New Governing Equations for the Realistic Representation of 2 Phase Flow

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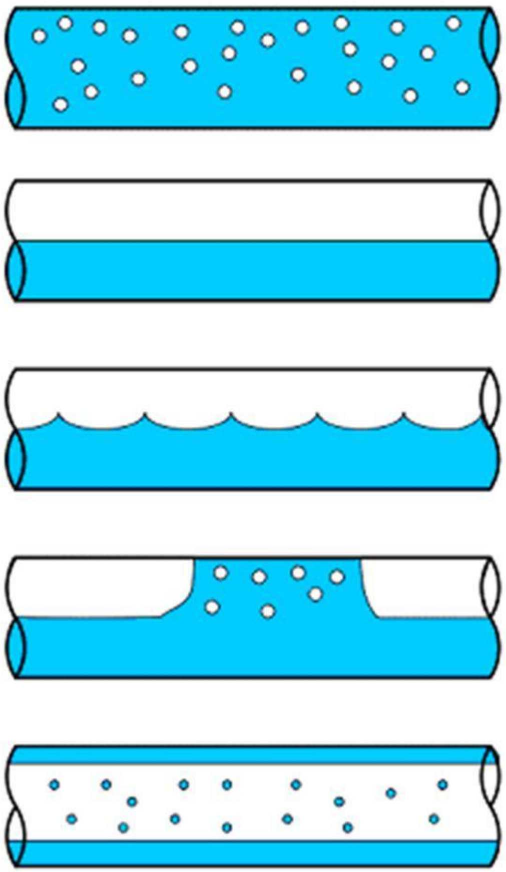
Overview

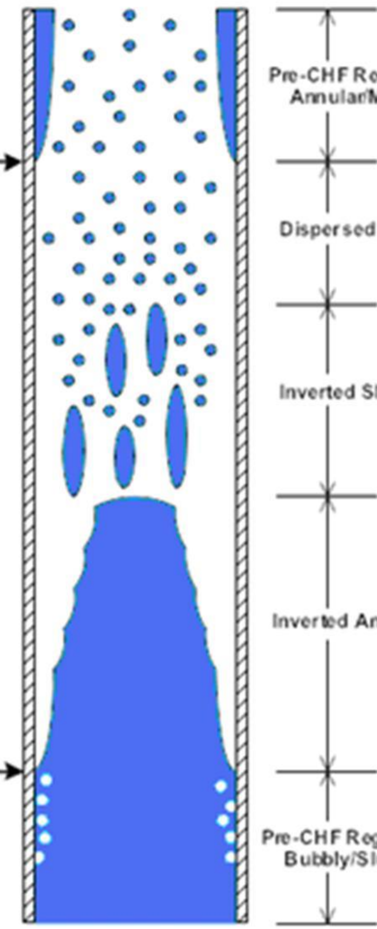
- Current Two-Phase Flow Methodology
- Opportunity for Improved Models
- New Governing Equations
- Future Work

Two-Phase Methodolgy

- 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

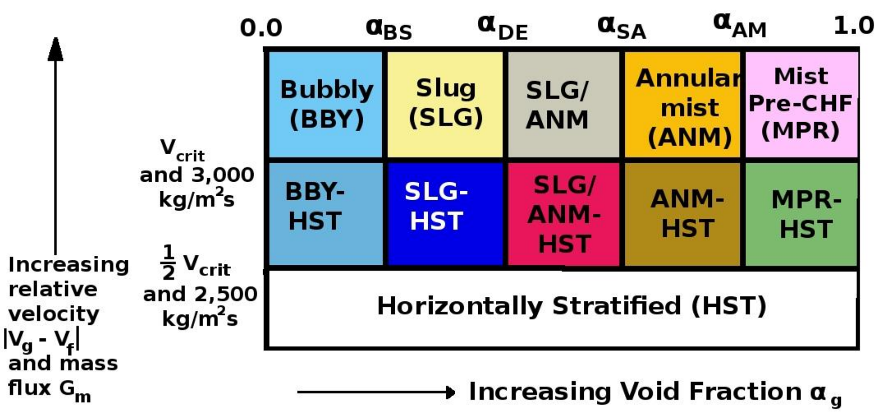
Flow Regimes





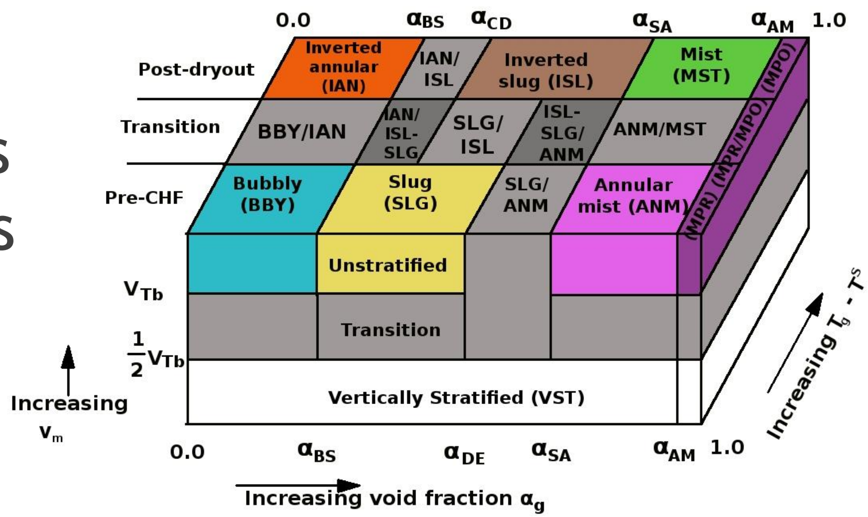
Flow Regime Determination

- 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

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_k \rho_k v_k A) = \Gamma_k$$

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)

$$
\begin{aligned}
\underbrace{\alpha_k \rho_k A \frac{\partial v_k}{\partial t} + \frac{1}{2} \alpha_k \rho_k A \frac{\partial v_k^2}{\partial x} =}_{\text{Rate of change of momentum}} \quad & \underbrace{-\alpha_k A \frac{\partial P}{\partial x} +}_{\text{Pressure gradient}} \\
& \underbrace{\alpha_k \rho_k B_x A -}_{\text{Body forces}} \\
& \underbrace{\left(\alpha_k \rho_k A\right) FW_k \cdot v_k +}_{\text{Wall drag}} \\
& \underbrace{\Gamma_k A \left(v_{kI} - v_k\right) -}_{\text{Phase change}} \\
& \underbrace{\left(\alpha_k \rho_k A\right) FI_k \cdot \left(v_k - v_r\right) -}_{\text{Interfacial drag}} \\
& \underbrace{C \alpha_k \alpha_r \rho_m A \left[\frac{\partial \left(v_k - v_r\right)}{\partial t} + v_r \frac{\partial v_k}{\partial x} - v_k \frac{\partial v_r}{\partial x}\right]}_{\text{Virtual mass}}
\end{aligned}
$$

RELAP5-3D Governing Equations

- Energy Conservation (Vapor)

$$\underbrace{\frac{\partial}{\partial t}(\alpha_k \rho_k U_k) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_k \rho_k U_k v_k A) =}_{\text{Rate of energy change}} \underbrace{-P\frac{\partial \alpha_k}{\partial t} - \frac{P}{A}\frac{\partial}{\partial x}(\alpha_k v_k A)}_{\text{From reversible flow work}} \; +$$

$$\underbrace{Q_{wk} + Q_{ik} +}_{\text{Heat from wall and interface}}$$

$$\underbrace{\Gamma_{ig} h_k^{*} + \Gamma_w h_k^{'} +}_{\text{Phase change}}$$

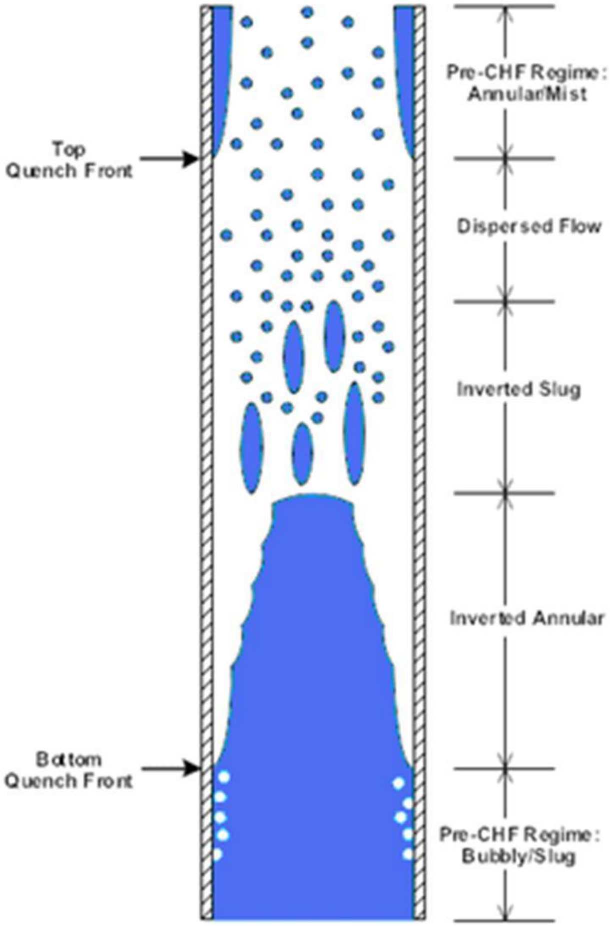
$$\underbrace{DISS_k}_{\text{Energy dissipation (wall friction, pump, turbine effects)}}$$

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

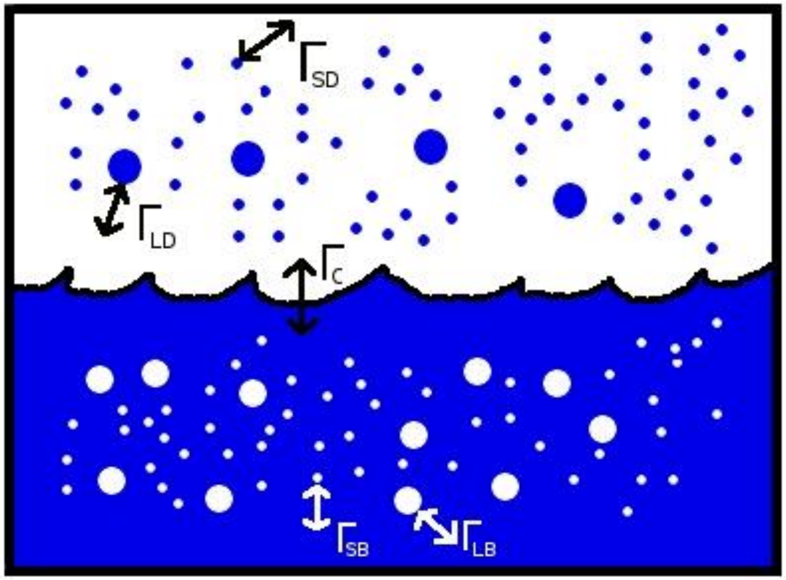
Six-Field Model

- Increase modeled fields to inclu ts
- Mass, Momentum, and Energy Ba 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

$$\underbrace{\frac{\partial}{\partial t}(\alpha_f\rho_f)}_{\text{Time rate of change of mass}} + \underbrace{\nabla\cdot(\alpha_f\rho_f\vec{v}_f)}_{\text{Mass convection}} = \underbrace{-\Gamma_g}_{\text{Phase change}} - \underbrace{S'''_{LD,E} - S'''_{SD,E} + S'''_{LD,DE} + S'''_{SD,DE}}_{\text{Mass exchange due to entrainment/de-entrainment}}$$

Momentum Balance – Continuous Liquid

$$\underbrace{\alpha_f \rho_f \frac{D\vec{v}_f}{Dt} =}_{\text{Rate of change of momentum}} \quad \underbrace{-\alpha_f \nabla p_f +}_{\text{Momentum change due to pressure gradient}}$$

$$\underbrace{\nabla \cdot \left[\alpha_f \left(\mathfrak{T}_f + \mathfrak{T}_f^T\right)\right] +}_{\text{Average viscous stress and turbulent stress effects}}$$

$$\underbrace{\alpha_f \rho_f \vec{g}_f +}_{\text{Body force effects}}$$

$$\underbrace{\left(p_{fi} - p_f\right) \nabla \alpha_f +}_{\text{Pressure change between interface and continuous liquid}}$$

$$\underbrace{\left(\vec{v}_{i,L} - \vec{v}_f\right) \Gamma_L + \left(\vec{v}_{i,LB} - \vec{v}_f\right) \Gamma_{LB} + \left(\vec{v}_{i,SBu} - \vec{v}_f\right) \Gamma_{SBu} +}_{\text{Momentum exchanged from phase change}}$$

$$\underbrace{M_{if} -}_{\text{Interfacial and skin drag}}$$

$$\underbrace{\nabla \alpha_f \cdot \mathfrak{T}_{fi,g} - \nabla \alpha_f \cdot \mathfrak{T}_{fi,SBu} - \nabla \alpha_f \cdot \mathfrak{T}_{fi,LB} -}_{\text{Momentum Transfer by Interfacial Shear}}$$

$$\underbrace{S'''_{LD,E} v_{LD} - S'''_{SD,E} v_{SD} + S'''_{SD,DE} v_{SD} + S'''_{LD,DE} v_{LD}}_{\text{Droplet Entrainment/De-Entrainment}}$$

Energy Balance – Continuous Liquid

$$\underbrace{\alpha_f \rho_f \frac{D_f h_f}{Dt}}_{\text{Rate of energy change, with convective effects}} = \underbrace{-\nabla\cdot \alpha_f \left(\vec{q}_f - \vec{q}_f^{\,T}\right) +}_{\text{Average conduction and turbulent heat flux}} \underbrace{\alpha_f \frac{D_f p_f}{Dt} +}_{\text{Flow work}} \underbrace{\Phi_f^T + \Phi_f^\mu +}_{\text{Turbulent work effect source and viscous dissipation}}$$

$$\underbrace{\Gamma_{f,i}\left(h_{f,i} - h_f\right) + \Gamma_{f,w}\left(h_{f,w} - |h_f\right) + \Gamma_{f,SBu}\left(h_{f,SBu} - h_f\right) + \Gamma_{f,LB}\left(h_{f,LB} - h_f\right) +}_{\text{Energy exchange due to phase change at interfaces and near the wall}}$$

$$\underbrace{a_i q'''_{f,i} + a_{i,SBu} q'''_{SBu,i} + a_{i,LB} q'''_{LB,i} + a_{w,f} q'''_{w,f} +}_{\text{Energy exchange due to heat transfer at interfaces and from the wall}}$$

$$\underbrace{\left(p_f - p_{f,i}\right)\frac{D_f \alpha_f}{Dt} +}_{\text{Interfacial pressure differences}} \quad \underbrace{M_{i,f}\cdot\left(\vec{v}_{f,i} - \vec{v}_f\right) -}_{\text{Interfacial drag between continuous fields}} \quad \underbrace{\nabla\alpha_f\cdot \mathfrak{T}_{f,i}\cdot\left(\vec{v}_{f,i} - \vec{v}_f\right) -}_{\text{Interfacial shear stress}}$$

$$\underbrace{S'''_{LD,E} h_f - S'''_{SD,E} h_f + S'''_{LD,DE} h_{LD} + S'''_{SD,DE} h_{SD}}_{\text{Entrainment/de-entrainment}}$$

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