Drag Laws 101

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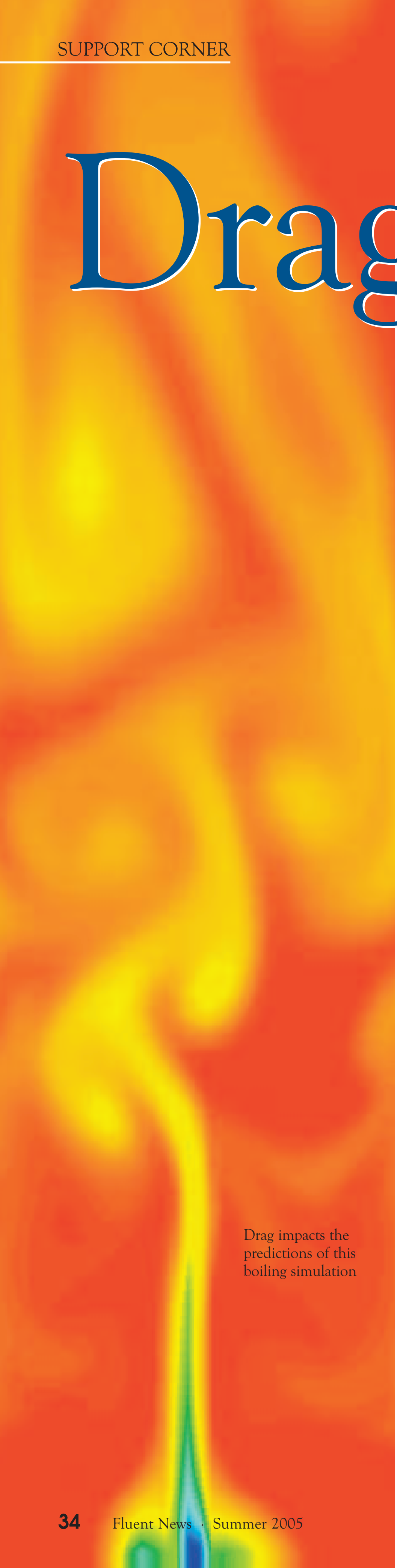


Drag impacts the predictions of this boiling simulation

WHEN DIFFERENT FLUIDS, or phases, occupy a system, their individual motions are predominately influenced by drag and gravity. The latter, gravity, is known exactly, but the former is harder to pin down. The success of a multiphase simulation, therefore, hinges on how well the drag is captured for the system of interest.

Drag is a friction force between phases. It originates from certain conditions that the velocity fields of two fluids must obey at the interface that separates them. One condition stipulates that the tangent velocity and stress components must be continuous across the interface. This condition is a generalization of the no-slip boundary condition at the wall. Another condition is that stress components normal to a curved interface must have a jump in magnitude across that interface due to surface tension. Therefore, drag appears only when there is a gradient of velocity across an interface, which only happens when the phases on either side of the interface move with different velocities. If two phases move with the same velocity, the fluids are in mechanical equilibrium, and the drag force is identically zero.

FLUENT has four multiphase models:

1. The Discrete Phase Model (DPM) consists of a continuous background fluid and a discrete secondary phase of particles, bubbles, or droplets. Trajectories of particle streams are allowed to exchange heat, mass, and momentum with the continuous phase.

2. The Eulerian Multiphase Model is the most general-purpose multiphase model, and is used for mixtures of gas, liquid, and solid phases. A complete set of momentum equations is solved for each phase, and different options exist for the solution of other transport equations, such as those for energy and turbulence.

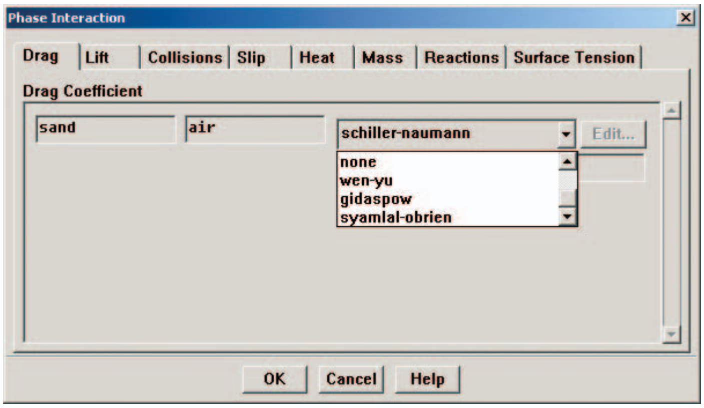
3. The Mixture Model is also designed for mixtures of gas, liquid, and solid phases. It is more economical than the Eulerian model but has a more limited range of applicability, working best if the phases are tightly coupled, that is, if the velocity vectors of the phases are approximately aligned. Rather than make use of separate sets of momentum equations, one set is used, and an algebraic equation is solved for the slip velocity between the phases.

4. The Volume of Fluid (VOF) Model is designed for free-surface and interface tracking between two or more immiscible fluids. As for the mixture model, a single set of momentum equations is solved, and a special routine is used to compute the shape of the interface.

Because the VOF model is used for bubbles or fluid regions that are larger than a typical computational cell, the calculation of drag is based on first principles – the flow around the actual bubble, for example – and a drag law is not required. For the other multiphase models, frictional drag is accounted for in momentum exchange terms that appear for each pair of phases in each momentum equation in a simulation. Thus for an Eulerian two-phase system in 3D, there are exchange terms in each of the three momentum equations for the primary phase, and equal and opposite exchange terms in the three momentum equations for the secondary phase. For DPM simulations, the exchange terms appear in the momentum equations for the continuous phase and a corresponding force is used in the trajectory equation(s) for the discrete phase.

In general, the momentum exchange term is proportional to the velocity differential between phases and a drag function, which is obtained empirically for a specific flow regime. The Schiller-Naumann (SN) drag law is the most basic one offered in FLUENT, and is the default choice for the Eulerian and mixture models. It depends on the relative Reynolds number, which, for primary phase p and secondary phase s, is:

$$\mathrm{Re} = \frac{\rho_p d_s \, |u_s - u_p|}{\mu_p}$$



Drag Coefficient

sand | air | schiller-naumann

The Phase Interaction panel is used to select the drag law in FLUENT

The SN drag law uses different coefficients for the two regimes Re > 1000 and Re < 1000. It is valid for particles in a dilute mixture (with volume fraction < 10%), as long as they are spherical.

The drag law of Morsi and Alexander (MA) is similar to the SN drag law, but the relative Reynolds number range is divided up into eight segments for which coefficients are defined. This is the default choice for DPM when spherical particles (or bubbles or droplets) are being tracked. When the MA drag law is used with the Eulerian or mixture models, it can be less stable than the SN approach. Thus for these models, it is good practice to estimate beforehand whether or not the added accuracy of the MA drag law is needed.

The symmetric model (SM) is a modification of SN that is recommended for cases where the secondary phase (as defined in the simulation) is dispersed in one region but continuous in another region. This might happen in a bubble column, where gas bubbles enter at the bottom, but the top of the column is completely filled with gas. To account for this condition, the standard SN drag coefficient is used, but the momentum exchange term itself is modified.

The three drag laws described so far are best suited for dilute flows with second phase volume fractions of 10% or less. They can be used for gas-liquid, gas-solid, or liquid-solid mixtures. Other drag laws are specifically designed for gas-solid flows, which are common in risers, cyclones, and fluidized beds. The Eulerian and mixture models offer additional drag laws for these special circumstances. The simplest of these is the Wen and Yu (WY) drag law, a modified form of the SN law, originally developed as a correlation for sedimentation experiments of solid particles in liquid columns. For gas-solid mixtures, it is recommended for low volume loading.

At higher volume fractions, particle-particle collisions become more frequent, and their impact on the drag must be accounted for. The Gidaspow (G) drag law does this by using a combination of the WY drag law for regions where the particle volume fraction is below 20%, and the Ergun drag law, which was developed for fixed (packed) beds, elsewhere. The Gidaspow drag law should be used whenever close packing is expected in any part of the computational domain, a condition typical of settling beds. The Syamlal and O'Brien (SO) drag law accounts for increased volume loading through the use of a drag coefficient that depends on volume fraction-dependent terminal velocities for falling particles in settling or fluidized beds. Other coefficients used to compute the momentum exchange term are computed based on the particle volume fraction. The minimum velocity at which the drag between particles and the fluid just balances the weight of the particle bed is called the minimum fluidization velocity, and is denoted by U_{mf}. The SO drag law contains adjustable parameters that can be used to tune the drag to match the theoretical U_{mf} to experimentally observed values.

Besides the form of the drag law, the momentum exchange term is strongly influenced by the diameter of the particle, bubble, or droplet, so it is very important that an appropriate value is used for this parameter. If experimental measurements of the secondary phase diameter are unavailable, a trial and error method can be adopted, and an appropriate diameter chosen based on the quality of the solutions obtained. In general, particles with very small diameters and densities close to the primary phase will more or less follow the primary phase. Separation of the phases will take time, and will be characterized by a diffuse interface. If the particle diameters and densities are large, separation of the phases will occur more quickly, and the resulting interface will be more crisp. ■

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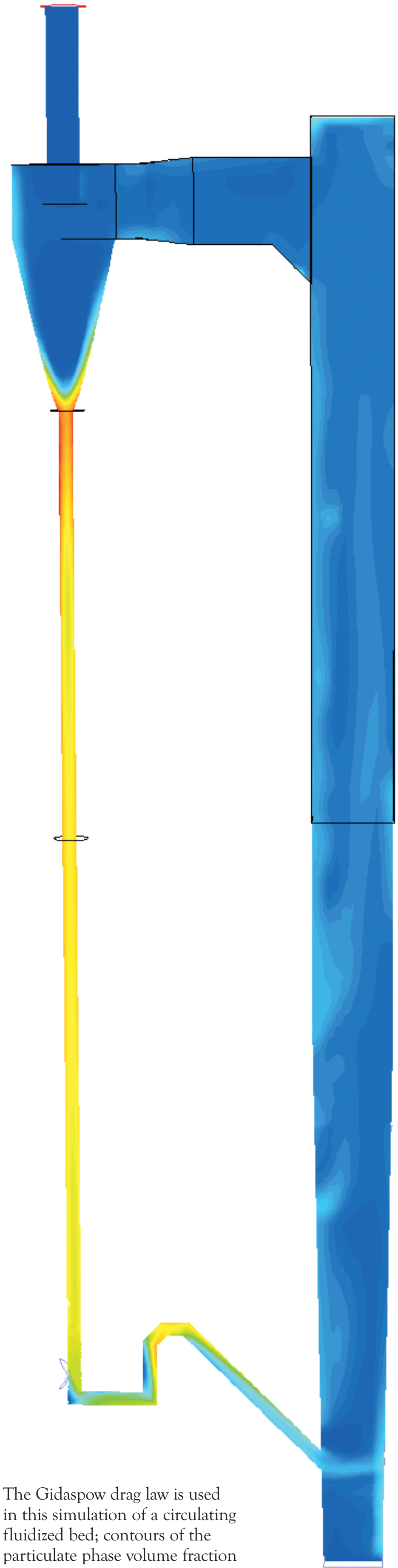

The Gidaspow drag law is used in this simulation of a circulating fluidized bed; contours of the particulate phase volume fraction are shown