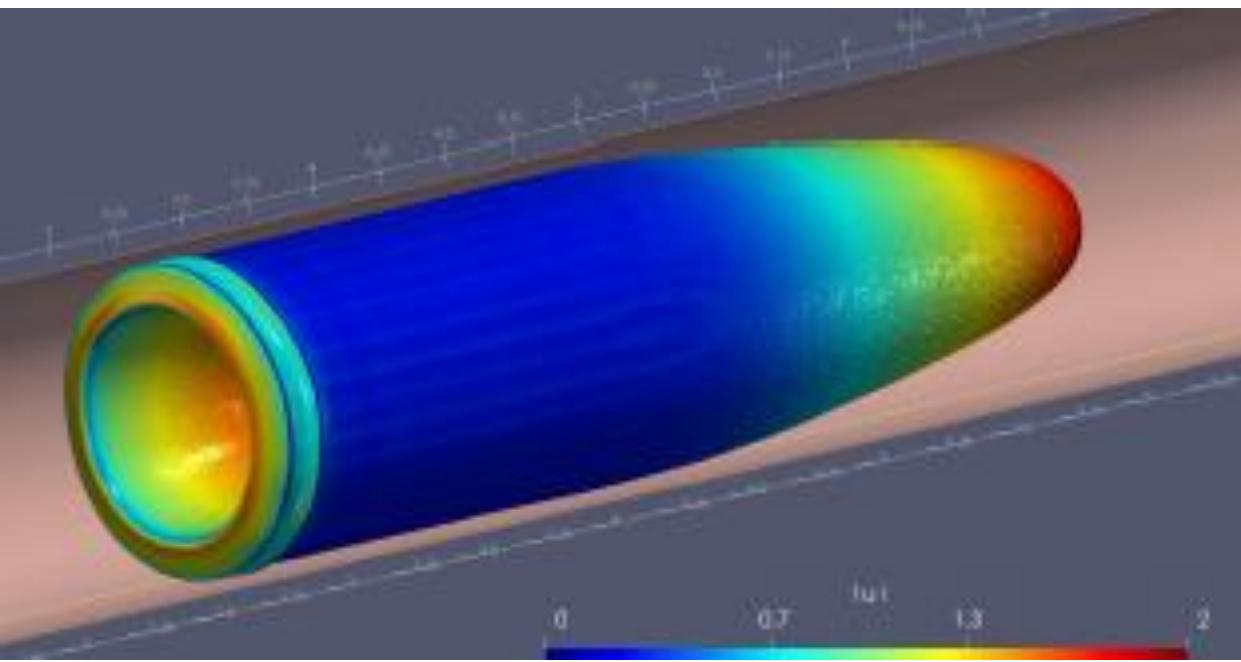


# Taylor Bubble



**Param Mankad (23BME052),  
Nishka Pandya (23BME064) &  
Harsh Trivedi (23BME023)**

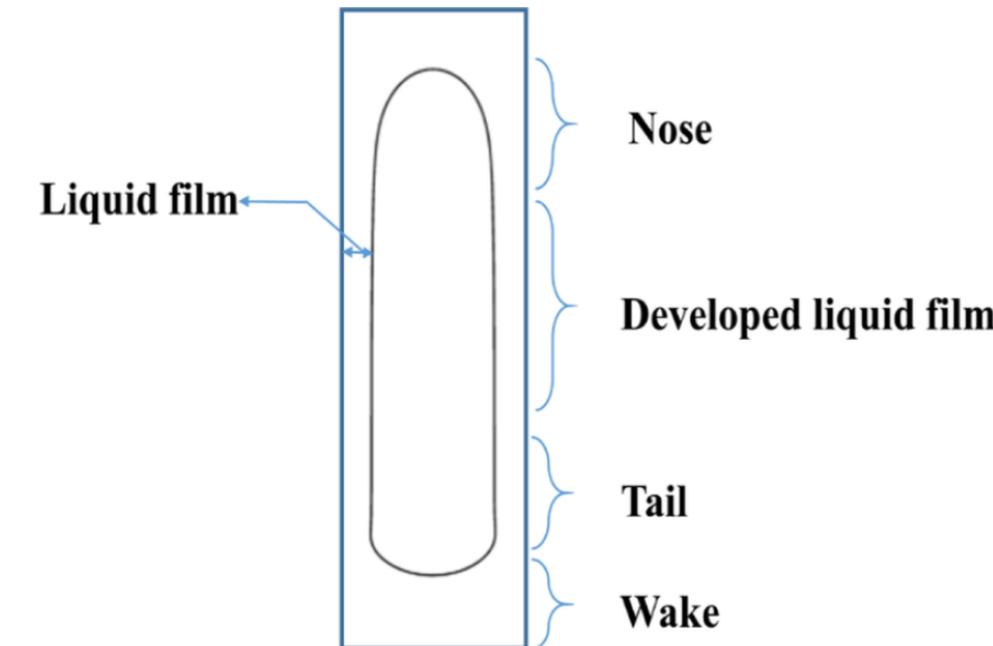
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# What is Taylor Bubble ?

- A Taylor bubble is a large, elongated gas pocket rising in a confined liquid-filled tube, fully occupying the cross-section.
- It typically forms slug flow regimes of gas–liquid systems.
- Its motion and shape is governed by interfacial tension, viscosity, inertia, and buoyancy.

It has Four regions:

- Nose (front) - Smooth, rounded cap shaped by surface tension.
- Body - Cylindrical core where bubble shape and film thickness become uniform.
- Tail (rear) - where liquid film drains downward and a wake forms. Sensitive to viscous and inertial effects; may be convex, flat, or concave.
- Wake - liquid experiences recirculation, vortices, and velocity reversal due to the passage of the bubble.



# Why a Taylor Bubble Rises in Vertical Tubes?

- A Taylor bubble rises due to the density difference between the gas inside the bubble and the surrounding liquid.
- The buoyancy force acts upward and is given by:

$$F_b = (\rho_l - \rho_g)gV$$

Where:

$\rho_l$  : liquid density

$\rho_g$  : gas density

$g$  : gravitational acceleration

$V$ : bubble volume

- While buoyancy pushes the bubble upward, several forces oppose its motion:
  1. Viscous Drag / Fluid Resistance
  2. Wall Confinement / Pressure Drag
  3. Interfacial Tension / Capillary Pressure

we can express these competing effects using non-dimensional numbers.



# Non-Dimensional Numbers used in Analysis of Taylor Bubble

Non-dimensional numbers simplify the analysis of Taylor bubbles and slug flow by reducing the complex interaction of forces into dimensionless ratios.

Instead of dealing with many physical variables (density, viscosity, surface tension, gravity, velocity, diameter), we group them into a few governing non-dimensional parameters that capture the dominant physics of the system.

These numbers represent ratios of dominant forces, and they determine:

- Bubble's shape
- Film thickness
- Tail curvature
- Wake formation.

To systematically compare these effects across different fluids, pipe diameters, and flow conditions, we use non-dimensional numbers derived directly from force ratios includes :

- |  |   |
|--|---|
| <ul style="list-style-type: none"><li>• Reynolds Number</li><li>• Capillary Number</li><li>• Bond Number</li></ul> | <ul style="list-style-type: none"><li>• Froude Number</li><li>• Weber Number</li><li>• Inverse viscosity number</li></ul> |
|--|---|

# Non-Dimensional Numbers used in Analysis of Taylor Bubble

## Reynolds Number

Force Ratio	Inertia / Viscous
Formula	$Re = \rho U D / \mu$
Effect on Shape	Effect on Film
<ul style="list-style-type: none"> <li>Low Re → rounded nose, convex tail, smooth interface</li> <li>High Re → concave tail, wake vortex pair, possible asymmetry</li> </ul>	<ul style="list-style-type: none"> <li>Low Re → thin film (viscous-dominated)</li> <li>High Re → thicker, wavy, unstable film</li> </ul>

## Capillary Number

Force Ratio	Viscous / Surface Tension
Formula	$Ca = \mu U / \sigma$
Effect on Shape	Effect on Film
<ul style="list-style-type: none"> <li>Low Ca → stiff, rounded interface</li> <li>High Ca → elongated and more deformable bubble</li> </ul>	<ul style="list-style-type: none"> <li>Low Ca → Thin Film</li> <li>High Ca → viscous thickening beyond Bretherton</li> </ul>

# Non-Dimensional Numbers used in Analysis of Taylor Bubble

Bond Number	
Force Ratio	Buoyancy / Surface Tension
Formula	$Bo = \Delta\rho g D^2 / \sigma$
Effect on Shape	Effect on Film
<ul style="list-style-type: none"> <li>Low Bo → bubble stays rounded; shape dominated by surface tension</li> <li>High Bo → strong flattening of nose/tail; taller bubble length</li> </ul>	<ul style="list-style-type: none"> <li>Low Bo → thin film (viscous-dominated)</li> <li>High Bo → thicker film</li> </ul>
Froude Number	
Force Ratio	Inertia / Gravity
Formula	$Fr = U / \sqrt{gD}$
Effect on Shape	Effect on Film
<ul style="list-style-type: none"> <li>Low Fr → Buoyancy-dominated symmetry</li> <li>High Fr → Inertia dominates, tail elongates</li> </ul>	<ul style="list-style-type: none"> <li>Low Fr → controlled, thinner lubrication film</li> <li>High Fr → more unstable, thicker film</li> </ul>

# Non-Dimensional Numbers used in Analysis of Taylor Bubble

## Weber Number

Force Ratio	Inertia / Surface Tension
Formula	$We = \rho U^2 D / \sigma$
Effect on Shape	Effect on Film
<ul style="list-style-type: none"> <li>• Low We → Stable and smooth interface</li> <li>• High We → interfacial breakup/oscillation, bubbles formation possible</li> </ul>	<ul style="list-style-type: none"> <li>• Low We → Film smooth and thin</li> <li>• High We → Film instability and thick</li> </ul>

## Inverse Viscosity Number

Force Ratio	Buoyancy / Viscous
Formula	$Nf = \sqrt{(\Delta\rho g D^3)/\mu^2}$
Effect on Shape	Effect on Film
<ul style="list-style-type: none"> <li>• Low Nf → viscous dominated; short smooth bubble</li> <li>• High Nf → concave tail, long bubble, strong vortex wake</li> </ul>	<ul style="list-style-type: none"> <li>• low Nf → thick film</li> <li>• high Nf → very thin film</li> </ul>

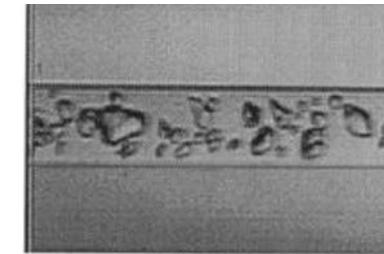
# Flow Regimes in Microchannel

## Flow regimes in microchannel:

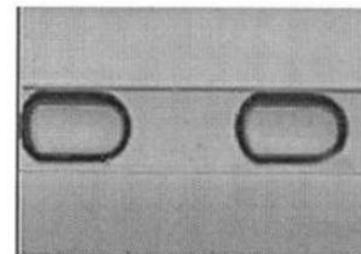
The phase distribution of liquid and gas is termed as flow regimes. It influences critical thermohydraulic properties such as pressure drop and heat transfer rate. Based on the gas flow rate in the liquid-filled microchannel, flow regimes are classified as:

- Bubbly
- Slug
- Annular
- Slug-Annular
- Churn

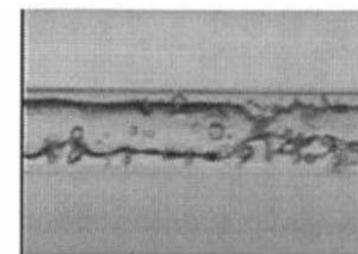
At high liquid and low gas flow rates, continuous bubbles are formed and distributed in the liquid phase. At low gas and liquid flow rates, regular periodic bubbles are produced, almost covering the channel, such that liquid separates two consecutive gas bubbles known as slug flow or Taylor flow. Bubble coalescence is formed when the gas flow rate further increases with large amplitude waves in the liquid-gas interface. This is called slug-annular flow. A further increase in gas velocity gives rise to longer bubbles dispersed in the liquid film with small amplitude waves; this is annular flow.



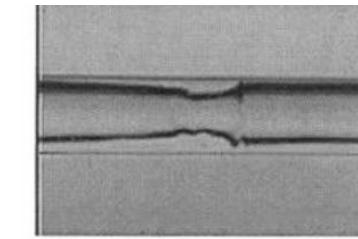
Bubbly



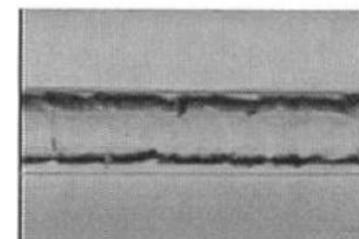
Slug



Churn



Slug-annular



Annular

# Characteristics of Taylor Bubble

Characteristics of Taylor bubble:

- Film Thickness:

In Taylor flow, gas bubbles travels faster than liquid and a liquid film is left behind.

Two different methods are used in film thickness measurement – (a) Direct Method and (b) Indirect Method

(a) Direct Method:

Film thickness measured using high-quality images either free from optical distortion or corrected for optical distortion.

(b) Indirect Method:

Bubble velocity is determined experimentally and film thickness calculated using continuity.

Using Finite Element Method, researchers suggested that film thickness initially decreases on increasing Reynold's Number and then increase monotonically.

Ratio of Reynold's and Capillary Number ( $Re/Ca$ ) plays an important role in determining effect of inertia on film thickness.

Effect of Reynold's Number:

Initially fluid inertia has no effect on film thickness upto certain Reynold's Number. Beyond this, film thickness first decrease slightly then increases with increasing  $Re$ .

$Re$  values above which inertial effects are significant decrease with increasing Capillary Number( $Ca$ ).

# Characteristics of Taylor Bubble

Han and Shikazono suggested equation(2):

$$\frac{\delta_F}{R} \sim \frac{Ca^{\frac{2}{3}}}{1 + Ca^{\frac{2}{3}} + f(Re, Ca) - g(We)}$$

$f(Re, Ca)$  reduce film thickness

$g(We)$  increases film thickness

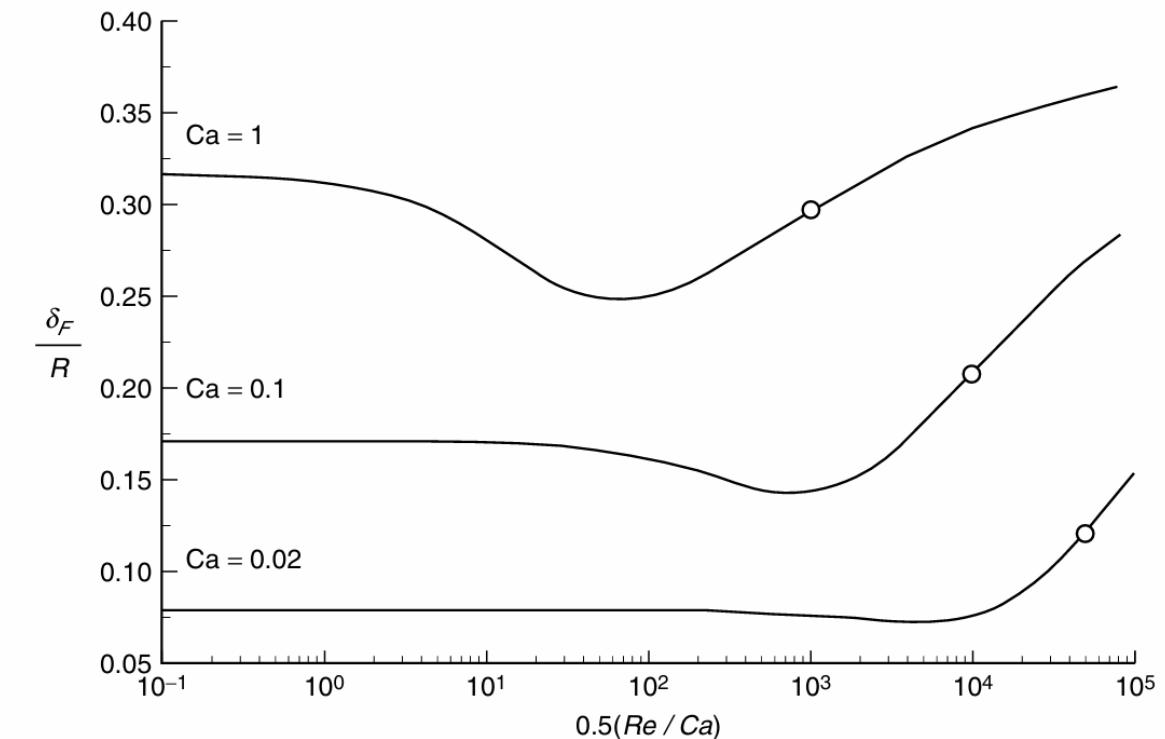
Effect of Gravity:

When bubble travel upwards additional liquid accumulates in the film whereas when bubble travels downward liquid film is thin.

At high values of Capillary Number effect of gravity is unimportant.

Han and Shikazono measured liquid film thickness in horizontal channels of Bond Numbers about 0.1 to 1.9.

For Bond Number 0.1 film thickness was same at all positions whereas at Bond Number 1.9 significant differences are observed in film thickness.



# Characteristics of Taylor Bubble

- Pressure Drop:

Pressure drop in the unit cell can be decomposed into three components:

$$\Delta P = \Delta P_{Slug} + \Delta P_{Film} + \Delta P_{Cap}$$

Head loss due to liquid film is neglected in comparison with head loss due to liquid slug. Thus, only two components of pressure i.e. frictional loss due to liquid slug and pressure drop over front and rear bubble is considered.

Pressure drop in Taylor flow when inertial effects are significant is given by Kreutzer equation:

$$\frac{\Delta P}{L} = \varepsilon_L \frac{4}{d} \left( \frac{1}{2} \rho_L U_{TP}^2 \right) \frac{16}{Re} \left( 1 + a \frac{d}{L_s} \left( \frac{Re}{Ca} \right)^{2/3} \right)$$

The value of fitting constant  $a$  is found to be between 0.07 to 0.17 from CFD simulations and experimental calculations. When gravitational force is small as compared to surface tension and viscous forces, pressure drop across liquid slugs scales as  $Ca^{2/3}$  whereas when gravitational force is comparable to surface tension and viscous force, it scales as  $Ca^{1/6}$ .

# Characteristics of Taylor Bubble

- **Bubble Shape:**

An ideal Taylor bubble has a cylindrical body with hemispherical caps, with a sharper nose and flatter tail. The bubble almost fills the channel cross-section, leaving just a thin liquid film around it.

The bubble shape can be analysed on basis of Capillary Number, Reynolds Number and Bond Number.

**Effect with Capillary number, Ca:**

At low Ca, the bubble ends are almost hemispherical. As Ca increases, the liquid film thickens, nose becomes sharper and tail becomes flatter.

**Effect with Reynolds number, Re:**

With increasing Re, the tail becomes flat, then concave at high Re.

At sufficiently high Reynolds number, axial symmetry of bubble is lost.

**Effect of Bond number, Bo:**

At low Bo, bubble remains axisymmetric as surface tension dominates against gravity. This is primarily observed in microchannels. At macro scale, the bubble tends to deflects towards the top of the tube in horizontal and inclined flow.

In vertical flow, Bo affects the length of bubble. Due to greater buoyant effects, bubbles tends to grow larger at high Bo.

# Characteristics of Taylor Bubble

- Heat Transfer:

Taylor bubbles lead to enhanced heat transfer. This is due to increased recirculation generated within the liquid slug after the bubble. The thin liquid film acts as region of low resistance, facilitating rapid heat transfer.

Nusselt number in Taylor flow is greatly enhanced, around 2.5 to 4 times compared to single-phase flows. Local Nusselt number is thus highest in the wake region of the bubble.

Increasing  $Ca$  leads to thicker liquid film and therefore increases the thermal resistance, slightly lower Nusselt number. With higher Prandtl number, Nusselt number also increases in the liquid film.

During phase change, the expansion of gas bubble increase the flow velocity, further thinning liquid film and enhancing heat transfer.

# How to Analyze Taylor Bubbles

Taylor Bubble phenomenon was first discovered in 1964 and since has been analysed with various methods:

## 1. Experimental Analysis:

- Initial experimental analysis was carried out in tubes with diameter in order of 10mm.
- With improvements in imaging technology, use of high-speed cameras with macro imaging can be used for experimentally analysing the bubbles in microchannels.

## 2. Numerical Analysis:

- Improvements in computers and numerical methods led to computational analysis of Taylor bubbles.
- CFD is now commonly used for analysis of Taylor flow in microchannels. Commonly used method is FVM, but FEM can also be used.

# Importance of Taylor Bubbles

Taylor Flow is considered significant in microchannel applications due to its unique hydrodynamic characteristics. Its importance stems from:

- Enhanced Mass Transfer: The structure of taylor bubble results in eddies in its wake in the liquid slug. This increases internal recirculation. Combined with large surface area to volume ratio, significant mass transfer takes place.
- Reduced Axial Mixing: Bubble flow reduces axial mixing, allowing the flow to behave like plug type reactor, which is desirable for lab-on-chip applications.
- Enhanced Heat Transfer: Due to presence of recirculation currents and thin liquid film, taylor flow improves heat transfer rate than single-phase systems, even at low velocities.
- Defined Interface: Taylor flow results in defined interface between the gas and liquid, controlling the reaction conditions and transport phenomenon.
- Predictable Transport Phenomenon: As flow in microchannels is generally laminar, transport phenomenon can be easily predicted without need of turbulence model.

# Application of Taylor Bubbles

Taylor bubble phenomenon provides various applications in industries:

## 1. Chemical Processing and Engineering:

- Catalytic Reactors: Used in three-phase or multiphase catalytic reactor due to increased mass transfer
- Catalyst Coating: Used in coating surfaces with catalyst in monolithic reactors

## 2. Heat transfer and Energy:

- Electronics Cooling: Used for high-density, multi-chip modules in supercomputers and X-ray generators
- Heat Exchangers: Compact heat exchangers for aerospace systems, cryogenic cooling and circuit board cooling.
- Fuel cells: Useful for two-phase methanol fuel cells

## 3. Biomedical Applications:

- Physiological Modelling: Modelling blood flow in capillaries and gas embolisms.
- Pulmonary studies: Lung airway opening
- Diagnostic and Pharmaceutical: Used in lab-on-chip applications in medical and pharmaceutical uses.

# Application of Taylor Bubbles

## 3. Other Uses:

- Filtration: Increases efficiency in microfiltration processes.
- Oil and Gas Industry: Increases oil extraction efficiency.
- Flow Measurement: Useful for measurement of liquid flow.

Thank You  
*for your Attention..*