Six-Field Model and RELAP5-3D

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Outline

- Six Field Equations
- Data to match
- Solution Algorithm
- RELAP Model
- Changes to Code
- Results
- References

Motivation for Six-Field Model

- Two-field models
  - Limited capability to model reactor transients and accidents
  - Cannot capture differences in temperature between liquid and droplet fields
  - Cannot track location of droplets or bubbles
- Six-field models
  - Improved accuracy of the calculations
  - Better accuracy will improve efficiency of nuclear reactor systems

Six Field Nomenclature

Index	Description
1	Continuous Liquid
2	Large Droplet
3	Small Droplet
4	Continuous Vapor
5	Large Bubble
6	Small Bubble

- Subscripts on terms in governing equations will indicate which field relates to that term
- Terms that refer to transition between fields (e.g., droplet entrainment, large droplets breaking into small droplets), two subscripts are provided.
    - The first subscript is the source field
    - The second subscript will indicate the result field (e.g. $S_{2,3}$).

Droplet Field Entrainment in RELAP5-3D

- First step in six-field implementation
- Single droplet field (small droplets) modeled
- Graded approach allows for confirmatory calculations before proceeding
- Entrainment correlation is added to vexplt
  - Computes rate of droplet entrainment based on local conditions in each control volume
  - Droplets not convected to other volumes
  - Droplets “disappear” each timestep

MASS (Continuity) Balance Governing Equations

- Continuous Liquid
- $\frac{\partial}{\partial t}(\alpha_1 \rho_f) + \nabla \cdot (\alpha_1 \rho_f \vec{v}_1) = -\Gamma_1 - Sink + Source$
- Droplet Field
- $\frac{\partial}{\partial t}(\alpha_3 \rho_f) + \nabla \cdot (\alpha_3 \rho_f \vec{v}_3) = -\Gamma_3 - Sink + Source$
- Continuous Vapor
- $\frac{\partial}{\partial t}(\alpha_4 \rho_g) + \nabla \cdot (\alpha_4 \rho_g \vec{v}_4) = -\Gamma_4 - Sink + Source$

MOMENTUM Governing Equations

- Continuous liquid field
- $\alpha_1 \rho_f \frac{\mathrm{D}\vec{v}_1}{Dt} = -\alpha_1 \nabla \mathrm{p}_f + \alpha_1 \rho_f \vec{g}_1 + \left(\vec{v}_{i,1} - \vec{v}_1\right)\Gamma_1 + \mathrm{M}_{i,1} + \mathrm{M}_{w,1} - Sink + Source$
- Droplet field
- $\alpha_3 \rho_f \frac{\mathrm{D}\vec{v}_3}{Dt} = -\alpha_3 \nabla \mathrm{p}_f + \alpha_3 \rho_1 \vec{g}_3 + \left(\vec{v}_{i,3} - \vec{v}_3\right)\Gamma_3 + \mathrm{M}_{i,3} - Sink + Source$
- Continuous vapor field
- $\alpha_4 \rho_g \frac{\mathrm{D}\vec{v}_4}{Dt} = -\alpha_4 \nabla \mathrm{p}_g + \alpha_4 \rho_g \vec{g}_4 + \left(\vec{v}_{i,4} - \vec{v}_4\right)\Gamma_4 + \left(\vec{v}_{i,3} - \vec{v}_4\right)\Gamma_3 + \mathrm{M}_{i,4} + \mathrm{M}_{w,4} - Sink + Source$

Where:
$\vec{g}$ – Body force (i.e., gravity)
$\vec{v}$ – Velocity of the field (subscript *i* indicates near the interface)
$\mathrm{M}_{i,1}$ – Momentum source from interfacial drag between continuous liquid and continuous vapor
$\mathrm{M}_{w,1}$ – Momentum source from interfacial drag between continuous liquid and the wall

ENERGY Governing Equations

- Continuous liquid
- $\alpha_1 \rho_f \frac{\mathrm{Dh}_1}{Dt} = \alpha_1 \frac{\mathrm{D}p_f}{Dt} + \Phi_1^T + \Phi_1^\mu + \Gamma_{i,1}\left(h_{i,1} - h_1\right) + \Gamma_{w,1}\left(h_{w,1} - h_1\right) + \mathrm{a}_i \mathrm{q}_{i,1}''' + \mathrm{a}_{w,1} \mathrm{q}_{w,1}''' + \mathrm{M}_{i,1}\left(\vec{v}_{i,1} + \vec{v}_1\right) - Sink + Source$
- Droplet field
- $\alpha_3 \rho_f \frac{\mathrm{Dh}_3}{Dt} = \Gamma_{i,3}\left(h_{i,3} - h_3\right) + \mathrm{a}_i \mathrm{q}_{i,3}''' + \mathrm{M}_{i,3}\left(\vec{v}_{i,3} + \vec{v}_3\right) - Sink + Source$
- Continuous vapor
- $\alpha_4 \rho_g \frac{\mathrm{Dh}_4}{Dt} = \alpha_4 \frac{\mathrm{D}p_g}{Dt} + \Phi_4^T + \Phi_4^\mu + \Gamma_{i,4}\left(h_{i,4} - h_4\right) + \Gamma_{w,4}\left(h_{w,4} - h_4\right) + \Gamma_{i,3-4}\left(h_{4,3} - h_4\right) + \mathrm{a}_i \mathrm{q}_{i,4}''' + \mathrm{a}_{4,3} \mathrm{q}_{4,3}''' + \mathrm{a}_{w,4} \mathrm{q}_{w,4}''' + \mathrm{M}_{i,4}\left(\vec{v}_{i,4} + \vec{v}_4\right) - Sink + Source$

Where:

Φ – Viscous dissipation (superscript m) or turbulent work effect (superscript T)

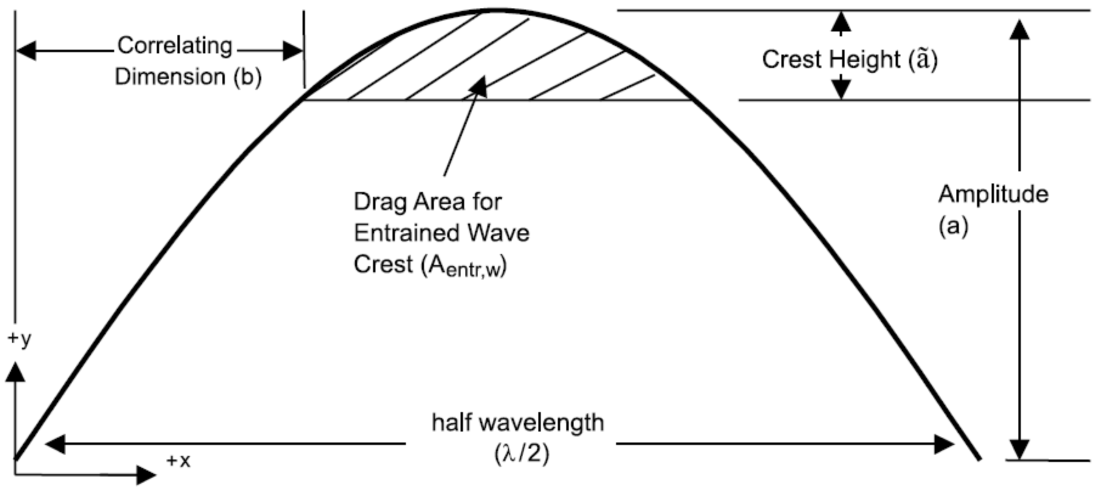
h – Enthalpy (subscript *i* indicates interface)

a – interfacial area concentration (area per unit volume) at the *w*-wall or *i*-interface

q'''– Heat flow to continuous liquid from the *w*-wall or *i*-interface to the field

Droplet Entrainment

- Three primary entrainment mechanisms
  - Reflood – droplets entrained by flashing vapor
  - Vertical annular flows – droplets entrained from wave formation
  - Horizontal annular flows – droplets entrained from wave formation
- Annular wave entrainment
  - Wavelets form on annular flow surface from shear with vapor flow
  - Tops of wavelets pulled by shear forces
  - Sufficient shear overcomes surface tension, and droplets are entrained



Droplet Entrainment

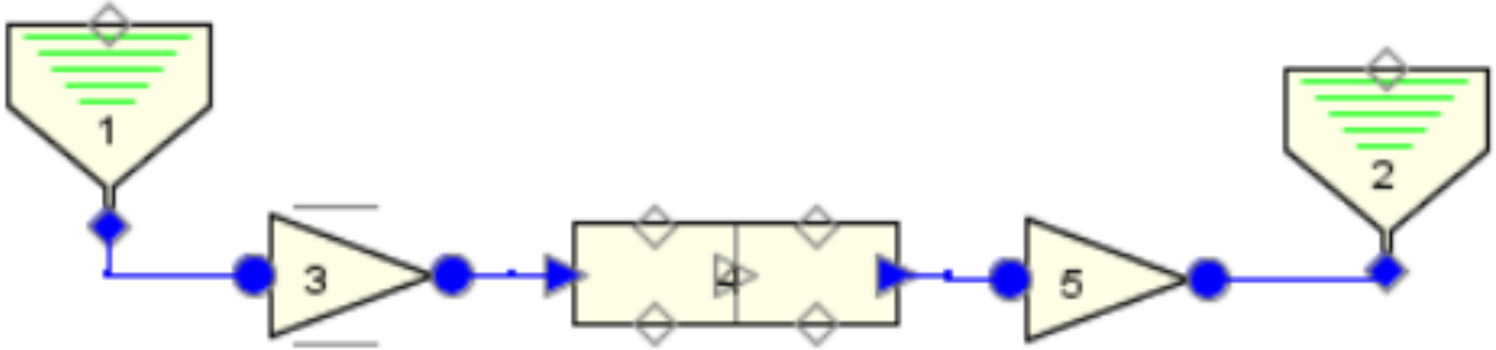
- Source of mass to droplet field
- Sink of mass from the continuous liquid field
- Droplet entrainment model
- $\mathrm{S}_{1,3}''' = \frac{k_A' U_g^2 \left(\rho_g \rho_f\right)^{1/2} \left(W_{film} - W_{LFC}\right)}{p \sigma t_{film}}$

Entrainment Model Implementation in RELAP5-3D

- Two data structures added
    - Contain droplet-specific values for junctions and volumes
- Immediately prior to call to vexplt in the hydro module, droplet specific values are updated with liquid field parameters
    - Limits entrainment results to a single timestep

Test Case

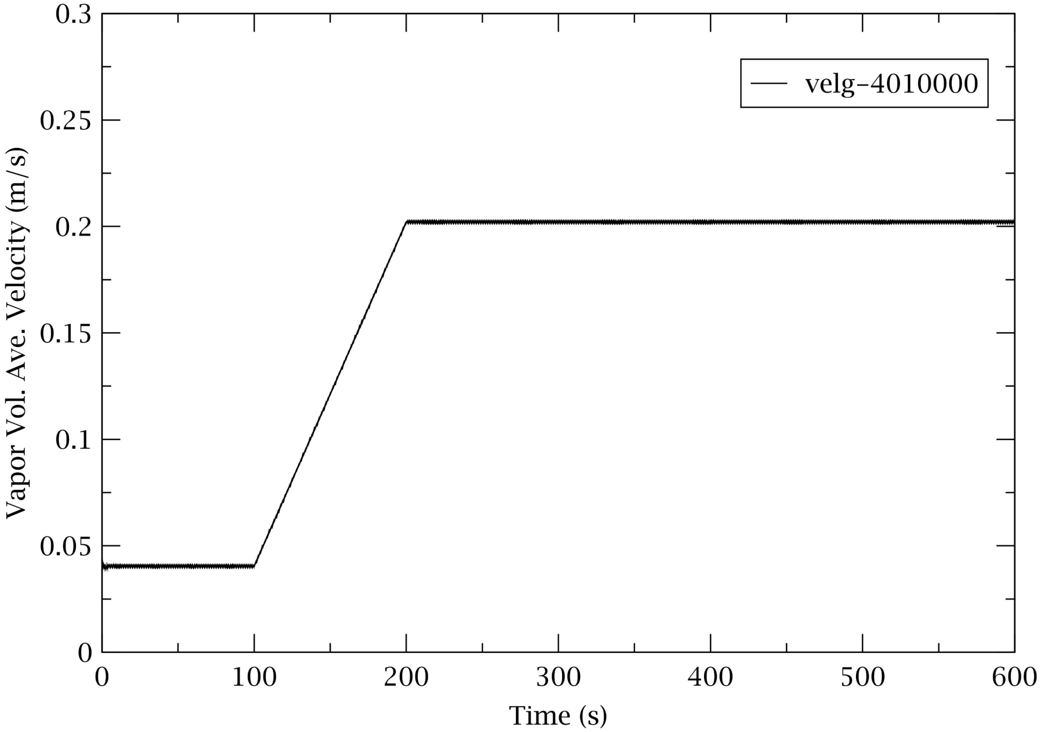
- Simple case that allows for 2-phase flow with control of the vapor and liquid velocities
- Two-volume PIPE connected to source and sink TDVs
- Inlet controlled by TDJ, outlet is a single junction

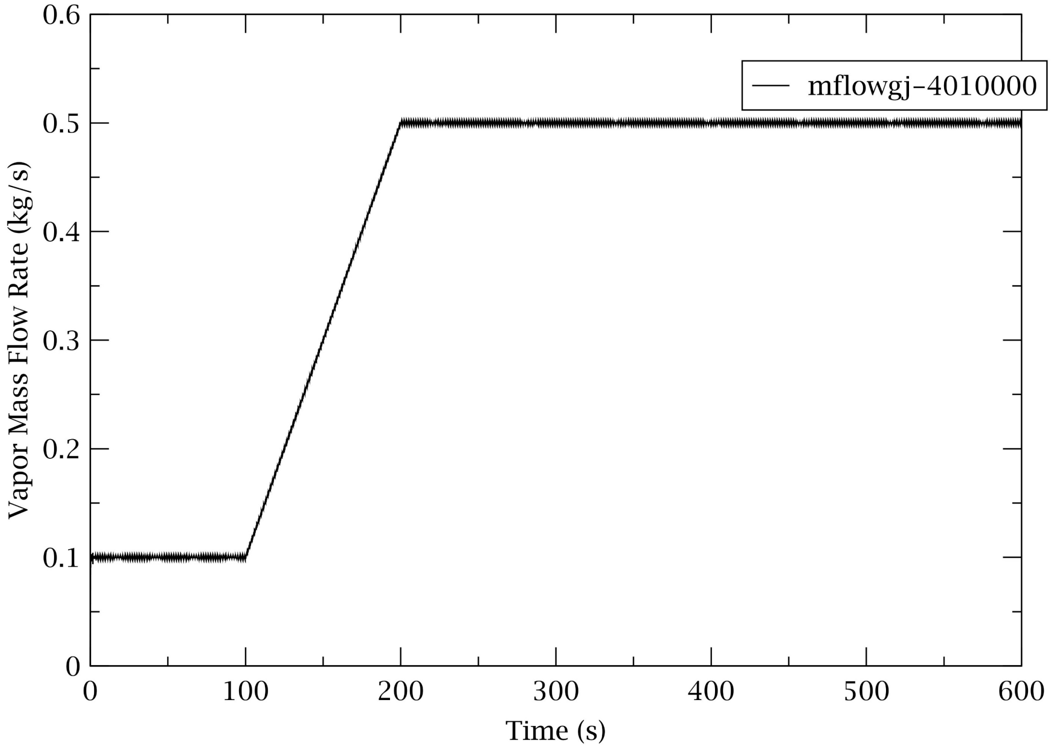


Test Case Conditions

- Inlet conditions
  - T = 422.0 K
  - X = 0.9
  - Mflowg = 0.1 kg/s -> 0.5 kg/s
  - Mflowf = 10 kg/s
- Test section PIPE
  - FA = 1.0 m^2
  - L = 2.0 m (each volume)
  - V = 2.0 m^3 (each volume)

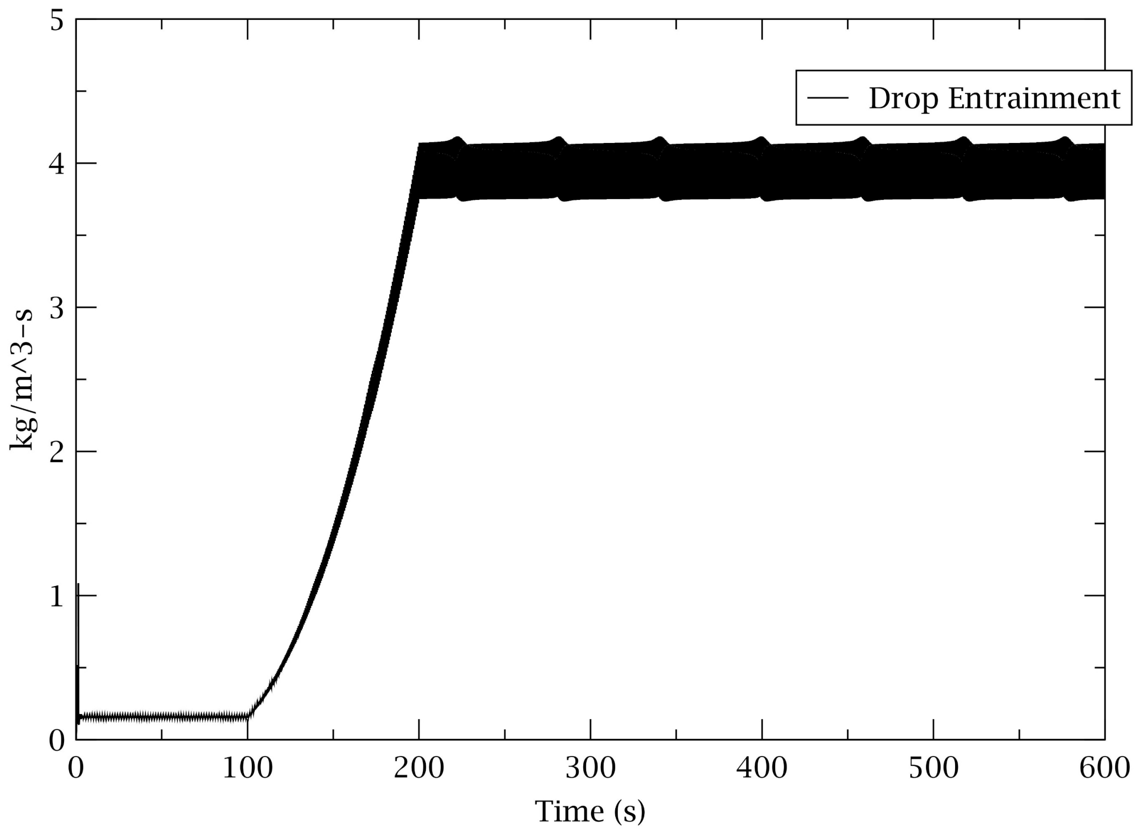
Test Section Vapor Flows





Droplet Entrainment Rate

- Volume of each PIPE cell is 2 m^3
- Liquid fractions as high as 0.0003
- Droplet entrainment peaks at ~4 kg/m^3-s
- Approximately 0.0024 kg of droplets entrained every second



References

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