Multiphase flow modeling

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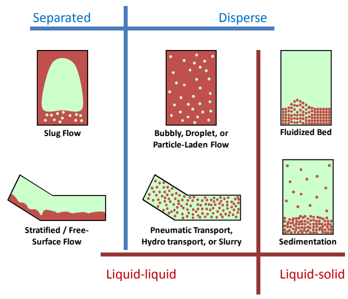
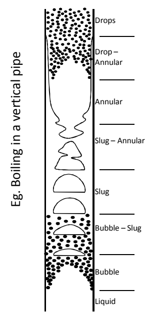
Flow regimes

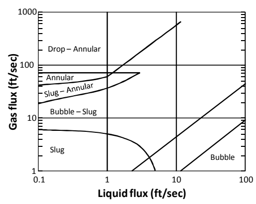


Definitions

- 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 physical or chemical properties but in the same state or phase (i.e. liquid-liquid, such as, oil-water).
- In contrast, **multi-component** / **multispecies flow** refers to a "mixture" formulation where components are mixed at molecular level and velocity and temperature are the same for all components.

Flow regimes in vertical gas-liquid flow





Models are available in FLUENT for all flow regimes, but neither can cover every regime.

Types of multiphase flows

- Gas-Liquid flow
  - Bubbly flows
  - Droplet flows
- Gas-solid flow
  - Pneumatic transport
  - Fluidized beds
- Liquid-solid flow (Slurry Flows)
  - Coal/ore transport
  - Mud flow
- Immiscible/Stratified flow

Every type can have various flow regimes

Multiphase models in FLUENT

- Volume of Fluid model (VOF)
  - Can be used for analyzing separated flows when the surface shape must be determined.
- Mixture Model
  - Assumes locally homogenous flow with variable volume fraction of each secondary phase.
  - The summed-up momentum equation of the phases with phase-averaged physical properties is solved. Relative velocities of all secondary phases are calculated by means of simplified algebraic relations.
- Eulerian Model
  - The multi-fluid approach used in the Eulerian and Granular multiphase models that all phases comprise, separate, but intermixed continua.
  - Eulerian model solves momentum equation for each phase using material properties of that phase. Momentum equations of different phases are coupled through inter-phase interaction forces.
- Lagrangian Dispersed Phase Model (DPM)
  - In DPM particle is described at a single point that moves at its velocity and each particle is treated individually, but with a point-wise representation. (Calculates particle trajectories.)
  - For a large number of particles, computational "parcels" are used where each parcel represents a cloud of many particles with the same characteristics.
  - Two-way coupling with the continuous phase. Inter-particle interactions (friction and coalescence) can be modeled as well.

Applicability of the VOF model

- VOF model is used to model immiscible fluids with clearly defined interface:
  - Two gases cannot be modeled since they mix at the molecular level;
  - Liquid-liquid interfaces can be modeled as long as the two liquids are immiscible (e.g. water-oil mixture).
- Surface tension and wall adhesion can be taken into account.
- Typical applications:
  - Break-up of liquid jets;
  - Motion of large bubbles;
  - Separator tanks;
  - Fuel tank sloshing;
  - Dam break;
  - Wave resistance of ships;
  - Ground water flow.
- VOF is not appropriate if interface length is very small compared to a computational domain.

Mixture model

- Simplified form of the multifluid (Eulerian) model. Lower computing cost and memory demand, and more numerical robustness.
- Mixture continuity, momentum equation and energy equation is solved along with additional transport equations for the volume fraction of all secondary phases.
- Relative velocities of the secondary phases are calculated by means of algebraic relations obtained from momentum equation of the phase by assuming zero relative acceleration (kinetic equilibrium).
- The main assumption is, that the relative velocity is much smaller than the mixture velocity. (Fluid particles follow the mixture path closely.)
- Assumes the same turbulent quantities for all phases.
- Can accommodate cavitation models.

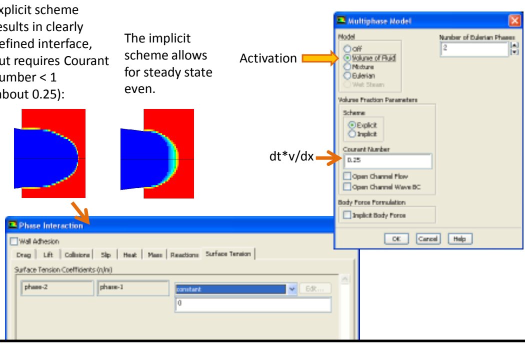
VOF model parameters

Explicit scheme results in clearly defined interface, but requires Courant number < 1 (about 0.25):

The implicit scheme allows for steady state even.

Activation

dt*v/dx



The relative velocity

$$\vec{v}_{pq} = \frac{\tau_p}{f_{drag}} \frac{\rho_p - \rho_m}{\rho_p} \vec{a}$$

+ one more term in turbulent flow

(Can be replaced by own model using an UDF.)

$\vec{a}$: the body-force and inertial forces in a frame moving with the primary phase.

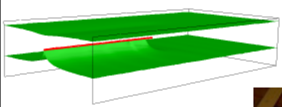
$\tau_p = \frac{\rho_p d_p^2}{18 \mu_q}$: Stokes time scale (particle relaxation time).

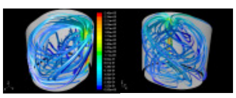
f_{drag} : drag function. Multiple models are available. The default option is the Shiller-Naumann modell:

$$f_{drag} = \begin{cases} 1 + 0.15\, Re^{0.687} & Re \le 1000 \\ 0.0183\, Re^{0.687} & Re > 1000 \end{cases}$$

Application examples

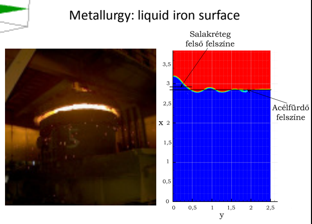
Oil-gas and water-oil surfaces around a horizontal oil well





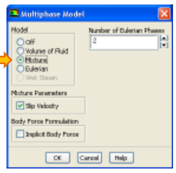
Waves in a swimming pool

Metallurgy: liquid iron surface

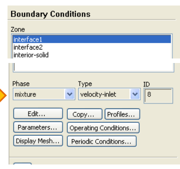


Mixture model parameters

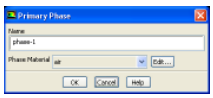
Activation

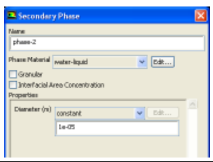


Boundary condition s for the mixture and for every phase

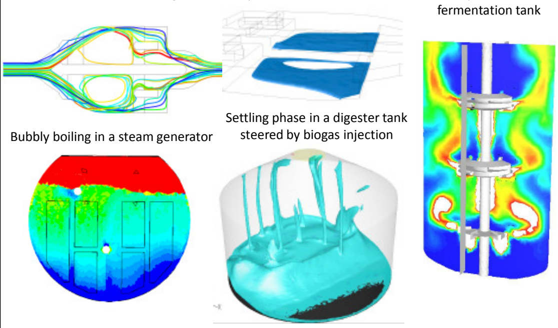


In the Phases menu:





Application examples



Granular temperature: Θ

- Kinetic energy stored in the random motion of granular particles is quantified by the granular temperature.
- Solid pressure and solid viscosity depend on Θ.
- Θ is increased by shear rate of the solid phase;
  Θ is decreased by inelastic collisions between particles.
- Can be evaluated by means of a transport equation or (in the case of dens granular beds) from an algebraic expression.

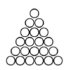
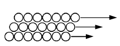
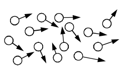
Multifluid model (Eulerian)

- Used to model dispersed phase (solid particles, bubbles, droplets) in continuous (primary) phase (liquid or gas).
- Allows for mixing and separation of phases.
- Solves momentum, enthalpy, and continuity equations for each phase and tracks volume fractions. The conservation equations are coupled via inter-phase interactions terms.
- Uses a single pressure field for all phases. (Solid pressure due to particle-particle collisions is also taken into account in the Granular model.)
- Uses inter-phase drag coefficient, virtual mass effect (for bubbly phases) and lift forces (in heavily sheared flows).
- Can solve turbulence equations for each phase.
- Can model homogenous and heterogeneous (e.g. surface combustion) chemical reactions.

Wet steam model

- Describes the initial phase of volume condensation in **Eulerian model**.
- Main applications: droplet erosion of steam turbines (and some other parts of power plants).
- Assumes low (<0.2) liquid phase mass fraction, droplets moving together with the gas phase, and no interparticle interactions.
- Mass concentration of the vapor phase and the number density of droplets are obtained from transport equations.
- Features a built-in real gas model for water vapor and material property functions of water valid in wide parameter range.
- Works only with the density based solver.

Granular models

Elastic Regime	Plastic Regime	Viscous Regime
Stagnant	Slow flow	Rapid flow
Stress is strain dependent	Stress is independent from the shear rate	Stress depends from the shear rate
		

This regimes can be modeled with **Mixture or Eulerian** approaches by taking into account inter/particle collision and friction forces.

Cavitation model

Evaporation and condensation of water due to the changing pressure.
Used for modeling cacitation characteristics of pumps and water turbines.

Continuity of the vapor phase:

$$\frac{\partial}{\partial t}(\alpha\rho_v)+\nabla\cdot(\alpha\rho_v\vec{v}_v)=\overbrace{\pm\frac{\rho_v\rho_\ell}{\rho}\alpha(1-\alpha)\frac{3}{\left(\frac{\alpha}{1-\alpha}\frac{3}{4\pi}\frac{1}{n}\right)^{\frac{1}{3}}}\underbrace{\sqrt{\frac{2}{3}\frac{\pm(p_v-p)}{\rho_\ell}}}_{\text{Velocity of bubble growing (Simplified Rayleigh-Plesset eq.)}}}^{\text{Evaporation rate (kg/m}^3\text{-s).}}$$

α: volume concentration of the vapor phase;
ρ_v: vapor density;
v_v: velocity of the vapor phase;
ρ_l: water density;
n: number density of bubles;
p_v: saturated vapor pressure;
p: mixture pressure.

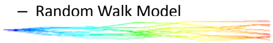
Can be used in **Mixture and in Eulerian** models in 3 different model variations.

Discrete phase model (DPM)

- Calculates particle trajectories in the continuous phase.
- Used for modeling particles such as solid particles or dropplets dispersed in a continuous phase.
- Main application areas: fuel injection; drying; cyclone separators; coal combustion; pneumatic transport systems.
- Can be used in steady and in unsteady flows.
- Mass, momentum, and heat transfer between disperse and continuous phases can be taken into account.
- With the exception of the Dens DPM:
  - Inter-particle interactions are not taken into account;
  - Disperse phase has low (<10%) volume fraction, but high mass fraction is allowed;
  - Assumes particles getting in and going out of the domain. No long particle residence time, such as, for suspension or sedimentation.

Effect of turbulence

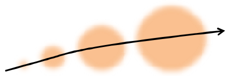
- When particles enter a turbulent eddy, they try to follow it for the time they are crossing the eddy.
- This effect leads to lateral dispersion which must be considered in modeling.
- Two approaches are available :
  - Random Walk Model



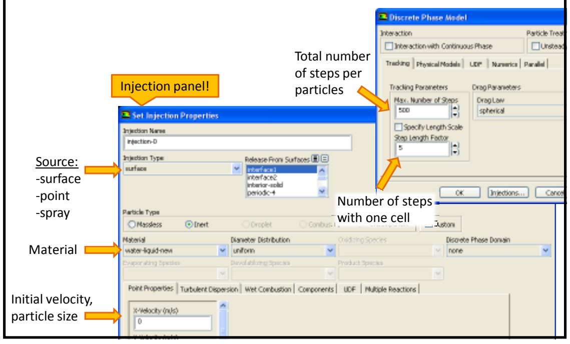
$$u'_i = \zeta\sqrt{\frac{2k}{3}}$$

ζ: Random number with Gaussian distribution

  - Particle Cloud Model

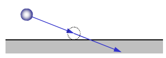


DPM parameters

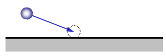


DPM boundary conditions on solid walls

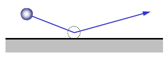
- Escape – Particle leaves the flow domain.



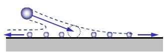
- Trap – Particle is collected on the wall.



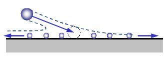
- Reflect – Particle bounces off the wall with user-prescribed coefficient of restitution.



- Wall Jet – Simulates an inviscid jet of particles impacting the wall (no significant liquid film is formed on the wall).



- Wall Film – Similar to wall jet; simulates case where significant film is formed on the wall.



Note: there are models for particle erosion.

Equation of motion

$$\frac{d\vec{v}_p}{dt} = \underbrace{F_D\left(\vec{v}-\vec{v}_p\right)}_{\text{Drag}} + \underbrace{\vec{g}\,\frac{\rho_p-\rho}{\rho_p}}_{\text{Gravity}} + \vec{F}_{other}$$

Other forces:

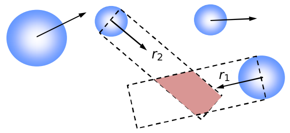
- Inertial force in rotating reference frame;
- Thermophoresis (Termophoretic force): small particles suspended in a gas that has a temperature gradient experience a force in the direction opposite to that of the gradient;
- Brown erő: random force representing the effect of molecular collisions. Diffusion of sub-micron particles due to Brownian motion can be taken into account in laminar flow, (if the energy equation is solved).
- Turbulent buffeting;
- Lift force in shearing flows (Saffman's lift force);
- User defined forces.

Spray models

- Primary break-up: formation large droplets from the liquid jet emitted by a nozzle. Depend on the turbulence and velocity profile at the nozzle outlet. The model randomly changes droplet size, injection angle, and time of particle release. 5 different spray models are available in the **Injections menu** (Atomizer models).
- Secondary break-up: Large droplets are taken apart by the relative gas flow. From time to time "Child parcels" are released from the vicinity of the parent parcel, and the mass of the parent parcel is reduced. Available in the **Discrete Phase menu** in two versions:
  1) Taylod Analogy Break-up (TAB) model: spring-mass-damper (surface tension-fluid mass-viscosity). Can be applied in the cases of low Weber-number (We<100).
  2) Wave model: Waves are generated on the droplet surface due to the shear stress. Size of the child droplets is determined from the wavelength of the fastest growing surface wave.

Collision and coalescence

- Particles move around and may collide or may not.
- Probability depends on particle velocity and diameter.



- Collision volume relative to the cell volume is a measure of the probability of collision.
- Only coalescence and bouncing are considered. (Droplets do not explode.)

A Dens DPM modell

- For the calculation of collision and friction forces volume fraction of the dispersed phase must be known.
- This approach is based on the Eulerian multiphase model, but the solutions of the continuity and the momentum equation of the dispersed phase are taken from the DPM model (via averaging).
- Granular temperature is calculated on the basis of volume fraction and shear rate of the solid phase obtained from the DPM calculations.
- Particle size classes does not require distinct continuous phases. Particle sizes are treated in the DPM model.

Mass and energy transfer laws in DPM model (Law 1-10)

Built-in expressions / UDF

- Innert heating and cooling of particles
- Evaporation
- Droplet boiling
- Devolatilization (evaporation of some flammable components)
- Surface combustion
- Multicomponent particle definition