Modeling of Two-phase Flow and Boiling with FLUENT

by

Nilanjana Basu, Andrey Troshko, and Greg Nurnberg

Fluent Inc.
Lebanon, New Hampshire
www.fluent.com

Presented at RELAP5 UGM, West Yellowstone, Montana
July 27, 2003
Outline

- FLUENT & RELAP5-3D© Coupling
- Multiphase models in FLUENT
- Boiling and two-phase flow Case studies with FLUENT
- Summary
FLUENT & RELAP5-3D© Coupling

Advantages

• Model entire system using 1 dimensional features of RELAP5-3D©

• Model some components of the system in detail using the 3 dimensional features of FLUENT

• Both the system and component behavior is more accurately predicted

• Boundary condition information is transferred back and forth between the two codes
Some key modeling capabilities in FLUENT to be utilized:

- Turbulence
- Two-phase flow
- Flow through packed bed
- Neutronics-fluid interaction in the core region

*Focus of this presentation: Two-phase flow*
Multiphase models in FLUENT

• Discrete Phase Model (DPM)
• Mixture Model
• Volume of Fluid Model (VOF)
• Eulerian Multiphase Flow Model
Discrete Phase Model (DPM)

- Trajectories of particles/droplets/bubbles are computed in a Lagrangian frame.
  - Particles can exchange heat, mass, and momentum with the continuous gas phase.
  - Particle-Particle interaction is neglected.
  - Turbulent dispersion can be modeled with stochastic tracking or a “particle cloud” model.

- Volume loading: volume fraction < 12%
- Particulate Loading: Low to moderate.

Application examples: Cyclones, spray dryers, particle separation and classification, aerosol dispersion, liquid fuel and coal combustion, etc.
The Mixture Model

- Modeling N-phase flows.

- Solves the mixture momentum equation (for mass-averaged mixture velocity)
  - Inter-phase exchange terms depend on relative (slip) velocities
  - Turbulence and Energy equations are solved for the mixture
  - Only one of the phases may be defined as compressible.

- Solves the transport equation of volume fraction for each secondary phase.
## Multiphase models in FLUENT (contd.)

### Applicability of Mixture Model

- **Flow regime:** Bubbly flow, droplet flow, slurry flow.
- **Volume loading:** Dilute to moderately dense.
- **Particulate Loading:** Low to moderate.
- **Turbulence modeling:** Weak coupling between phases.
- **Stokes Number:** Stokes Number $< < 1$.

*Application examples: Hydrocyclones, bubble column reactors, solid suspensions, gas sparging.*
The Volume of Fluid Model (VOF)

- Model to track the position of the interface between two or more immiscible fluids.

- A single momentum equation is solved and the resulting velocity field is shared by all phases.
  - Surface tension and wall adhesion effects can be taken into account.

- Solves transport equation for volume fraction of each secondary phase.

- Recommended that simulation be performed in unsteady mode.
Multi-phase models in FLUENT (contd.)

Applicability of VOF Model

- Flow regime: Slug flow, stratified/free-surface flow.
- Volume loading: Dilute to dense.
- Particulate Loading: Low to high.
- Turbulence modeling: Weak to moderate coupling between phases.
- Stokes Number: All ranges of Stokes number.

Application examples: Large slug flows, filling, off-shore oil tank sloshing, boiling, coating.
The Eulerian Multiphase Model

- Solves continuity, momentum and energy equations for each phase.
  - Volume fractions characterize equation set for each phase.
  - Several models available to define inter-phase exchange coefficients.
  - Strong coupling makes this model more difficult to use than Mixture Model.

- **Euler Granular option**: each granular phase is treated as a distinct interpenetrating granular ‘fluid’.

- **Heat and mass transfer between n-phases**: Ranz-Marshall (Euler/Euler), Gunn (Euler/granular) and user-defined models.
Applicability of Eulerian model

- Flow regime: Bubbly flow, droplet flow, slurry flow, fluidized beds, particle-laden flow.
- Volume loading: Dilute to dense.
- Particulate Loading: Low to high.
- Turbulence modeling: Weak to strong coupling between phases.
- Stokes Number: All ranges of Stokes number.

Application examples: High particle loading flows, slurry flows, sedimentation, hydro-transport, fluidized beds, risers, packed bed reactors.
Boiling and two-phase flow Case studies with FLUENT

Advanced Pressurized Reactor

- The Advanced Pressurized Reactor is light water reactor being designed
- The In-containment Refueling Water Storage Tank (IRWST) is passive safety system for heat removal
- During a small break loss of coolant accident (SBLOCA) it allows steam to cool in a pool of water and escape through vents at the top
Boiling and two-phase flow Case studies with FLUENT (contd.)

Advanced Pressurized Reactor

- FLUENT is used to simulate the 2-phase flow in the IRWST
- The mixture is injected through a sparger
- The **Eulerian multiphase** model allows for separate transport equations for
  - liquid (water)
  - vapor (steam)
- The 2D model makes use of a porous region to allow only vapor to exit through most of the top boundary
Boiling and two-phase flow Case studies with FLUENT (contd.)

Advanced Pressurized Reactor

- Steady-state simulations are performed for different bubble sizes and vapor volume fraction

- For 1mm bubbles and 40% vapor at the inlet, most vapor escapes but some is entrained in recirculation in the water near the side of the vessel.
Boiling and two-phase flow Case studies with FLUENT (contd.)

Advanced Pressurized Reactor

- For 100mm bubbles and 10% vapor at the inlet the flow is very different
- Larger buoyant forces cause steam to rise and escape quickly
- Results suggest that FLUENT is well suited to assist in the design of these systems
Boiling and two-phase flow Case studies with FLUENT (contd.)

Subcooled Nucleate Boiling

Wall heat flux = Single phase heat flux + Quenching heat flux + Evaporation heat flux

Implemented as a source term in energy equation

A user-defined function (UDF) in FLUENT includes temperature-driven heat and mass transfer between phases

Subcooled Nucleate Boiling

An annular domain, with heated inner wall is simulated

- FLUENT 6.1 is used to simulate this process for three sets of experimental conditions\(^2\) (below)

- User-defined functions are used with the Eulerian multiphase model to implement the RPI model\(^1\) for

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EXP 1</th>
<th>EXP 2</th>
<th>EXP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner wall heat flux, W/m(^2)</td>
<td>80,000</td>
<td>95,000</td>
<td>116,000</td>
</tr>
<tr>
<td>Fluid mass velocity, kg/m(^2)/sec</td>
<td>565</td>
<td>785</td>
<td>785</td>
</tr>
<tr>
<td>Mean liquid subcooling at test section inlet, °C</td>
<td>37.8</td>
<td>30.3</td>
<td>30.3</td>
</tr>
</tbody>
</table>

Boiling and two-phase flow Case studies with FLUENT (contd.)

Subcooled Nucleate Boiling

Radial profiles of vapor void fraction prediction

Temperature predictions are in acceptable range.
Boiling and two-phase flow Case studies with FLUENT (contd.)

Boiling flow in nuclear reactor

- Flow in nuclear fuel assembly
  - Pressure 50 atm
  - \( \text{Re}_{\text{liq}} = 300,000 \)
  - Heat flux 0.522 MW/m\(^2\)
  - Inlet subcooling 4.5 K
  - \( y_+ = 100 \)
Boiling and two-phase flow Case studies with FLUENT (contd.)

Boiling flow in nuclear reactor

- Condensation or evaporation at surface of bubbles in free stream
- Turbulent dispersion of bubbles if liquid flow is turbulent
- Additional turbulence created by bubbles
- Modified lift force to account for vortex shedding by bubbles
Boiling and two-phase flow Case studies with FLUENT (contd.)

Boiling flow in nuclear reactor

- Wall temperature is defined by bisection method from flux partitioning
- ~3-4 hours to get converged solution on 2GHz CPU
  80,000 cells

Comparison with experiment for vapor void fraction
Film boiling

- Using VOF modeling in Fluent

\[ \lambda_0 = 2\pi \left( \frac{3\sigma}{(\rho_l - \rho_g)g_y} \right)^{1/2} = 0.0778m \]
Boiling and two-phase flow Case studies with FLUENT (contd.)

Film boiling

Animation

Contours of volume fraction of the vapor
Boiling and two-phase flow Case studies with FLUENT (contd.)

Film boiling

Velocity

Mass transfer rate, kg/m³/sec
Film boiling

Boiling and two-phase flow Case studies with FLUENT (contd.)

Berenson’s correlation

Mean Nusselt number

$$Nu = \frac{|q''| \lambda_0}{k_l (T_{wall} - T_{sat})}$$

Mean void fraction

Time, sec
Summary

• Case studies of nucleate boiling and film boiling with FLUENT have been presented.

• These case studies demonstrate that FLUENT can successfully model two-phase flow and boiling.

• Two-phase modeling capabilities will enhance Reactor thermal hydraulic study using FLUENT-RELAP5 coupling.