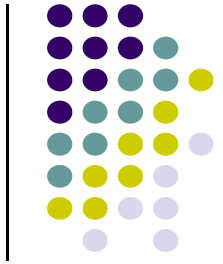
Validation of simulation results for Taylor bubble shape profile for cases 1, and 2 with the work of Taha and Cui (2006) - x is axial distance from bubble nose.



Effect of $\mathbf{N_f}$ on Taylor bubble shape profile for cases 2, 3 and 4 - x is axial distance from bubble nose.

4. Results and Discussions

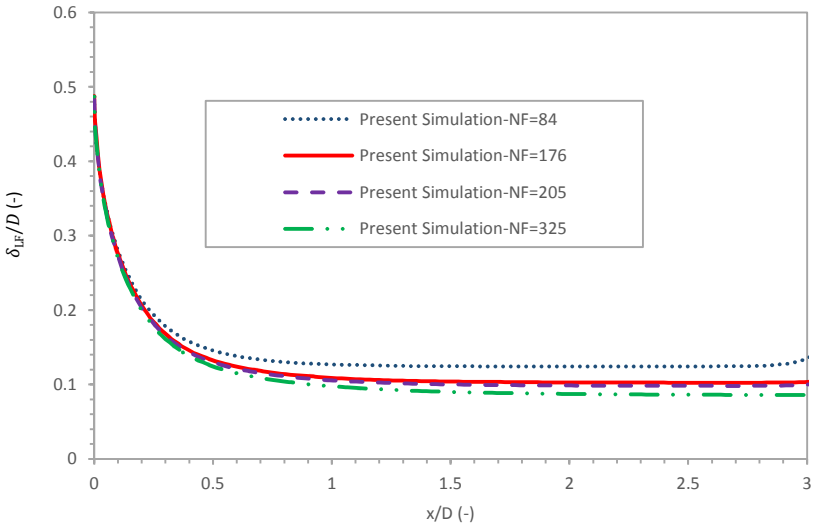
b. Taylor Bubble Rise Velocity, U_{TB}



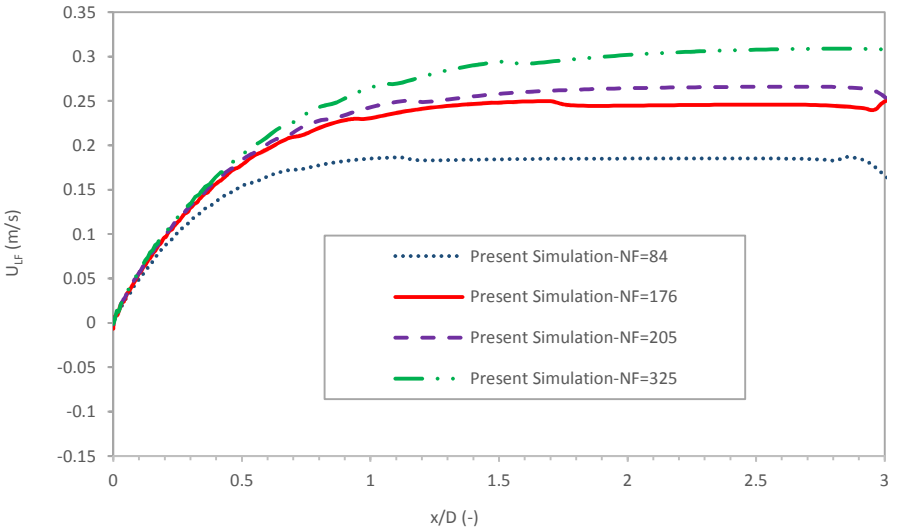
Cases	Simulation	White and Beardmore (1961)	Wallis Correlation (1969)
Case 1			
U_{TB}	0.1251	0.1381	0.1340
Error (%)	…	9.41	6.62
Case 2			
U_{TB}	0.1374	0.1467	0.1473
Error (%)	…	6.35	6.71
Case 3			
U_{TB}	0.1390	0.1467	0.1480
Error (%)	…	5.24	6.02
Case 4			
U_{TB}	0.1425	0.1424	0.1485
Error (%)	…	-0.07	4.0

4. Results and Discussions

c. Liquid Film



Effect of N_f on liquid film thickness δ_{LF} - x is axial distance from bubble nose.

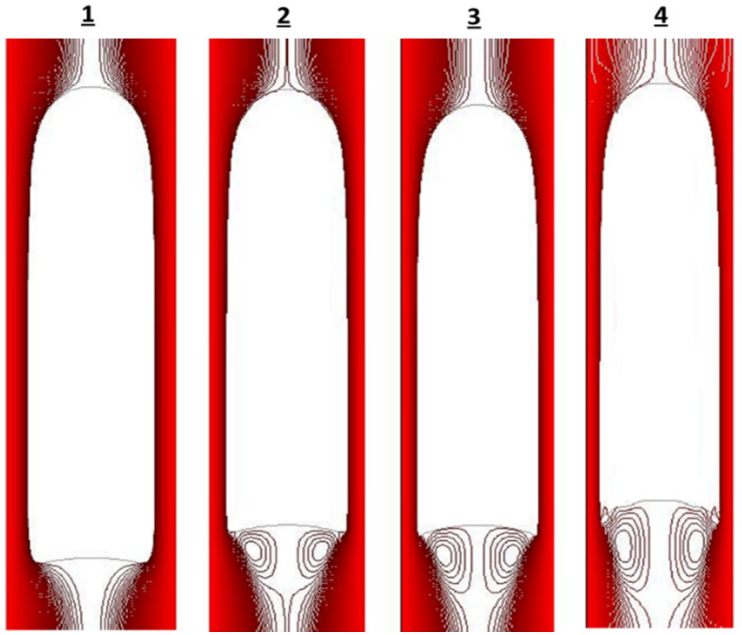


Effect of N_f on liquid film axial velocity U_{LF} - x is axial distance from bubble nose.

4. Results and Discussions

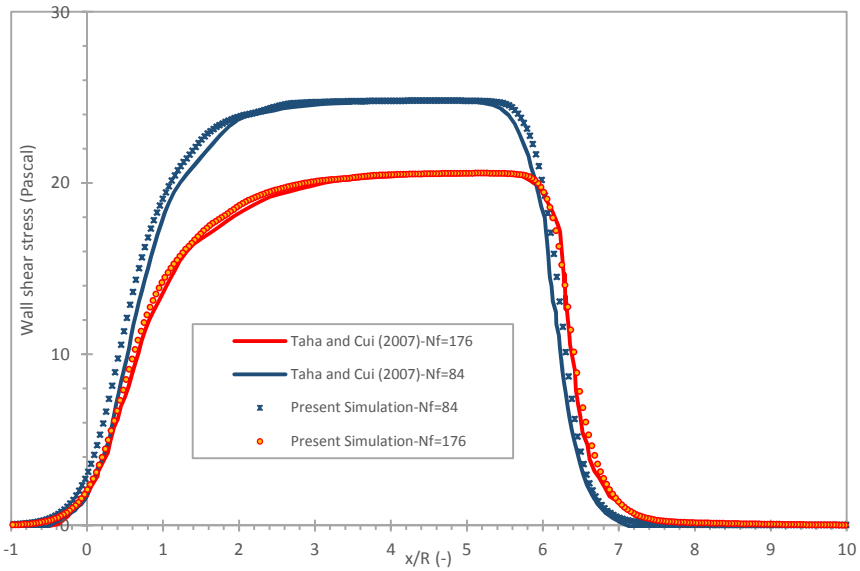
c. Wake Flow Structure

- Effect of inverse viscosity number N_f on wake flow pattern.
- The simulated results are in good agreement with;
  1. the experimental observations of Campos and Carvalho (1988).
  2. the numerical work of Araújo et al. (2012), Taha and Cui (2006), and Zheng et al. (2007).

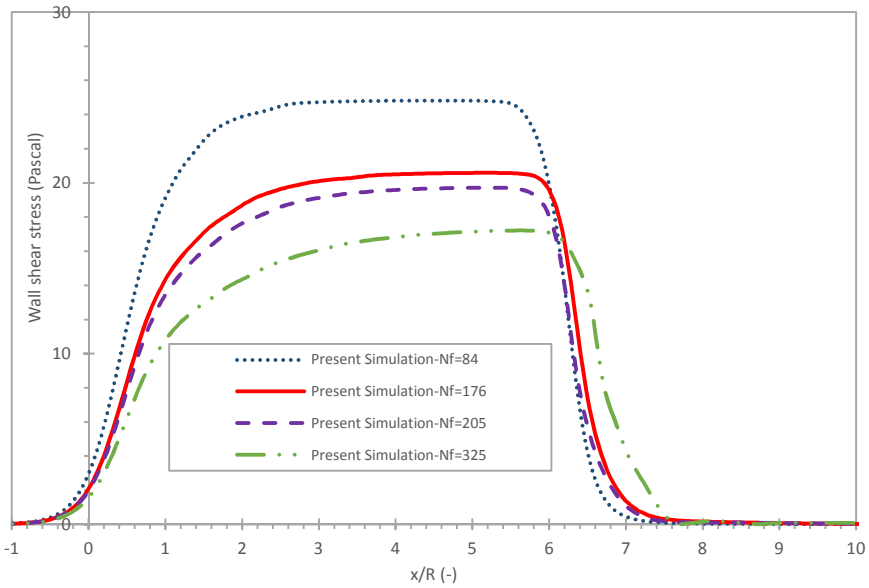


4. Results and Discussions

d. Wall Shear Stress Distribution

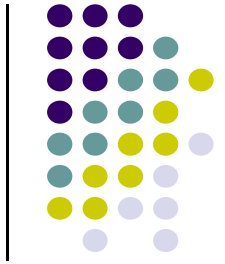


Validation of simulation results for the wall shear stress distribution τ_w around a slug unit with the work of Taha and Cui (2006) - x is axial distance from bubble nose.



Effect of N_f on the wall shear stress distribution τ_w around a slug unit-x is axial distance from bubble nose.

Presentation Overview



1. Introduction.
2. Aim of the study.
3. Model development;
   a) Governing equations.
   b) Model geometry and boundary conditions.
   c) Solution strategy and convergence criterion.
4. Results and discussions;
   a) Taylor bubble shape.
   b) Taylor bubble rise velocity.
   c) Liquid film.
   d) Wake flow structure.
   e) Wall shear stress distribution.
5. **Conclusions.**
6. Recommendations for future work.

4. Conclusions

- The following conclusions can be pointed out;

1) The Taylor bubble bottom depends on the liquid viscosity where the increase in the inverse viscosity number, N_f, increases the concave shape of the Taylor bubble bottom surface.

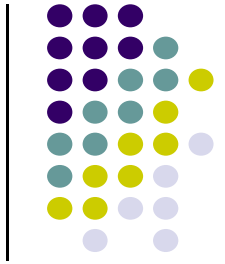
2) The calculated Taylor bubble rise velocity, U_{TB}, is in an acceptable range when compared with experimental values and commonly used correlations in the literature.

3) The liquid film zone can be describes using the liquid film thickness, δ_{LF}, and the liquid film axial velocity, U_{LF} that are both directly affected by the inverse viscosity number, N_f.

4) The wake flow structure has a closed axisymmetric nature for all the simulation cases with the development of circulatory vortex in the bubble wake with the increase in N_f.

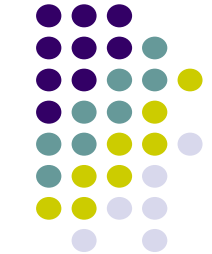
5) The wall shear stress, τ_W is mainly dependent on the liquid film thickness, δ_{LF}, and has a peak positive values in the stabilized liquid film zone.

Presentation Overview



1. Introduction.
2. Aim of the study.
3. Model development;
    a) Governing equations.
    b) Model geometry and boundary conditions.
    c) Solution strategy and convergence criterion.
4. Results and discussions;
    a) Taylor bubble shape.
    b) Taylor bubble rise velocity.
    c) Liquid film.
    d) Wake flow structure.
    e) Wall shear stress distribution.
5. Conclusions.
6. **Recommendations for future work.**

4. Recommendations for Future Work



- This study set out to develop a basic simulation model for gas-liquid slug flow in vertical pipe under laminar flow regime.
- It is recommended that further research could be undertaken in the following areas;
    1. Investigating the hydrodynamic characteristics of slug flow for different fluid system including the effect of viscosity and density ratios,
    2. Investigating the hydrodynamic characteristics of slug flow under turbulent regime with $N_f > 500$,
    3. Exploring the hydrodynamic characteristics of slug flow including the flow of two consecutive Taylor bubbles in vertical pipe,
    4. Studying the wake flow pattern of single Taylor bubble or two consecutive Taylor bubbles under turbulent flow regime in terms of wake volume and length.



Any Questions?