Two-Phase Flows

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Numerical modeling: Approaches

Choosing a General Multiphase Model

- The first step in solving any multiphase problem is to determine which of the regimes provides some broad guidelines for determining appropriate models for each regime, and how to determine the degree of interphase coupling for flows involving bubbles, droplets, or particles, and the appropriate model for different amounts of coupling.

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- There are two approaches for the numerical calculation of multiphase flows: the Euler-Lagrange approach and the Euler-Euler approach

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E-L

- In the Euler-Lagrange 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 is acceptable.

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E-L

- 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 fuel combustion, and some particle-laden flows, but inappropriate or expensive for the modeling of liquid-liquid mixtures, fluidized beds, or any application where the volume fraction of the second phase is not negligible.
- This approach will be discussed in detail later

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E-E

- 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 theory.

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- There are three different Euler-Euler multiphase models:
  - Volume of fluid (VOF) model,
  - Mixture model,
  - Eulerian model.

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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.

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The VOF Model

- 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.

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The Mixture Model

- The mixture model is designed for two or more phases (fluid or particulate).

- The mixture model solves for the mixture momentum equation and prescribes relative velocities to describe the dispersed phases.

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The Mixture Model

- 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.

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The Eulerian Model

- The Eulerian is a more complex model among the multiphase models.
- It solves a set of 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 (fluid-solid) flows are handled differently than nongranular (fluid-fluid) flows.

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The Eulerian Model

- For 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.
- Applications of the Eulerian multiphase model include bubble columns, risers, particle suspension, and fluidized beds.

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Comparison

- In general, once you have determined the flow regime that best represents your multiphase system,
- Selecting the appropriate model could be based on the following guidelines:
  - For bubbly, droplet, and particle-laden flows in which the phases mix and/or dispersed-phase volume fractions exceed 10%, use either the mixture model or the Eulerian model.
  - For slug flows, use the VOF model.
  - For stratified/free-surface flows, use the VOF model.

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Comparison

- For pneumatic transport, use the mixture model for homogeneous flow or the Eulerian model for granular flow.
- For fluidized beds, use the Eulerian model for granular flow.
- For slurry flows and hydrotransport, use the mixture or Eulerian model.
- For sedimentation, use the Eulerian model.

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Comparison

- For general, complex multiphase flows that involve multiple flow regimes, select the aspect of the flow that is of most interest, and choose the model that is most appropriate for that aspect of the flow.

- Note that the accuracy of results will not be as good as for flows that involve just one flow regime, since the model you use will be valid for only part of the flow you are modeling.

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Comparison

- As discussed, the VOF model is appropriate for stratified or free-surface flows, and the mixture and Eulerian models are appropriate for flows in which the phases mix or separate and/or dispersed-phase volume fractions exceed 10%.

- Flows in which the dispersed-phase volume fractions are less than or equal to 10% can be modeled using the discrete phase model.

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Comparison

- To choose between the mixture model and the Eulerian model, consider the following guidelines:
  - If there is a wide distribution of the dispersed phases the mixture model may be preferable (i.e., less computationally expensive).
  - If the dispersed phases are concentrated just in portions of the domain, use the Eulerian model instead.
  - If you want specify the particle distribution use discrete phase model.

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Comparison

- If interphase drag laws that are applicable to your system are available, the Eulerian model can usually provide more accurate results than the mixture model.

- Even though you can apply the same drag laws to the mixture model, as you can for a nongranular Eulerian simulation, if the interphase drag laws are unknown or their applicability to your system is questionable, the mixture model may be a better choice.

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Comparison

- If you want to solve a simpler problem, which requires less computational effort, the mixture model may be a better option, since it solves a smaller number of equations than the Eulerian model.
- If accuracy is more important than computational effort, the Eulerian model is a better choice.
- Keep in mind, however, that the complexity of the Eulerian model can make it less computationally stable than the mixture model.

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Comparison

- For stratified and slug flows, the choice of the VOF model, is straightforward.
- Choosing a model for the other types of flows is less straightforward. As a general guide, there are some parameters that help to identify the appropriate multiphase model.
- The particulate loading, and the Stokes number, St, are important parameters which will be defined later.

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The Significance of Particulate Loading

- Depending on the particulate loading, the degree of interaction between the phases can be divided into the following three categories:
  - For very low loading, the coupling between the phases is one-way (i.e., the fluid carrier influences the particles via drag and turbulence, but the particles have no influence on the fluid carrier). The discrete phase, mixture, and Eulerian models can all handle this type of problem correctly. Since the Eulerian model is the most expensive, the discrete phase or mixture model is recommended.

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The Significance of Particulate Loading

- For intermediate loading, the coupling is two-way (i.e., the fluid carrier influences the particulate phase via drag and turbulence, but the particles in turn influence the carrier fluid via reduction in mean momentum and turbulence). The discrete phase, mixture, and Eulerian models are all applicable in this case, but you need to take into account other factors in order to decide which model is more appropriate. (See below for information about using the Stokes number as a guide.)
- For high loading, there is two-way coupling plus particle pressure and viscous stresses due to particles (four-way coupling). The Eulerian model can handle this type of problem correctly

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The Significance of the Stokes Number

- For systems with intermediate particulate loading, estimating the value of the Stokes number can help you select the most appropriate model. The Stokes number can be defined as the relation between the particle response time and the system response time:

$$\mathrm{St} = \frac{\tau_d}{t_s}$$

$$\tau_d = \frac{\rho_d d_d^2}{18\mu_c}$$

$$t_s = \frac{L_s}{V_s}$$

L_s: characteristic length

V_s: characteristic velocity

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The Significance of the Stokes Number

- For St<<1, the particle will follow the flow closely and any of the three models (discrete phase, mixture, or Eulerian) is applicable; you can therefore choose the least expensive (the mixture model, in most cases), or the most appropriate considering other factors.
- For St>>1, the particles will move independently of the flow and either the discrete phase model or the Eulerian model is applicable.
- For St≈1, again any of the three models is applicable; you can choose the least expensive or the most appropriate considering other factors.

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Stability and Convergence

- The process of solving a multiphase system is inherently difficult, and you may encounter some stability or convergence problems. If a time-dependent problem is being solved, and patched fields are used for the initial conditions, it is recommended that you perform a few iterations with a small time step, at least an order of magnitude smaller than the characteristic time of the flow. You can increase the size of the time step after performing a few time steps. For steady solutions it is recommended that you start with a small under-relaxation factor for the volume fraction.

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Stability and Convergence

- It is also recommended not to start with a patch of volume fraction equal to zero.
- Another option is to start with a mixture multiphase calculation, and then switch to the Eulerian multiphase model.
- Many stability and convergence problems can be minimized if care is taken during the setup and solution processes.

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The End