CHMLTECH 501 Computational Fluid Dynamics

Introduction to Modeling Multiphase Flows

A large number of flows encountered in chemical engineering are a mixture of phases. Physical phases of matter are gas, liquid, and solid, but the concept of phase in a multiphase flow system is applied in a broader sense. In multiphase flow, a phase can be defined as an identifiable class of material that has a particular inertial response to and interaction with the flow and the potential field in which it is immersed. For example, different-sized solid particle of the same material can be treated as different phases because each collection of particles with the same size will have a similar dynamical response to the flow field.

Multiphase Flow Regime
Multiphase flow can be classified by the following regimes, grouped into four categories:

- gas-liquid or liquid-liquid flows
  - bubbly flow: discrete gaseous or fluid bubbles in a continuous fluid.
  - droplet flow: discrete fluid droplets in a continuous gas.
  - slug flow: large bubbles in a continuous fluid.
  - stratified/free-surface flow: immiscible fluids separated by a clearly-defined interface.
- gas-solid flows
  - particle-laden flow: discrete solid particles in a continuous gas
  - pneumatic transport: flow pattern depends on factors such as solid loading, Reynolds numbers, and particle properties. Typical patterns are dune flow, slug flow, packed beds, and homogeneous flow.
  - fluidized beds: consists of a vertical cylinder containing particles where gas is introduced through a distributor. The gas rising through the bed suspends the particles. Depending on the gas flow rate, bubbles appear and rise through the bed, intensifying the mixing within the bed.
- liquid-solid flows
  - slurry flow: transport of particles in liquids. the fundamental behavior of liquid-solid flows varies with the properties of the solid particles relative to those of the liquid. In slurry flows, the Stokes number ($St = \tau_d / t_s$) is normally less than 1. When the Stokes number is larger than 1, the characteristic of the flow is liquid-solid fluidization.
  - hydrotransport: densely-distributed solid particles in a continuous liquid.
  - sedimentation: a tall column initially containing a uniform dispersed mixture of particles. At the bottom, the particles will slow down and form a sludge layer. At the top, a clear interface will appear, and in the middle a constant settling zone will exist.
- three-phase flows, e.g. gas-liquid-solid flows.

Each of these flow regimes is illustrated in Figure (1).

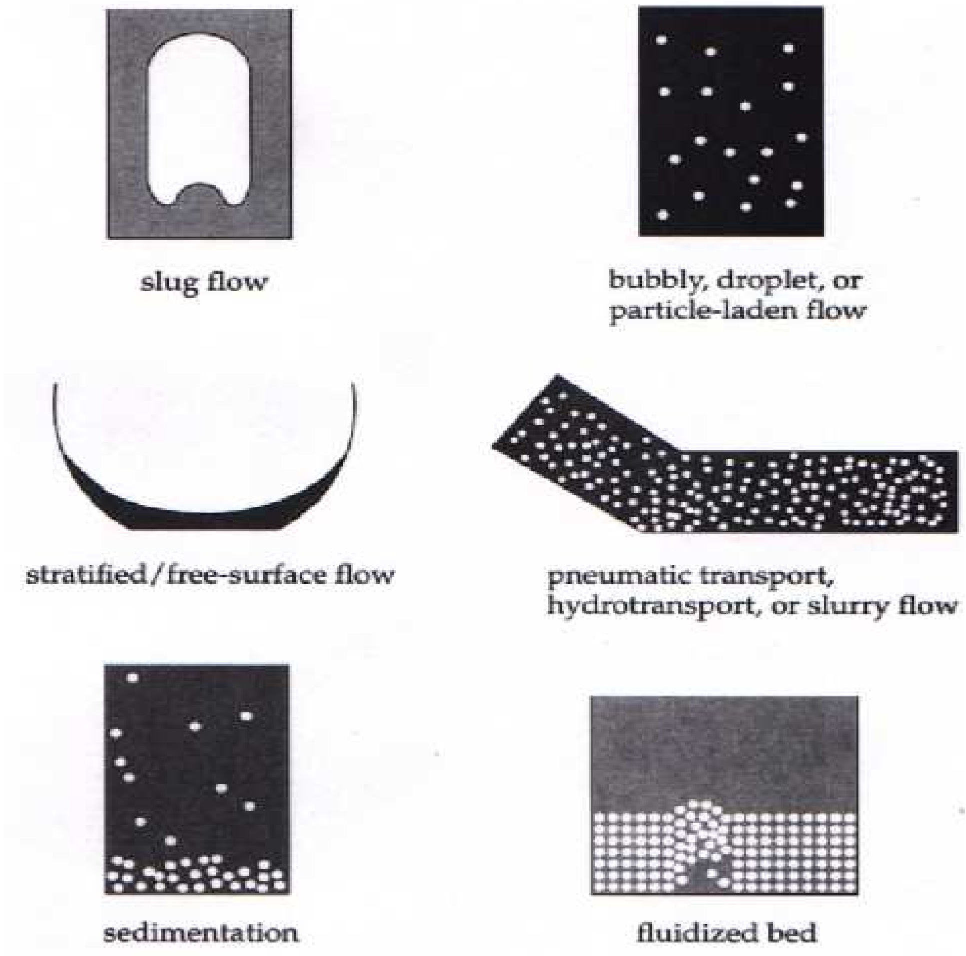

Figure 1: Multiphase Flow Regimes.

Examples of Multiphase Systems
Specific examples of each regime are listed below:

- Bubbly flow examples: absorbers, aeration, air lift pumps, cavitation, evaporators, flotation, scrubbers
- Droplet flow examples: absorbers, atomizers, combustors, cryogenic pumping, dryers, evaporation, gas cooling, scrubbers
- Slug flow examples: large bubble motion in pipes or tanks.
- Stratified/free-surface flow examples: sloshing in offshore separator devices, boiling and condensation in nuclear reactors
- Particle-laden flow examples: cyclone separators, air classifiers, dust collectors, and dust-laden environmental flows
- Pneumatic transport examples: transport of cement, grains, and metal powders
- Fluidized bed examples: fluidized bed reactors, circulating fluidized beds
- Slurry flow examples: slurry transport, mineral processing
- Hydrotransport examples: mineral processing, biomedical and physiochemical fluid systems
- Sedimentation examples: mineral processing

APPROACHES TO MULTIPHASE MODELING

Advances in computational fluid mechanics have provided the basis for further insight into the dynamics of multiphase flows. Currently there are two approaches for the numerical calculation of multiphase flows: the Euler-Langrange approach and the Euler-Euler approach.

The Euler-Lagrange Approach

The Lagrangian discrete phase model (in FLuent) follows the Euler-Langrange approach. The fluid phase is treated as a continuum by solving the time-averaged Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets through the calculated flow field. The dispersed phase can exchange momentum, mass, and energy with the fluid phase.

A fundamental assumption made in this model is that the dispersed second phase occupies a low volume fraction, even though high mass loading ($m_{particles} m_{fluid}$) is acceptable. The particle or droplet trajectories are computed individually at specified intervals during the fluid phase calculation. This makes the model appropriate for the modeling of spray dryers, coal and liquid combustion, and some particle-laden flows, but inappropriate for the modeling of liquid-liquid mixtures, fluidized beds, or any application where the volume fraction of the second phase is not negligible.

The Euler-Euler Approach

In the Euler-Euler approach, the different phases are treated mathematically as interpenetrating continua. Since the volume of a phase cannot be occupied by the other phases, the concept of phasic volume fraction is introduced. These volume fractions are assumed to be continuous functions of space and time and their sum is equal to one. Conservation equations for each phase are derived to obtain a set of equations, which have similar structure for all phases. These equations are closed by providing constitutive relations that are obtained from empirical information, or, in the case of granular flows, by application of kinetic energy.

Three different Euler-Euler multiphase models (are available in FLUENT): the volume of fluid (VOF), the mixture model, and Eulerian model.

The VOF Model

The VOF model is a surface-tracking technique applied to a fixed Eulerian mesh. It is designed for two or more immiscible fluids where the position of the interface between the fluids is of interest. In the VOF model, a single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain. Applications of the VOF model include stratified flows, free-surface flows, filling, sloshing, the motion of large bubbles in a liquid, the motion of liquid after a dam break, the prediction of jet breakup (surface tension), and the steady or transient tracking of any liquid-gas interface.

The Mixture Model

The mixture model is designed for two or more phases (fluid or particulate). As in the Eulerian model, the phases are treated as interpenetrating continua. The mixture model solves for the mixture momentum equation and prescribes relative velocities to describe the dispersed phases. Applications of the mixture model include particle-laden flows with low loading, bubbly flows, sedimentation, and cyclone separators. The mixture model can also be used without relative velocities for the dispersed phases to model homogeneous multiphase flow.

The Eulerian Model

The Eulerian model is the most complex of the multiphase models (in FLUENT). It solves a set of n momentum and continuity equations for each phase. Coupling is achieved through the pressure and interphase exchange coefficients. The manner in which this coupling is handled depends upon the type of phases involved; granular flows, the properties are obtained from application of kinetic theory. Momentum exchange between the phases is also dependent upon the type of mixture being modeled. (FLUENT's user-defined functions allow you to customize the calculation of the momentum exchange). Applications of the Eulerian mutiphase model include bubble columns, risers, particle suspension, and fluidized beds.