Introductions and Definitions

Advanced Multiphase Modeling Course

Why Model Multiphase Flow?

- Multiphase flow is important in many industrial processes:
  - Riser reactors
  - Bubble column reactors
  - Fluidized bed reactors
  - Scrubbers, Dryers, etc.
- Typical objectives of a modeling analysis
  - Maximize the contact between the different phases, typically different chemical compounds
  - Flow dynamics

Definitions

- A phase is a class of matter with a definable boundary and a particular dynamic response to the surrounding flow/potential field. Phases are generally identified by solid, liquid or gaseous states of matter but can also refer to other forms e.g. particles of different size.

- Multiphase flow is simultaneous flow of:
  - Materials with different states or phases (i.e. gas, liquid or solid).
  - Materials with different chemical properties but in the same state or phase (i.e. liquid-liquid, such as, oil-water).

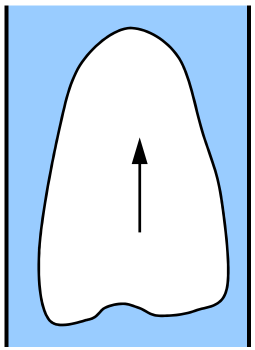
- In contrast, multicomponent / multispecies flow refers to a “mixture” formulation where components are mixed at molecular level and velocity and temperature are the same for all components.

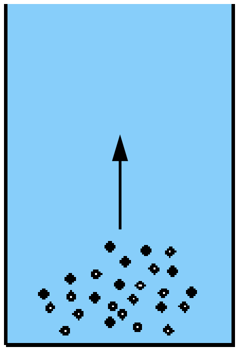
Definitions

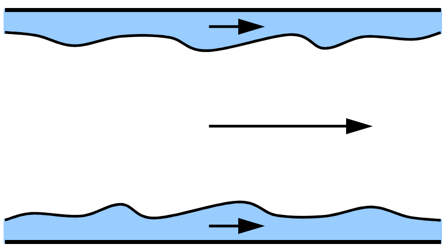
- There are different types of multiphase flows depending on combination of phase materials, each type may have different flow regimes
  - Gas-Liquid flow regimes
    - Bubbly flows
    - Separated Flows
    - Gas-droplet flows
  - Gas-solid flow regimes
    - Gas-Particle flows
    - Pneumatic transport
    - Fluidized beds
  - Liquid-solid flow regimes
    - Slurry flows
    - Hydro-transport
    - Sediment transport

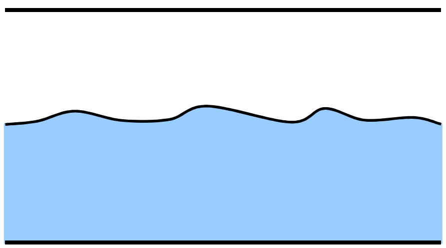
Examples of Multiphase Flow Regimes

- Bubbly flow: Discrete gaseous bubbles in a continuous liquid
- Droplet flow: Discrete fluid droplets in a continuous gas
- Particle-laden flow: Discrete solid particles in a continuous fluid
- Slug flow: Large bubbles in a continuous liquid
- Annular flow: Continuous liquid along walls, gas in core
- Stratified/free-surface flow: Immiscible fluids separated by a clearly-defined interface.


Slug Flow


Bubble / Droplet / Particle-Laden Flow

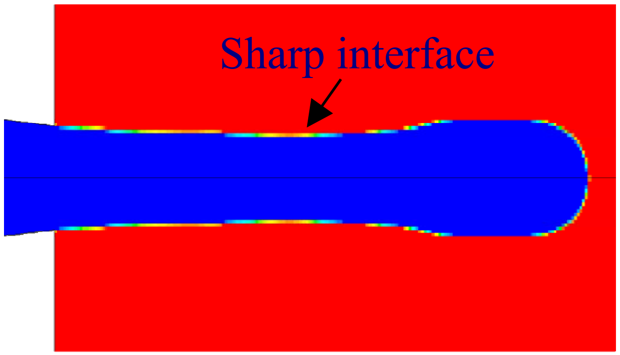

Annular Flow


Stratified Flow

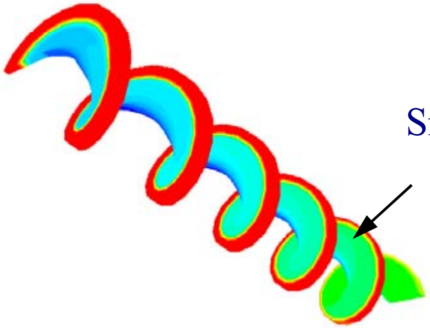
Multiphase Flow Regimes

- There is no universal multiphase model for all regimes
- To choose model, use must know a priori certain characteristics of the flow
  - Flow regime – dispersed (particles) or stratified (large interface length scale)
    - Stratified flow regimes can be modeled by direct tracking of interface – Volume of Fluid (VOF) model in FLUENT.
    - Dispersed regimes can be modeled by averaged models – Euler or Mixture model in FLUENT.

Direct interface tracking of drop formation in an inkjet print head

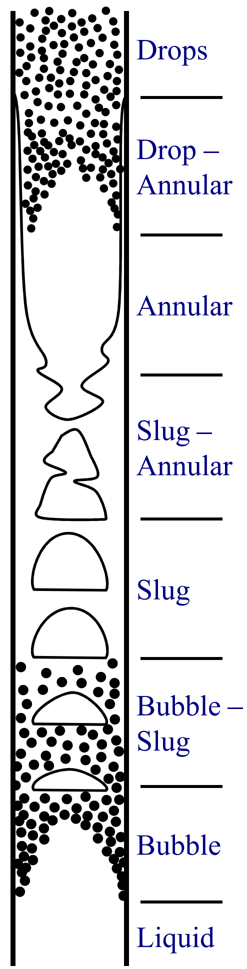


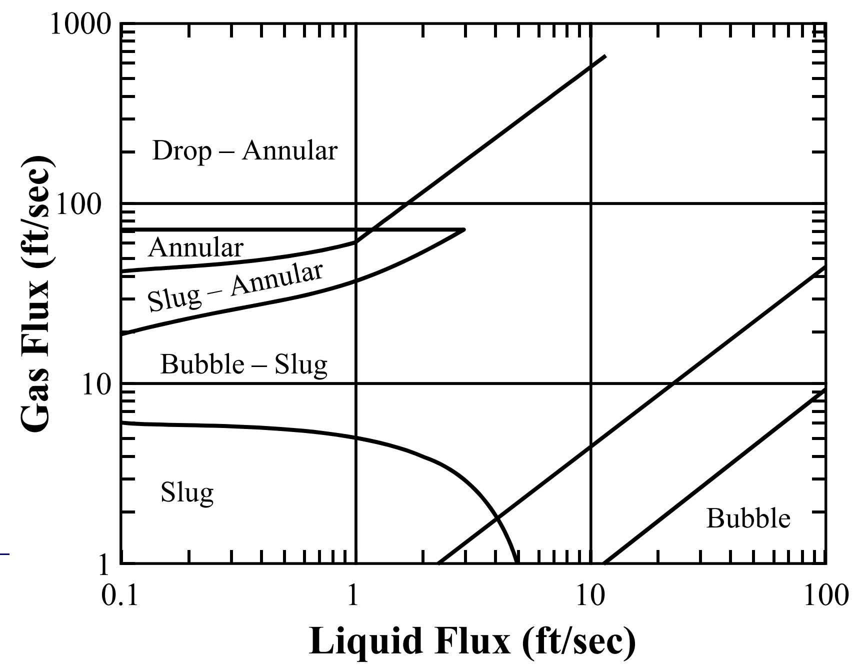
Gradual separation of oil droplets in water in auger separator



Multiphase Flow Regimes

- How to find which regime you have? Mass flow rates of every phase are known at inlet at inlet.
  - Use flow pattern maps
  - Run VOF model (direct simulation) at domain surrounding inlet area where phases "meet" each other
  - Common knowledge – flow regime is directly observable or known from indirect measurement.



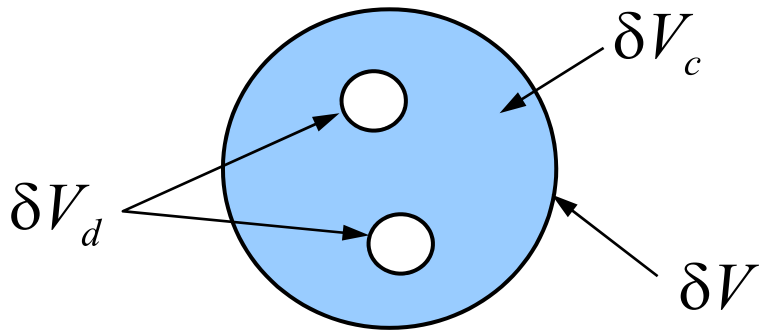


Definition of Volume Fraction

$$\alpha_d = \lim_{\delta V \to \delta V^0} \frac{\delta V_d}{\delta V}$$

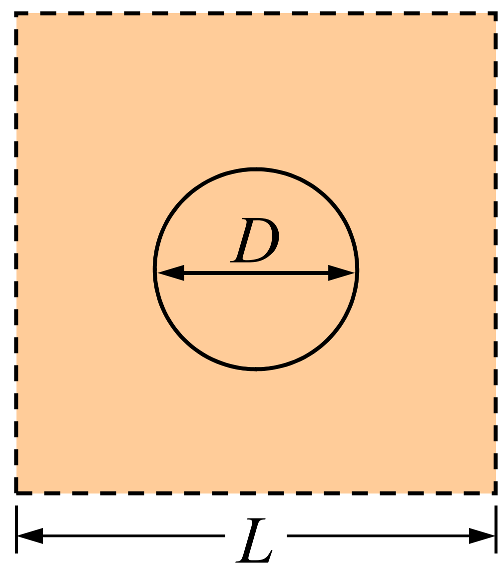
$$\alpha_c = \lim_{\delta V \to \delta V^0} \frac{\delta V_c}{\delta V}$$

$$\alpha_c + \alpha_d = 1$$



$$\frac{L}{D} = \left(\frac{\pi}{6\alpha_d} \right)^{1/3}$$

$$\text{For } \alpha_d = 10\%, \ \frac{L}{D} = 1.7$$

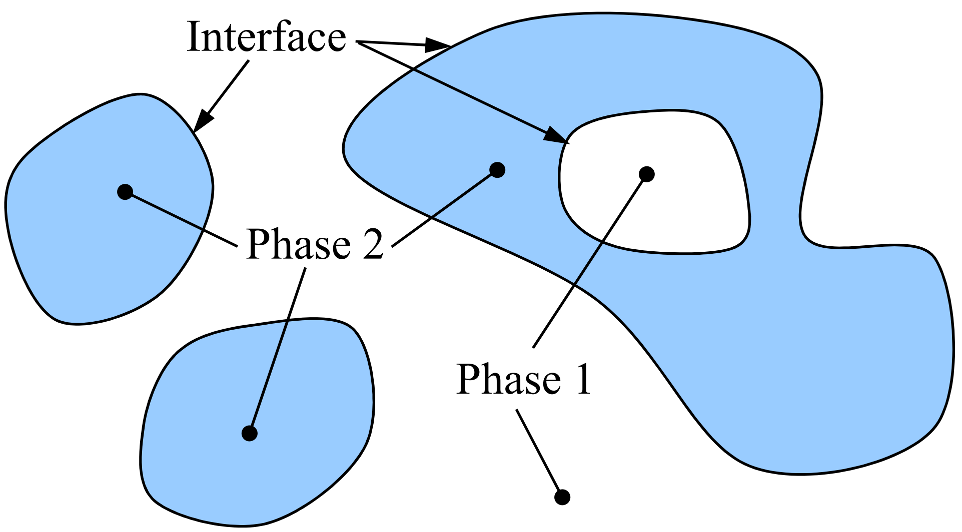


Multiphase Models in FLUENT 6.3

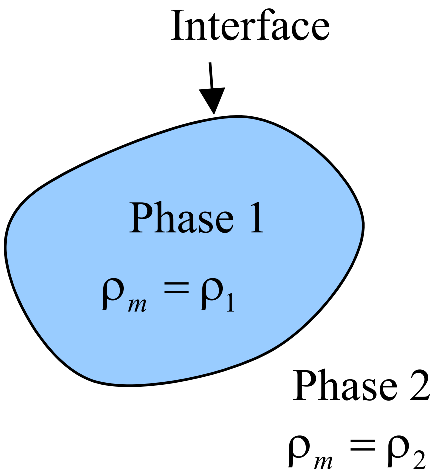
- Lagrangian Dispersed Phase Model (DPM)
  - Lagrangian particle/bubble/droplet tracking
- Volume of Fluid model (VOF)
  - Direct method of predicting interface shape between immiscible phases
- Eulerian Model
  - Model resulting from averaging of VOF model applicable to dispersed flows.
- Mixture Model
  - Simplification of Euler model; applicable when inertia of dispersed phase is small.

Basic Equations

- Instantaneous snapshot of two arbitrary phases in arbitrary volume.
- Navier-Stokes equations are valid with each phase
- Interface is a boundary between phases so we need boundary conditions for each conservation equation at the interface



Basic Equations



- VOF method
  - Explicit update of interface by accurate solution of mass equation solved for volume fraction. For example, for phase 1 this equation looks like

$$\frac{\partial(\rho_1\alpha_1)}{\partial t} + \nabla\cdot(\rho_1\vec{u}\alpha_1) = 0$$

  - Summing up conservation equations for phases and introducing mixture density we get total mass conservation which looks suspiciously like … single phase mass conservation

$$\frac{\partial(\rho_1\alpha_1)}{\partial t} + \nabla\cdot(\rho_1\vec{u}\alpha_1) = 0$$

$$+\quad \frac{\partial(\rho_2\alpha_2)}{\partial t} + \nabla\cdot(\rho_2\vec{u}\alpha_2) = 0$$

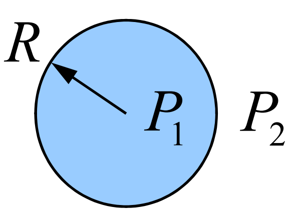
$$\frac{\partial(\rho_m)}{\partial t} + \nabla\cdot(\rho_m\vec{u}) = 0$$

$$\Rightarrow \rho_m = \alpha_1\rho_1 + \alpha_2\rho_2$$

Basic Equations

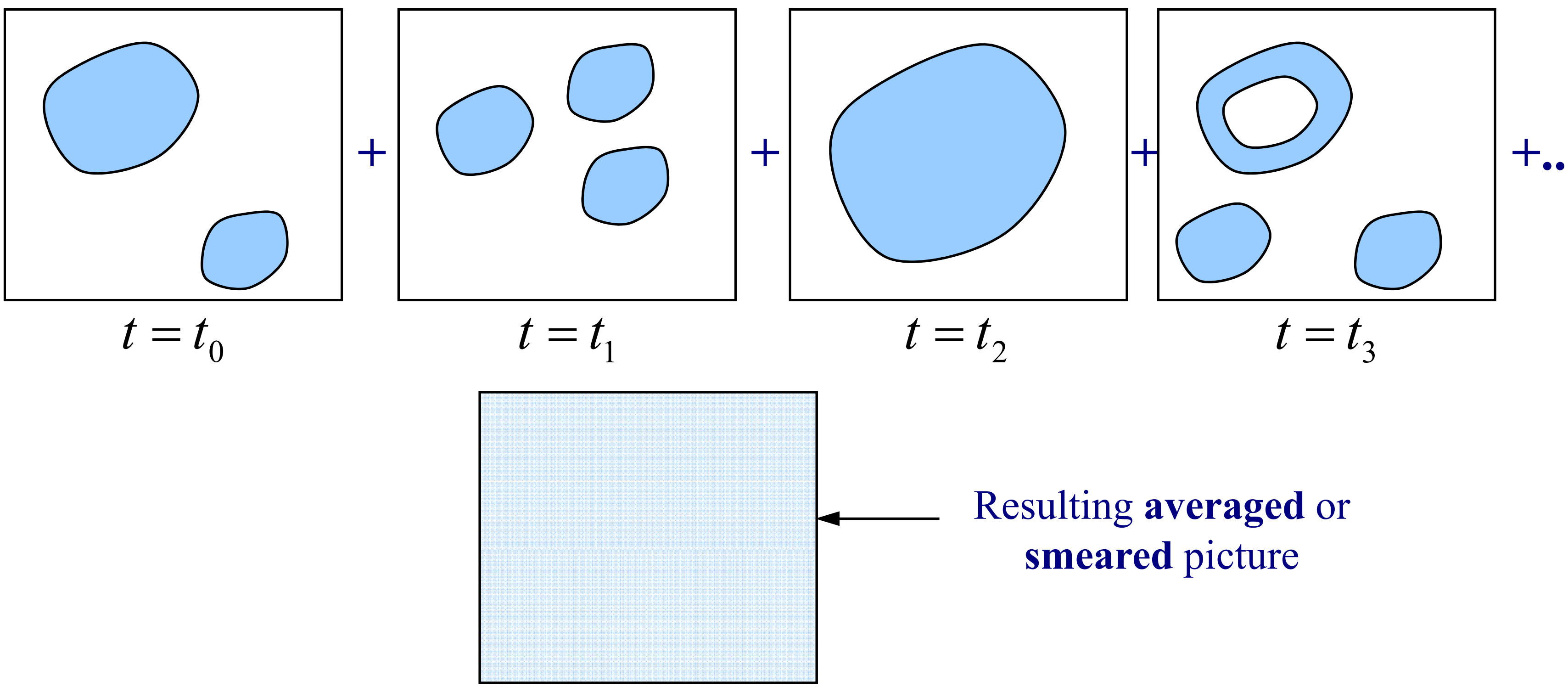
- VOF method (cont'd)
  - Simultaneous solution of phase continuity and total continuity equations automatically satisfies fundamental boundary condition for mass conservation at the interface – continuity of mass flux across interface
  - For momentum equation momentum flux vector may not be continuous across interface if interfacial forces are present
    - Tangential component is continuous
    - Normal momentum may be discontinuous due to surface tension effect, for example, for spherical droplet or bubble

$$P_1 - P_2 = \frac{2\sigma}{R}$$



Basic Equations

- Euler method
  - Exact equations together with interface BCs are averaged over time or volume or ensemble.



Explicit (VOF) vs. Averaged (Eulerian) Models

- VOF model solves one set of momentum equations using for mixture using mixture properties. It is not different from single phase Navier-Stokes equations. Phase interaction is computed in exact fashion as interface.
- Eulerian model solves momentum equation for each phase using material properties of that phase. Momentum equations of different phases are coupled through interfacial forces acting on phases. These forces are unknown and must be modeled (for example, drag).
- VOF model solves phase and total continuity equations – the result is pressure and volume fraction which points out where the interface is.
- Eulerian model solves phase and total continuity equations the same way as VOF – the result is pressure and volume fraction which points out the probability where phase may exist.

Things to Remember

- VOF model solves exact multiphase equations and boundary conditions at interface.
- Eulerian model solves set of averaged Navier-Stokes equations for every phase. The equations contain unknown terms describing interfacial interaction. These terms are a direct consequence of boundary conditions at the interface which are solved for exactly in VOF model. These terms must be modeled like we have to model a Reynolds stress to model turbulence
- All multiphase models solve
  - Phase continuity equation – to find volume of fluid of each phase.
  - Total phase continuity – to solve for pressure which is shared by all phases (this is approximation).
  - Momentum equation – VOF model solves for mixture velocity components and Eulerian models solve for phase velocity components.