Resolution of Flow Direction
Dependence of Critical Flow Models in RELAP5-3D

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Overview

• Definition of faces and flow directions
• Flow direction dependence of Henry-Fauske critical flow model implementation
  – Identification
  – Resolution
  – Verification
• Changes to Flow Quality calculation
Definition of Faces and Directions

- Each volume in RELAP5-3D has 6 faces
  - Primary flow is in the $x$-direction
  - Gravity can be assigned to any direction

- Positive flow is defined as:
  - Face 1 $\rightarrow$ Face 2 in $x$-direction
  - Face 3 $\rightarrow$ Face 4 in $y$-direction
  - Face 5 $\rightarrow$ Face 6 in $z$-direction
Definition of Faces and Directions

• Positive flow direction for junctions is user defined as:
  – **From** volume → **To** volume

• Pipe internal junctions
  – **From** volume = lower numbered volume
  – **To** volume = higher numbered volume

• User defined junctions (single junctions, valves, etc.)
  – User inputs **From** and **To** volumes
Identification of the Problem

• User problem reported
  – Choked flow rate given by Henry-Fauske under-predicted by up to 30%
  – Incorrect flow rates obtained when flow through the volume upstream of the break was negative (negative velocities)

• Further investigation showed incorrect choked flow rates for:
  – Negative flow through upstream volume
  – Negative flow through the choked junction
Steady-State Choked Flow

Henry-Fauske

pipe orientation – break orientation

Default

pipe orientation – break orientation
Steady-State Choked Flow

Henry-Fauske

Default

\[ \text{Diff} = \frac{(M_1 - M_2)}{\frac{1}{2}(M_1 + M_2)} \times 100 \]
Transient Choked Flow

Henry-Fauske

pipe orientation – break orientation

Default

pipe orientation – break orientation

Choked Flow Rate

Time (s)

Normal – Normal
Reverse – Normal
Normal – Reverse
Reverse – Reverse
Transient Choked Flow

Henry-Fauske

Default

\[ \text{Diff} = \frac{(M_1 - M_2)}{\frac{1}{2}(M_1 + M_2)} \times 100 \]
Cause of flow direction dependence

• Assumption inherent in the implementation that the model would only be applied with flow in the positive flow direction

• Results in incorrectly calculated stagnation pressure at the choked junction

• Appendix K choked flow model is similarly impacted
Henry-Fauske Choked Flow Model

• Why was this not previously observed?
  – Models developed to test choked flow are generally one dimensional
    • Marviken
    • Edwards-O’brien
  – Models are purposefully developed with flow in the positive direction

• Where is it important?
  – Double ended breaks
  – SG tube rupture
Changes to RELAP5-3D

• Five separate issues have been addressed
  – Three are related to the calculation of stagnation pressure at the break
    1. Momentum head term in the pressure loss formulation contained incorrectly applied sign adjusted velocities

\[
P_{\text{loss}} = 0.5 \cdot \omega_{v,\text{sign}} \left( \alpha_{f,j} \rho_{f,j} |v_f| v_f + \alpha_{g,j} \rho_{g,j} |v_g| v_g \right)
\]

\[
\omega_{v,\text{sign}} = \text{SIGN}(1.0, v_{f,j})
\]

  – Corrected by taking the absolute value of the net momentum head

\[
P_{\text{loss}} = 0.5 |\alpha_{f,j} \rho_{f,j} v_f| v_f + |\alpha_{g,j} \rho_{g,j} v_g| v_g
\]
Changes to RELAP5-3D

2. Pressure loss due to wall friction used an incomplete sign correction
   – Corrected by adding an additional sign correction based on location of the choked junction compared to the orientation of the velocity

\[ P_{loss} = P_{loss} - \omega_{Vol,sign} \Delta x \left( F_{wall,f} v_f + F_{wall,g} v_g \right) \]

3. Pressure loss due to gravity contained an incorrectly applied sign correction
   – Corrected the sign term to remove dependence on junction velocity

\[ P_{loss} = P_{loss} - \omega_{Vol,sign} g_c \Delta h \left( \alpha_f,j \rho_{f,j} + \alpha_g,j \rho_{g,j} \right) \]
Changes to RELAP5-3D

- Two are related to change of critical flow rate with time
  4. Derivative of velocity with respect to pressure (used to calculate implicit velocity) contained an unnecessary sign term
    - Corrected by removing the sign term

5. Selection of the weighting factor in the time-smoothing of velocity was done using velocity
    - Corrected by using absolute value of velocity
Verification of Changes

- Four verification problem sets developed
  - One steady-state
  - Three transient
  - Flow in all directions
    - Through junction that is experiencing critical flow
    - In upstream volume
  - Choked flow at all Faces
  - Both semi and nearly-implicit
  - Test all choking options
    - Henry-Fauske
    - Default (Ransom-Trapp)
    - No choking
Choked Flow Verification

• Depressurization problem
  – Transient blowdown through a pipe
  – Various pipe and valve orientations
  – Flow always left-to-right (as shown)
Depressurization Results

pipe orientation – break orientation

- Normal – Normal
- Reverse – Normal
- Normal – Reverse
- Reverse – Reverse

Change Pipe, Forward Break

Change Pipe, Reverse Break

Forward Pipe, Change Break

Reverse Pipe, Change Break
Choked Flow Verification

• Steady-state problem
  – Steady-state choked flow through a single volume
  – Same volume and junction orientations as depressure problem (only first orientation shown)
Steady-State Results

pipe orientation – break orientation

![Graphs showing flow rate over time for different orientations.](image)

- Normal – Normal
- Reverse – Normal
- Normal – Reverse
- Reverse – Reverse
Choked Flow Verification

• Side-top-bottom problem
  – Transient blowdown through a pipe
  – Same as depressure problem except:
    • Choked junction located at face 3, 4, 5, or 6
    • Choked junction oriented facing into and out of the pipe
Side-Top-Bottom Results

- Changing break orientation with break located at each of the six faces
Side-Top-Bottom Results

Changing pipe orientation with break oriented into the pipe

Change Pipe Orientation
Face 1 – Face 2
Face 2 – Face 2 (Reverse)
Face 1 – Face 2
Face 2 – Face 2 (Reverse)

Changing pipe orientation with break oriented out of the pipe

Change Pipe Orientation
Face 1 – Face 2
Face 2 – Face 2 (Reverse)
Face 1 – Face 2
Face 2 – Face 2 (Reverse)
Choked Flow Verification

• **Flow-past-break**
  – Transient blowdown
  – Flow through a pipe
  – Various pipe and valve orientations
  – Break located in the middle of the pipe
  – Reduced break area compared to pipe area
  – Break is located on the **downstream** face of the **third** pipe volume
    • Flow out of break is in the **same** direction as the flow in the pipe
Flow-Past-Break Results

pipe orientation – break orientation

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IRUG October 2012
Choked Flow Verification

- Flow-past-revbreak
  - Transient blowdown through a pipe
  - Various pipe and valve orientations (only one is shown)
  - Break located in the middle of the pipe
  - Reduced break area compared to pipe area
  - Break is located on the \textit{upstream} face of the \textbf{fourth} pipe
  - Flow out of break is in the \textbf{opposite} direction as the flow in the pipe
Flow-Past-RevBreak Results

pipe orientation – break orientation

- Normal – Normal
- Reverse – Normal
- Normal – Reverse
- Reverse – Reverse

Change Pipe, Forward Break

Change Pipe, Reverse Break

Forward Pipe, Change Break

Reverse Pipe, Change Break
Flowing Quality

- Ratio of gas field flow rate to total flow rate
  \[ x_{\text{flow}} = \frac{M_g}{M_g + M_l} \]

- Used to calculate the equilibrium quality
  \[ x_e = \frac{[x_{\text{flow}} h_g + (1 - x_{\text{flow}}) h_f] - h_{f,\text{sat}}}{h_{g,\text{sat}} - h_{f,\text{sat}}} \]

- Fluid enthalpies are “exit” conditions
  - Change in fluid energy calculated over the length of volume
  - An attempt is made to determine flow direction so that matching “exit” flows are used
Flowing Quality

• Identification of “Exit” Faces of a volume
  – Original Code
    • Identify sign of largest gas mass flux
      – If positive: Exit Faces are 2, 4, and 6
      – If negative: Exit Faces are 1, 3, and 5
    • Does not take into account actual flow conditions in each direction
    • Produces asymmetric results for symmetric problem
      – Identified during investigation of Henry-Fauske error
      – Break attached to Face 3 provided different results than break attached to Face 4 with choking turned off
Flowing Quality

- Identification of “Exit” Faces of a volume
  - Modified RELAP5-3D
    - Examine each Face independently
    - If gas is flowing out of Face it is an Exit Face
      - Only the gas flow rate is examined to allow definition of an Exit Face in counter-current flow situations
    - Provides a more realistic physical representation of flow conditions
Calculating Flowing Quality

- Once Exit Faces have been identified
  - Calculated average exit mass flow rates

\[
\overline{M_g} = \left[ \sum_{N=1}^{N_{exit}} M_{g,N}^2 \right]^{1/2}
\]

\[
\overline{M_l} = \left[ \sum_{N=1}^{N_{exit}} M_{l,N}^2 \right]^{1/2}
\]

\[
x_{flow} = \frac{\overline{M_g}}{\overline{M_g} + \overline{M_l}}
\]
Calculating Flowing Quality

• If sum of gas and liquid flow rates is zero
  – Original
    • Use static quality
  – Modified
    • Use volume velocities
      \[
      \overline{M}_g = \alpha_g \rho_g \left[ (U_{g,x} A_x)^2 + (U_{g,y} A_y)^2 + (U_{g,z} A_z)^2 \right]^{1/2}
      \]
      \[
      \overline{M}_l = \alpha_l \rho_l \left[ (U_{l,x} A_x)^2 + (U_{l,y} A_y)^2 + (U_{l,z} A_z)^2 \right]^{1/2}
      \]
    • If sum is still zero use static quality
      \[
      x_{flow} = \frac{\overline{M}_g}{\overline{M}_g + \overline{M}_l}
      \]
Conclusions

• Modified Henry-Fauske critical flow model implementation
  – Removed flow direction dependence

• Developed comprehensive set of quantitative verification problems

• Developed and implemented a symmetric definition of Exit Face for use in the calculation of Flowing Quality