

Introduction to Computational Fluid Dynamics (CFD) – Part III

Multiphase flow modelling

Prepared by:
Dr Milinkumar Shah
Senior Lecturer, Chemical Engineering Discipline, Curtin University,
Western Australia

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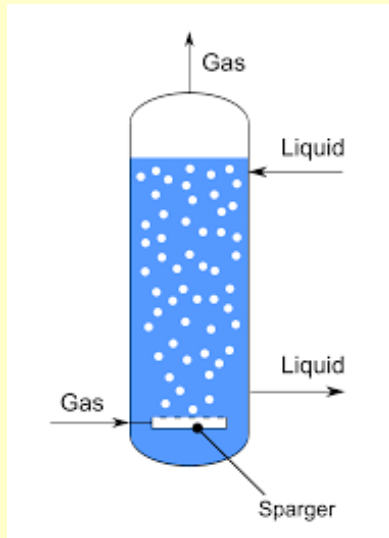
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Outline

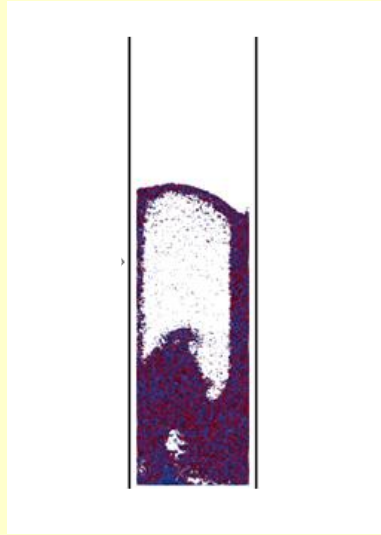
- Multiphase flows – examples
- Modelling approaches
 - Eulerian-Eulerian model
 - Eulerian-Lagrangian model
 - Volume of Fluid model
- Modelling Challenges
- Model validation
 - Experimental techniques and their limitations
- Industrial case studies
 - Case study-1: CFD of multi-scale flows – gas-solid flow in riser
 - Case study-2: CFD and PINN coupling

Examples of Multiphase Flows

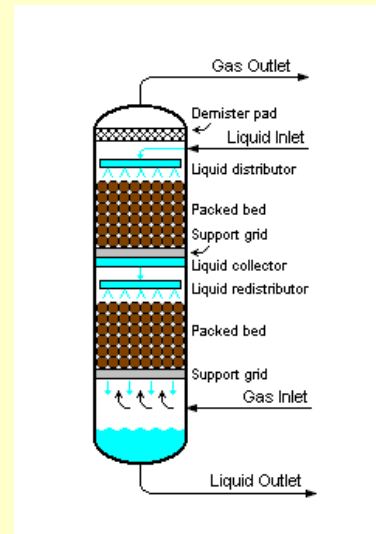
Multiphase reactors in chemical engineering



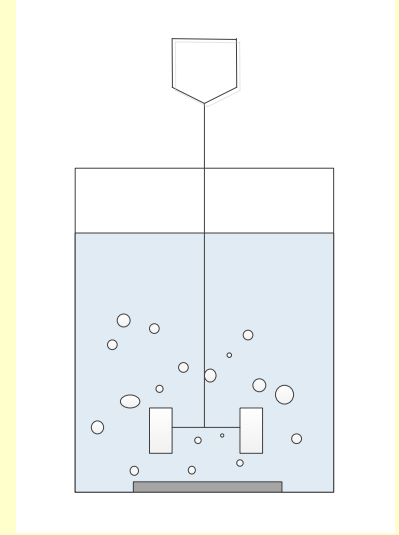
Bubble columns



Fluidized bed



Packed column



Stirred tank

Fluid flow system consisting of:

Two or more distinct phases flowing simultaneously in mixture, and
Have some level of phase separation at a scale well above the molecular level

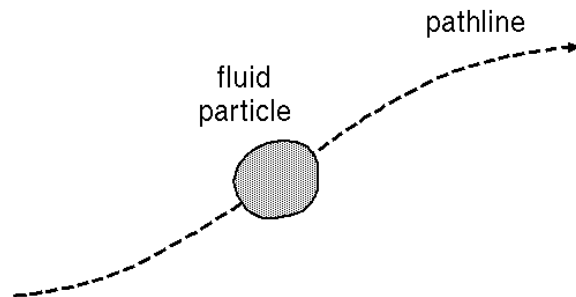
Two phase flows can be classified:

Gas-liquid mixture, gas-solid mixture, liquid-solid mixture, immiscible liquid mixture

Lagrangian vs. Eulerian description

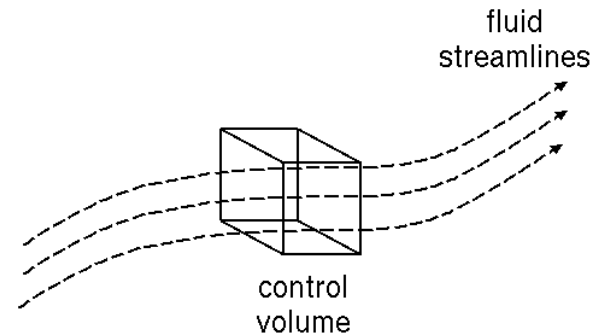
Lagrangian

A fluid flow field can be thought of as being comprised of a large number of finite sized fluid particles which have mass, momentum, internal energy, and other properties. Mathematical laws can then be written for each fluid particle. This is the Lagrangian description of fluid motion.

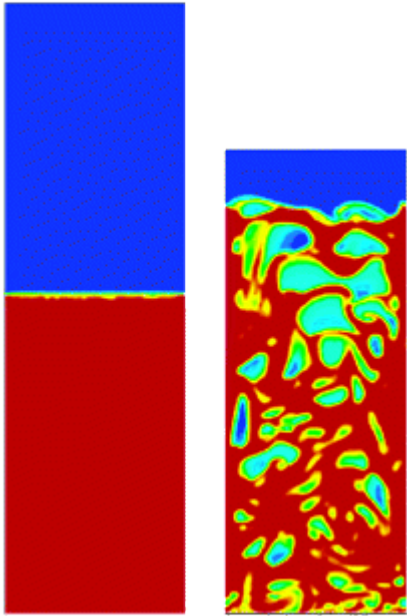


Eulerian

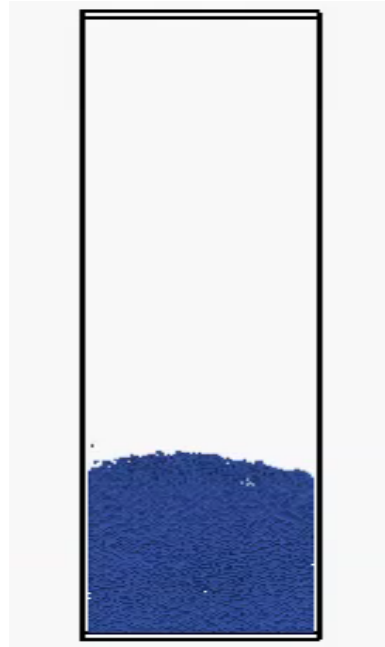
Another view of fluid motion is the Eulerian description. In the Eulerian description of fluid motion, we consider how flow properties change at a fluid element that is fixed in space and time (x,y,z,t) , rather than following individual fluid particles.



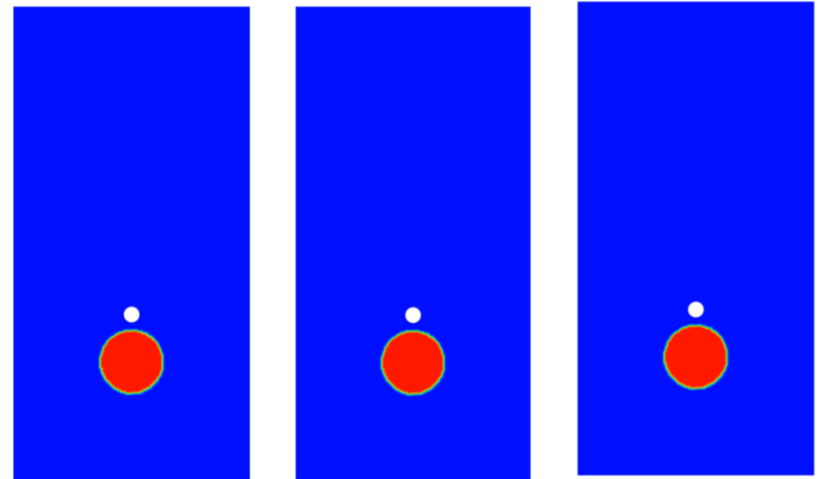
Modelling Approaches



Eulerian-
Eulerian



Eulerian-
Lagrangian



Volume of fluid

Eulerian-Eulerian Approach

Primary and secondary phases are treated as interpenetrating continua.

Equations of change (mass, momentum and energy conservation equations) are solved for each phase. A condition that the sum of volume fractions of each phase is equal to zero is applied.

The conservation equations are coupled with momentum exchange (drag and lift forces), energy exchange and mass exchange terms.

Eulerian-Eulerian Approach

Continuity (mass balance equation)

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \vec{u}_p) = S_{pq}; \quad \frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{u}_q) = -S_{pq}$$

Momentum balance

$$\frac{\partial}{\partial t}(\alpha_q \rho_q \vec{u}_q) + \nabla \cdot (\alpha_q \rho_q \vec{u}_q \vec{u}_q) = -\alpha_q \nabla p + \nabla \cdot \bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} + \vec{F}_{pq} + S_{Mq}$$
$$\frac{\partial}{\partial t}(\alpha_q \rho_q \vec{u}_q) + \nabla \cdot (\alpha_q \rho_q \vec{u}_q \vec{u}_q) = -\alpha_q \nabla p + \nabla \cdot \bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} + \vec{F}_{pq} + S_{Mq}$$

Phasic interactions (e.g., drag);

$$\vec{F}_{pq} = \frac{3}{4} C_D \frac{\alpha_p \alpha_q |\vec{u}_p - \vec{u}_q|^2}{d_q}, \quad C_D = \begin{cases} \frac{(24 + 3.6 Re^{0.687})}{Re} & Re \leq 1000 \\ 0.44 & Re > 1000 \end{cases}$$

Eulerian-Lagrangian Approach

Primary is treated as continuum, whereas secondary phase is treated as discrete.

Equations of change (mass, momentum and energy conservation equations) are solved only for the primary phase; while for the secondary phase, Newton's force balance equation is solved for position and velocity of each particle/bubble.

The equations are coupled with momentum exchange (drag and lift forces), energy exchange and mass exchange terms.

Eulerian-Lagrangian Approach

Governing equations for primary (continuous) phase

Continuity (mass balance equation)

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \vec{u}_p) = S_p$$

Momentum balance

$$\frac{\partial}{\partial t}(\alpha_q \rho_q \vec{u}_q) + \nabla \cdot (\alpha_q \rho_q \vec{u}_q \vec{u}_q) = -\alpha_q \nabla p + \nabla \cdot \bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} + \vec{F}_D + S_{Mq}$$

Governing eq. for secondary (discrete) phase

Force balance equation over each particle or bubble

$$m^{(i)} \frac{d}{dt}(\mathbf{u}_s^{(i)}(t)) = \mathbf{F}_T^{(i)} = m^{(i)} \mathbf{g} + \mathbf{F}_D^{(i \in k)}(t) + \mathbf{F}_C^{(i)}(t)$$

Phasic interactions (e.g., drag);

$$\vec{F}_D = \frac{3}{4} C_D \frac{\alpha_p \alpha_q |\vec{u}_p - \vec{u}_q|^2}{d_q}, \quad C_D = \begin{cases} \frac{(24 + 3.6 Re^{0.687})}{Re} & Re \leq 1000 \\ 0.44 & Re > 1000 \end{cases}$$

Volume of Fluid Approach

The VOF is applicable for separated flows or stratified or where the dispersed phase is well separated from the continuous phase with a distinct interface

A single set of governing equations is solved where physical properties of multiphase are represented as mixture properties. The volume fraction of the fluid in each computational cell is tracked throughout the domain.

It is a surface-tracking technique that tracks interface between two or more immiscible fluids.

The equations are coupled with momentum exchange (drag and lift forces), energy exchange and mass exchange terms.

Volume of Fluid Approach

Multiphase Modelling Strategies

Dilute

All volume loading

DPM

Eulerian Multiphase

Mixture Models

Eulerian/Eulerian Models

Homogenous

Non-Homogeneous

Dispersed

Separated

VOF/Mixture Model

Slip Mixture Model

Eulerian

DDPM

Multi-fluid VOF/Eulerian

Summary

Modeling multiphase flows is very complex, due to interdependence of many variables.

Three approaches: EE, EL and VOF

Selection of approach:

- For applications with low volume fraction of particles, droplets, or bubbles, use EL approach or DPM model .
- For particle-laden flows (dense gas-solid/gas-liquid flows), Eulerian granular multiphase model is best.
- For separated gas-liquid flows (stratified, free-surface, etc.) VOF model is best.