New Governing Equations for the Realistic Representation of 2 Phase Flow

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Overview

• Current Two-Phase Flow Methodology
• Opportunity for Improved Models
• New Governing Equations
• Future Work
Two-Phase Methodology

• RELAP5-3D has two fields: liquid and vapor
• Control volumes are completely liquid, completely vapor, or partially liquid/vapor
  – Void fraction computed to determine percentage of control volume that is vapor
Flow Regimes

- Dispersed Bubble
- Stratified Smooth
- Stratified Wavy
- Plug / Slug
- Annular / Dispersed
- Top Quench Front
- Pre-CHF Regime: AnnularMist
- Dispersed Flow
- Inverted Slug
- Inverted Annular
- Bottom Quench Front
- Pre-CHF Regime: Bubbly/Slug
Flow Regime Determination

- Flow regime determined by void fraction, flow velocity, subcooling, and orientation
- Regime determines heat transfer correlations between phases and pipe walls
Flow Regime Determination

- Same maps used for channel and pipe flows
  - Individual correlations for channels and pipes
Six-Equation Model

• Mainstay of two-field, two-phase system codes

• Mass, Momentum and Energy conservation (3 eqns) for two fields (2x3=6 equations)
  – Some codes have an additional equation for noncondensable gasses or dissolved solids
RELAP5-3D Governing Equations

- Mass Conservation

\[
\frac{\partial}{\partial t} (\alpha_k \rho_k) + \frac{1}{A} \frac{\partial}{\partial x} (\alpha_k \rho_k u_k A) = \Gamma_k
\]

- Time rate of change of mass
- Mass convected in or out of control volume
- Mass exchange rate due to phase change
RELAP5-3D Governing Equations

- Momentum Conservation (Vapor)

\[
\alpha_k \rho_k A \frac{\partial v_k}{\partial t} + \frac{1}{2} \alpha_k \rho_k A \frac{\partial v_k^2}{\partial x} = -\alpha_k A \frac{\partial P}{\partial x} + \alpha_k \rho_k B_x A - (\alpha_k \rho_k A) F W_k \cdot v_k + \Gamma_k A (v_k - v_k) - (\alpha_k \rho_k A) F I_k \cdot (v_k - v_r) - C \alpha_k \alpha_r \rho_m A \left[ \frac{\partial (v_k - v_r)}{\partial t} + v_r \frac{\partial v_k}{\partial x} - v_k \frac{\partial v_r}{\partial x} \right]
\]
RELAP5-3D Governing Equations

- Energy Conservation (Vapor)

\[
\frac{\partial}{\partial t} (\alpha_k \rho_k U_k) + \frac{1}{A} \frac{\partial}{\partial x} (\alpha_k \rho_k U_k v_k A) = \underbrace{-P \frac{\partial \alpha_k}{\partial t}}_{\text{Rate of energy change}} - \underbrace{\frac{P}{A} \frac{\partial}{\partial x} (\alpha_k v_k A)}_{\text{From reversible flow work}} + \underbrace{Q_{wk} + Q_{ik} + \Gamma_{ig} h_k^* + \Gamma_w h_k'}_{\text{Heat from wall and interface}} + \underbrace{DISS_k}_{\text{Phase change}} + \underbrace{\text{Energy dissipation (wall friction, pump, turbine effects)}}
\]
Two-Field Model Shortcomings

• Lumped-capacitance approximation
  – All liquid (droplets, continuous liquid) has same temperature, pressure, and velocity
  – Same limitation for vapor

• Struggles with steady state BWR conditions, design basis accident scenarios, and anticipated accidents without scram
  – Reflood
  – LOCA
  – Etc.

• Code development efforts trying to increase the number of fields
  – NEPTUNE
  – TRACE
  – WCOBRA-TRAC
  – RELAP
Six-Field Model

• Increase modeled fields to include:

Mass, Momentum, and Energy Balance Equations must be developed for:
  – Continuous Liquid
  – Continuous Vapor
  – Large Bubble
  – Small Bubble
  – Large Droplet
  – Small Droplet
Considerations For Multiple Field Models

- Multiple interfaces between fields
  - Phase change
  - Shear forces
- Closure relationships required
  - Heat Transfer
  - Relative Velocities
- Physical phenomena that cause field transitions
  - Entrainment
  - De-entrainment
  - Spacer grids
  - Flow breakup
Mass Balance - Continuous Liquid

\[
\frac{\partial}{\partial t} \left( \alpha_f \rho_f \right) + \nabla \cdot \left( \alpha_f \rho_f \vec{v}_f \right) = -\Gamma_g - S'''_{LD,E} - S'''_{SD,E} + S'''_{LD,DE} + S'''_{SD,DE}
\]

- Time rate of change of mass
- Mass convection
- Phase change
- Mass exchange due to entrainment/de-entrainment
Momentum Balance - Continuous Liquid

\[
\begin{align*}
\frac{D\mathbf{p}_f}{Dt} &= -\alpha_f \nabla p_f + \\
&\quad -\nabla \cdot \left[ \alpha_f \left( \mathbf{e}_f + \mathbf{e}_f^T \right) \right] + \\
&\quad \alpha_f \rho_f \mathbf{g}_f + \\
&\quad (p_{fl} - p_f) \nabla \alpha_f + \\
&\quad (\bar{u}_{i,L} - \bar{u}_f) \Gamma_L + (\bar{u}_{i,LB} - \bar{u}_f) \Gamma_{LB} + (\bar{u}_{i,SBu} - \bar{u}_f) \Gamma_{SBu} + \\
&\quad M_{if} - \\
&\quad \text{Interfacial and skin drag} \\
&\quad \nabla \alpha_f \cdot \mathbf{e}_{fl,a} - \nabla \alpha_f \cdot \mathbf{e}_{fl,SBu} - \nabla \alpha_f \cdot \mathbf{e}_{fl,LB} - \\
&\quad \text{Momentum Transfer by Interfacial Shear} \\
&\quad \sum S_{LD,E} v_{LD} - \sum S_{SD,E} v_{SD} + \sum S_{SD,D} v_{SD} + \sum S_{LD,DE} v_{LD} \\
&\quad \text{Droplet Entrainment/De-Entrainment}
\end{align*}
\]
Energy Balance - Continuous Liquid

\[ \alpha_f \rho_f \frac{D_f h_f}{Dt} = -\nabla \cdot \alpha_f (\bar{q}_f - \bar{q}_f^T) + \]

Rate of energy change, with convective effects

\[ \frac{\alpha_f D_f p_f}{Dt} + \]

Average conduction and turbulent heat flux

\[ \Phi_f^T + \Phi_f^m + \]

Flow work

\[ \Gamma_f, (h_{f,i} - h_f) + \Gamma_f, (h_{f,w} - h_f) + \Gamma_f,SBu (h_{f,SBu} - h_f) + \Gamma_f,LB (h_{f,LB} - h_f) + \]

Energy exchange due to phase change at interfaces and near the wall

\[ a_i q_{f,i} + a_i,SBu q_{SBu,i} + a_i,LB q_{LB,i} + a_w,f q_{w,f} + \]

Energy exchange due to heat transfer at interfaces and from the wall

\[ (p_f - p_{f,i}) \frac{D_f \alpha_f}{Dt} + \]

Interfacial pressure differences

\[ M_i,f \cdot (\bar{v}_f,i - \bar{v}_f) - \]

Interfacial drag between continuous fields

\[ \nabla \alpha_f \cdot \Sigma_f,i \cdot (\bar{v}_f,i - \bar{v}_f) - \]

Interfacial shear stress

\[ S_{LD,E} h_f - S_{SD,E} h_f + S_{LD,DE} h_{LD} + S_{SD,DE} h_{SD} \]

Entrainment/de-entrainment
Future Work

- Article submitted to Progress in Nuclear Energy
- Re-cast equations in “RELAP” form
- Determine closure models to use
- Implement governing equations and closure models in RELAP5-3D