Modeling of Two-phase Flow and Boiling with FLUENT

by

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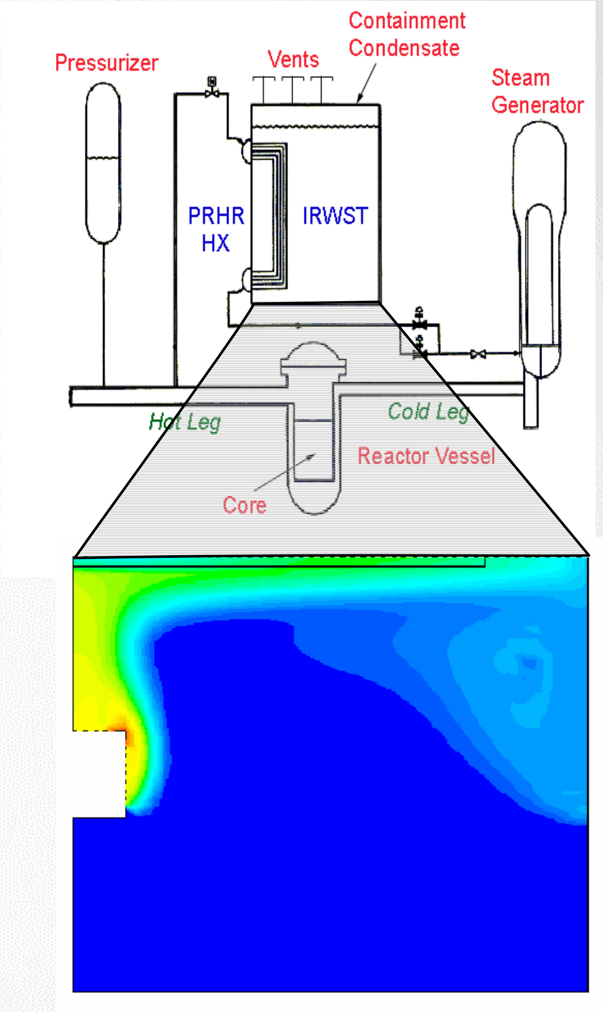
Outline

- 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



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FLUENT & RELAP5-3D© Coupling (contd.)

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

Multiphase models in FLUENT (contd.)

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.

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Multiphase models in FLUENT (contd.)

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.

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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.

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Multiphase models in FLUENT (contd.)

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.

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Multiphase 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.

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Multiphase models in FLUENT (contd.)

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.

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Multiphase models in FLUENT (contd.)

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.

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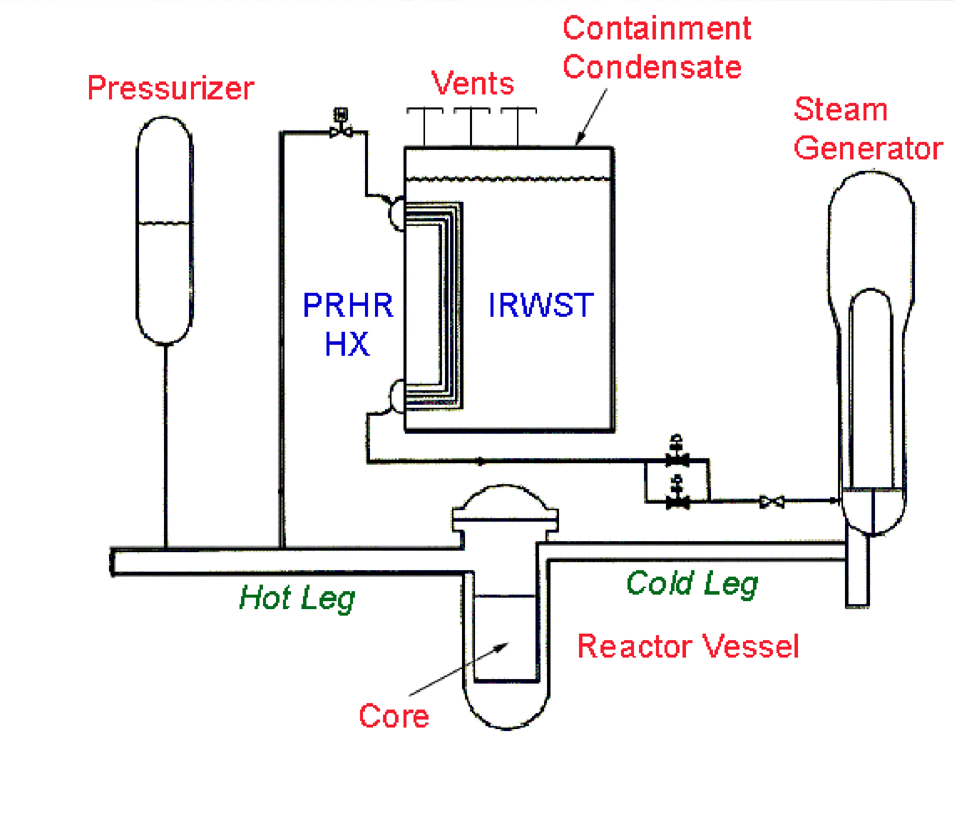
Boiling and two-phase flow Case studies with FLUENT

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



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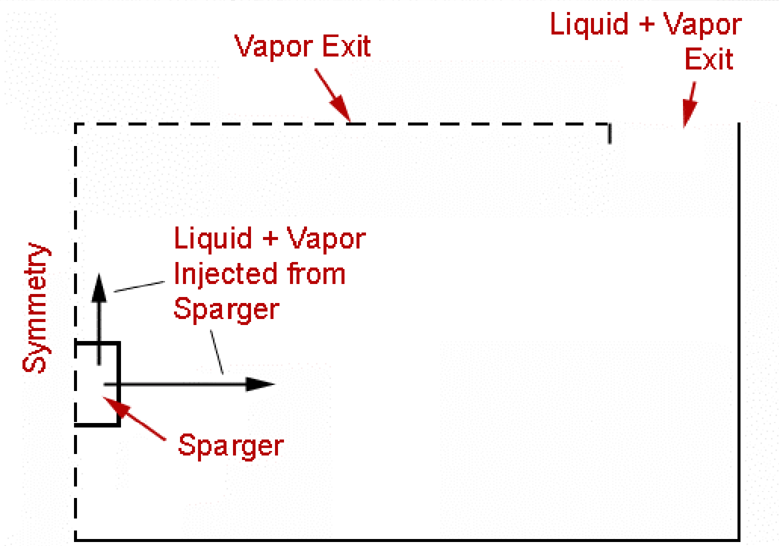
Boiling and two-phase flow Case studies with FLUENT (contd.)

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**

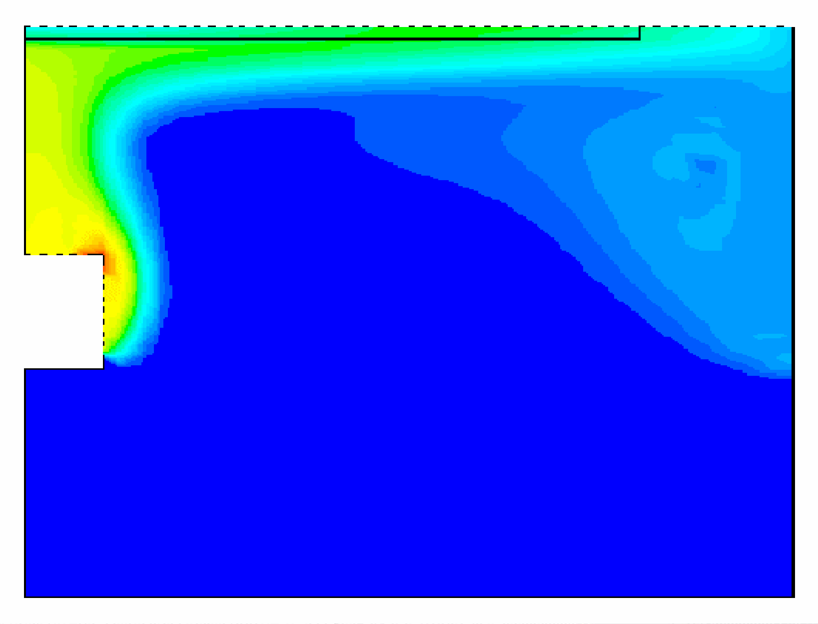


Boiling and two-phase flow Case studies with FLUENT (contd.)

Advanced Pressurized Reactor

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

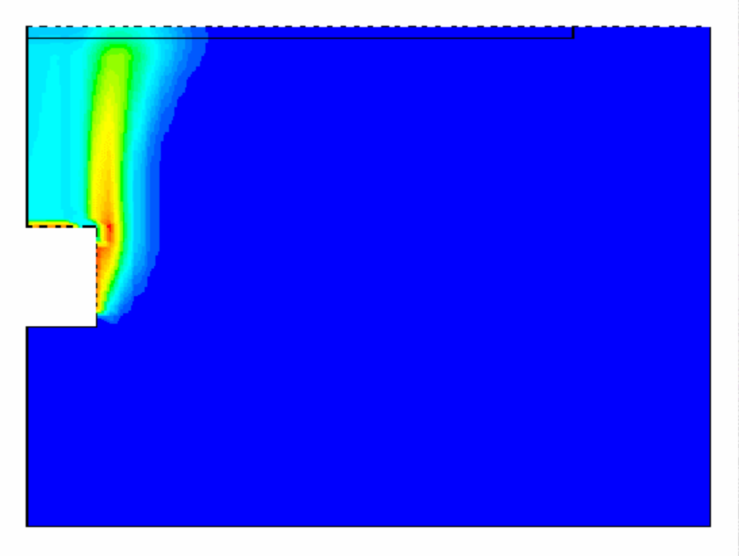
- **For 1mm bubbles and 40% vapor at the inlet, most vapor escapes but some is entrained in recirculation in the water near the side of the vessel**



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

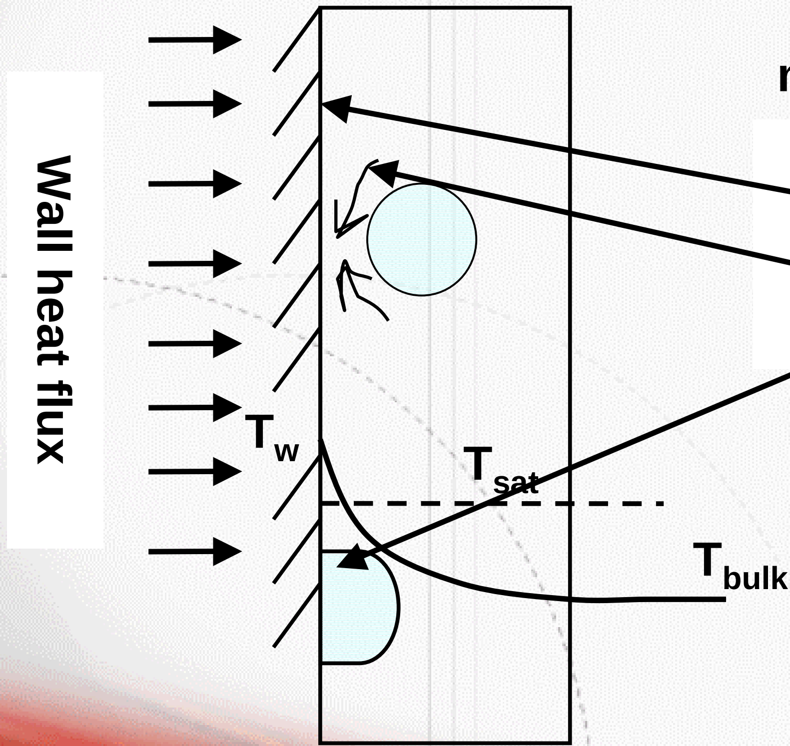
Advanced Pressurized Reactor

- 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



RPI (Rensselaer Polytechnic Institute) model of wall heat flux partitioning[1]

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[1]

[1]*Kurul, N., and Podowski, M. Z., 9th Int. Heat Trans. Conf. Jerusalem, p. 21-16, 1990.*

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

Subcooled Nucleate Boiling

An annular domain, with heated inner wall is simulated

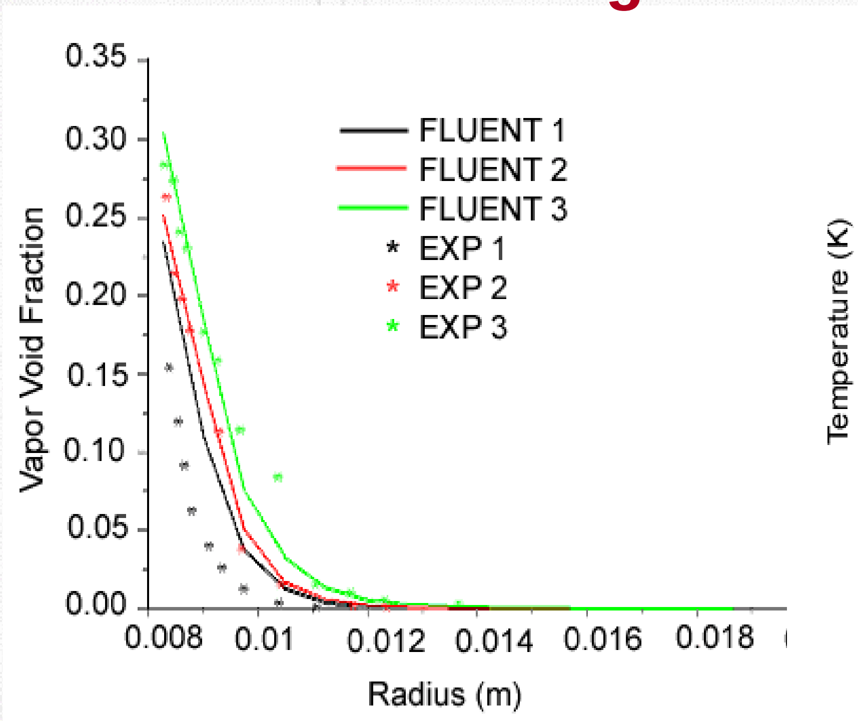
- **FLUENT 6.1 is used to simulate this process for three sets of experimental conditions[2] (below)**
- **User-defined functions are used with the Eulerian multiphase model to implement the RPI model[1] for**

Parameter	EXP 1	EXP 2	EXP 3
Inner wall heat flux, W/m^2	80,000	95,000	116,000
Fluid mass velocity, kg/m^2/sec	565	785	785
Mean liquid subcooling at test section inlet, ^{0}C	37.8	30.3	30.3

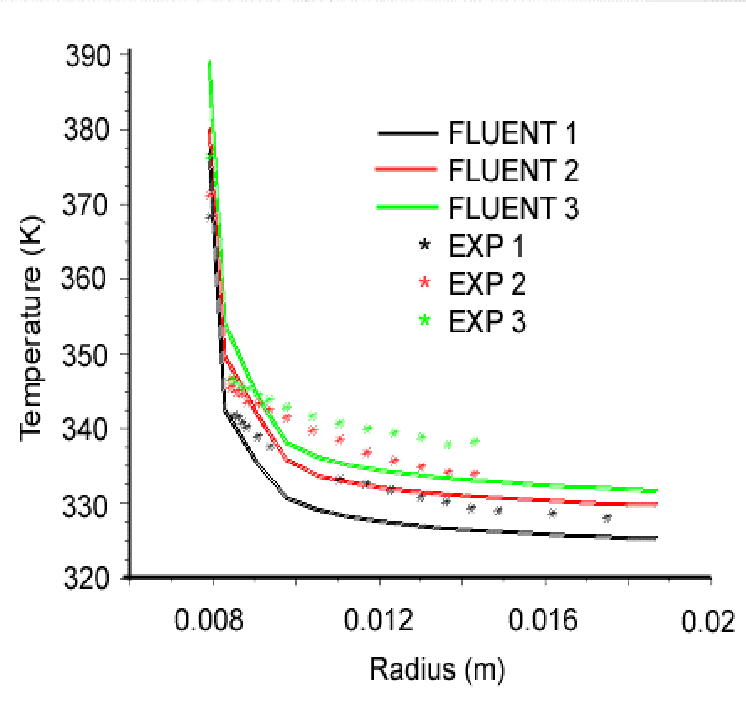
[2]*Roy, R. P., Velidandla, V., and Kalra, S. P., ASME J. Heat Trans. 119, 754-766 (1997).*

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

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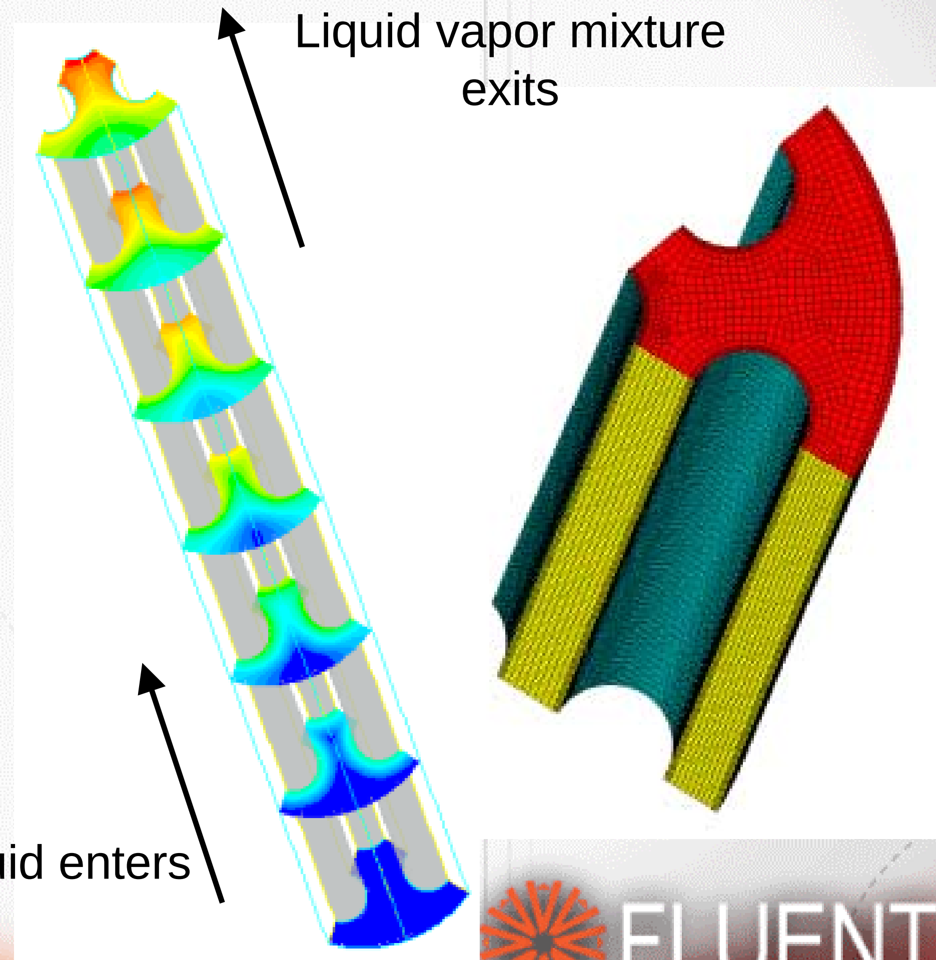
Boiling and two-phase flow Case studies with FLUENT (contd.)

Boiling flow in nuclear reactor

- **Flow in nuclear fuel assembly**
  - **Pressure 50 atm**
  - **Re_{liq}=300,000**
  - **Heat flux 0.522 MW/m^2**
  - **Inlet subcooling 4.5 K**
  - **y_+=100**



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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

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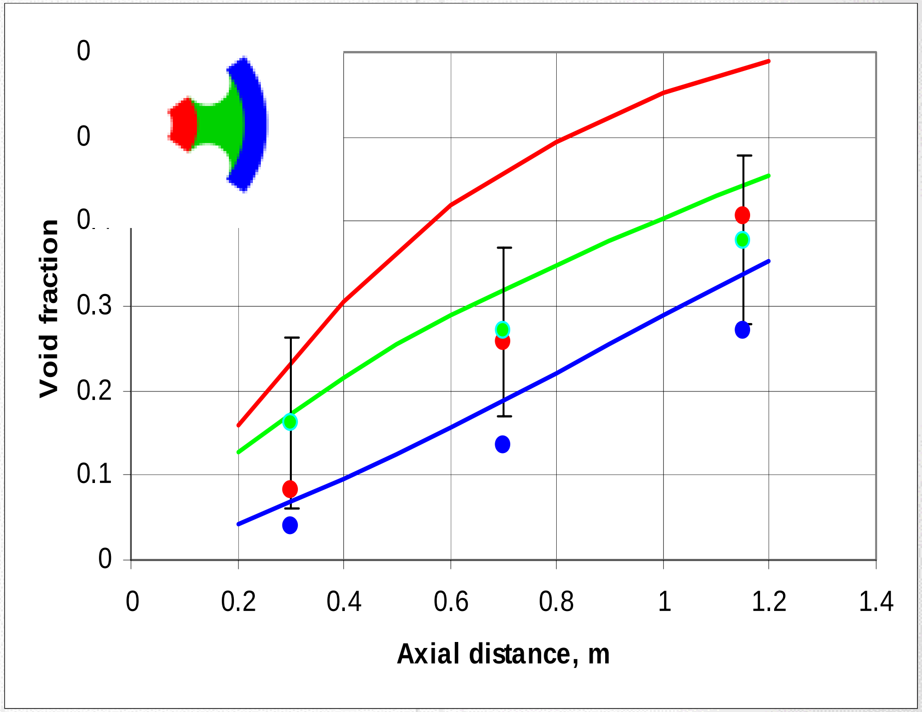
Boiling and two-phase flow Case studies with FLUENT (contd.)

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

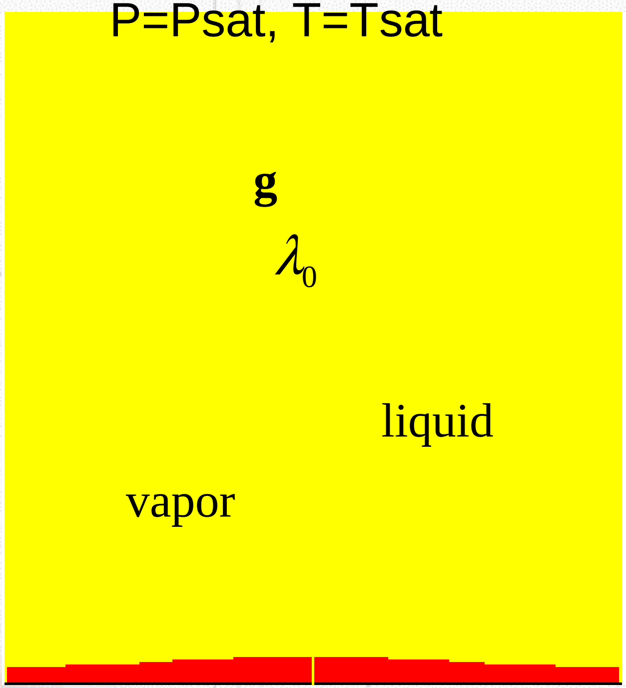


Comparison with experiment for vapor void fraction

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

Film boiling

- **Using VOF modeling in Fluent**



$\frac{3\lambda_0}{2}$

symmetry

symmetry

Wall
T=Tsat+10K

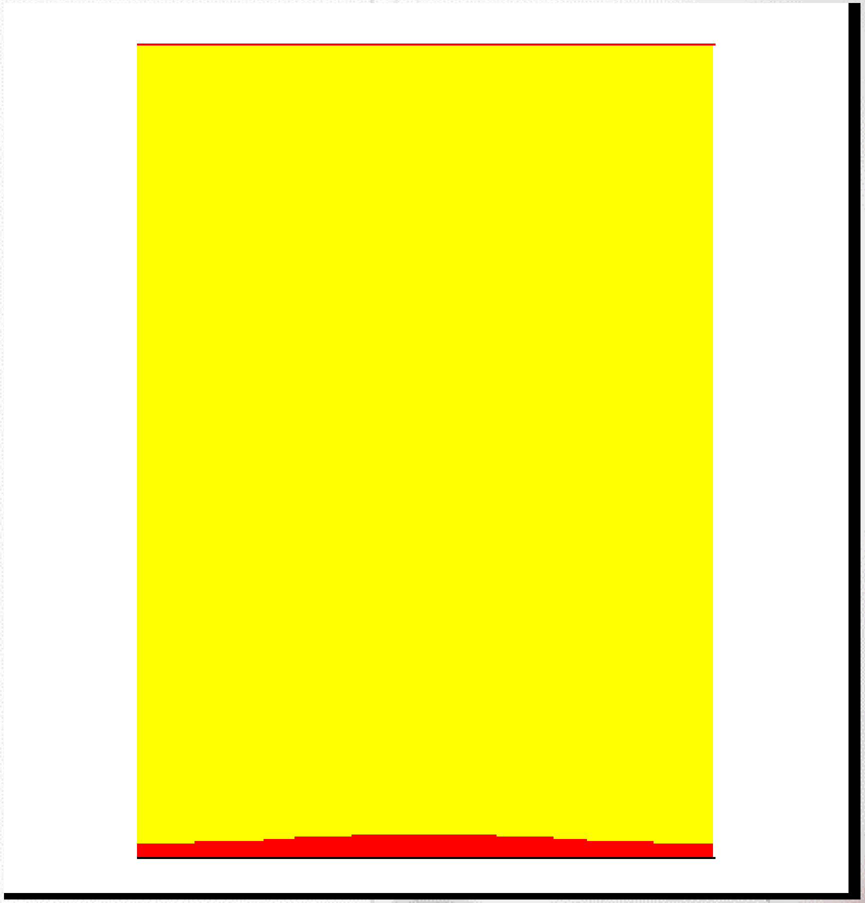
$$\lambda_0 = 2\pi\left(\frac{3\sigma}{(\rho_l - \rho_g)g_y}\right)^{1/2} = 0.0778m$$

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

Film boiling

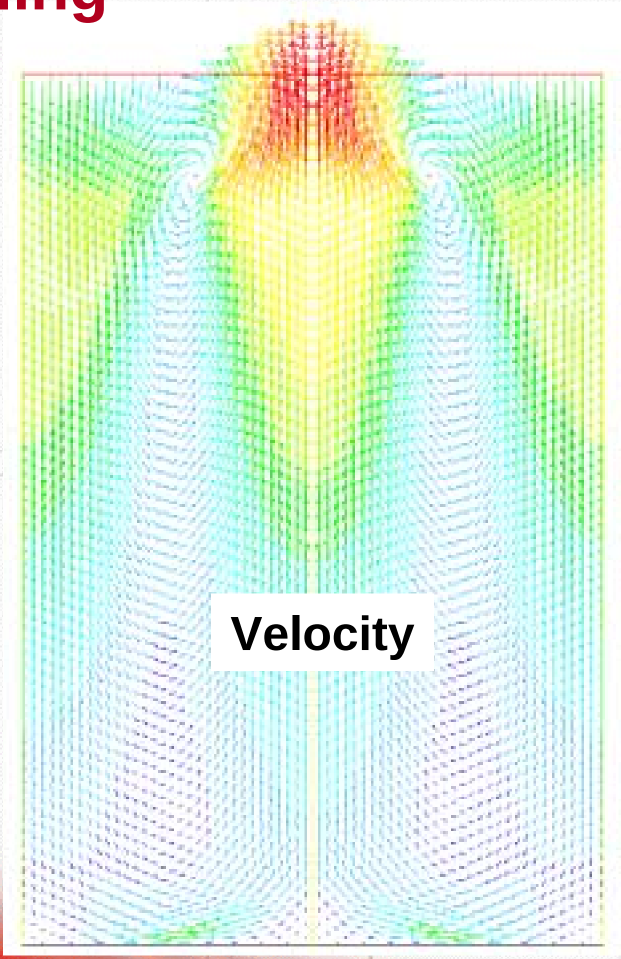
Animation

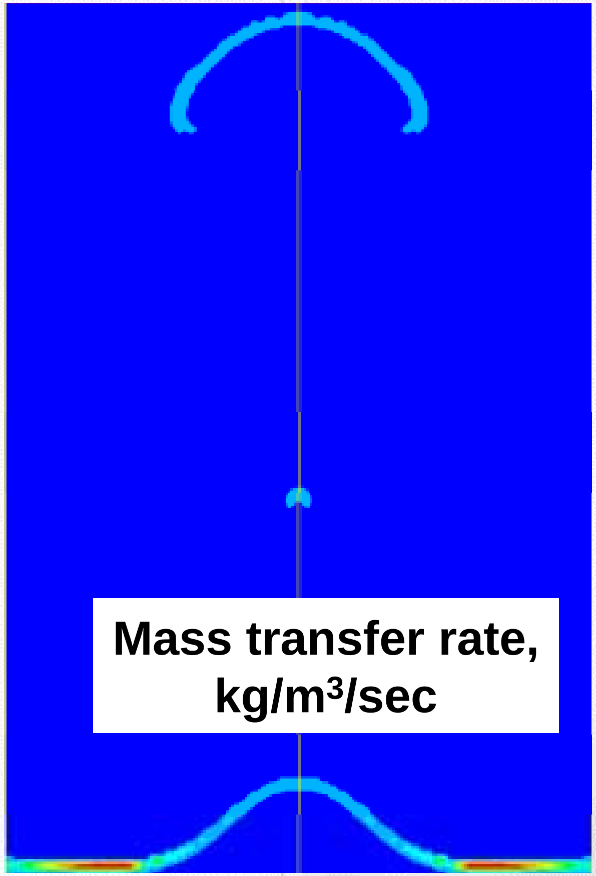
Contours of volume fraction of the vapor



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

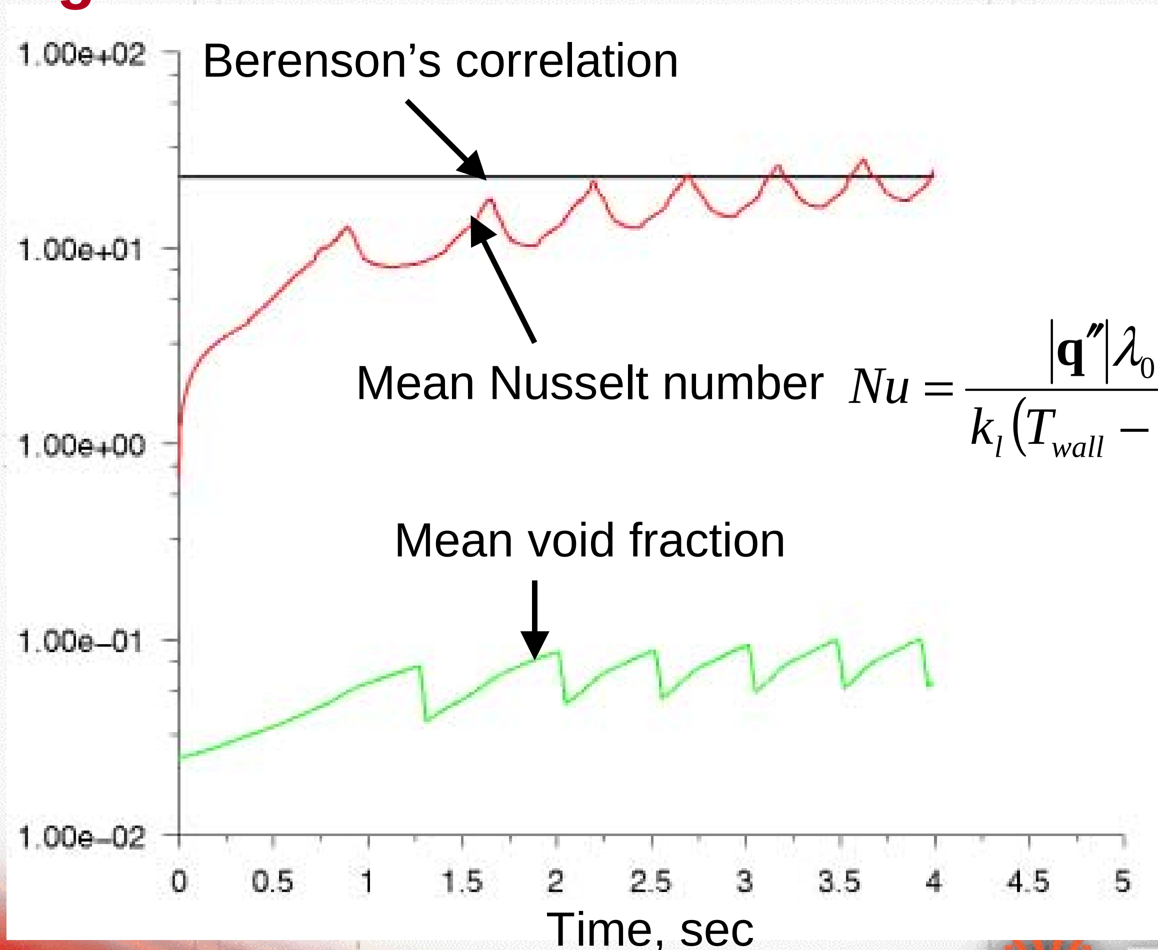
Film boiling





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

Film boiling



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

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

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