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

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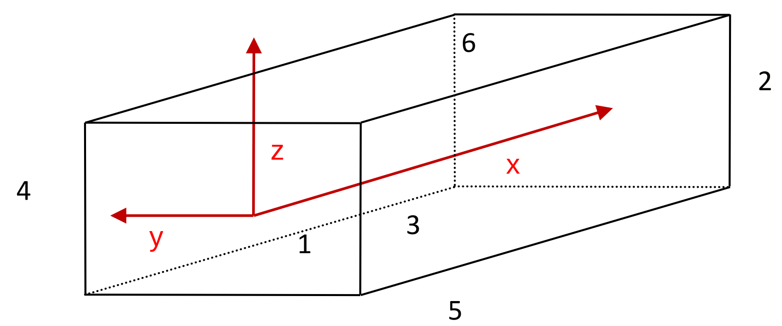
Overview

- 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 → Face 2 in x-direction
    - Face 3 → Face 4 in y-direction
    - Face 5 → 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

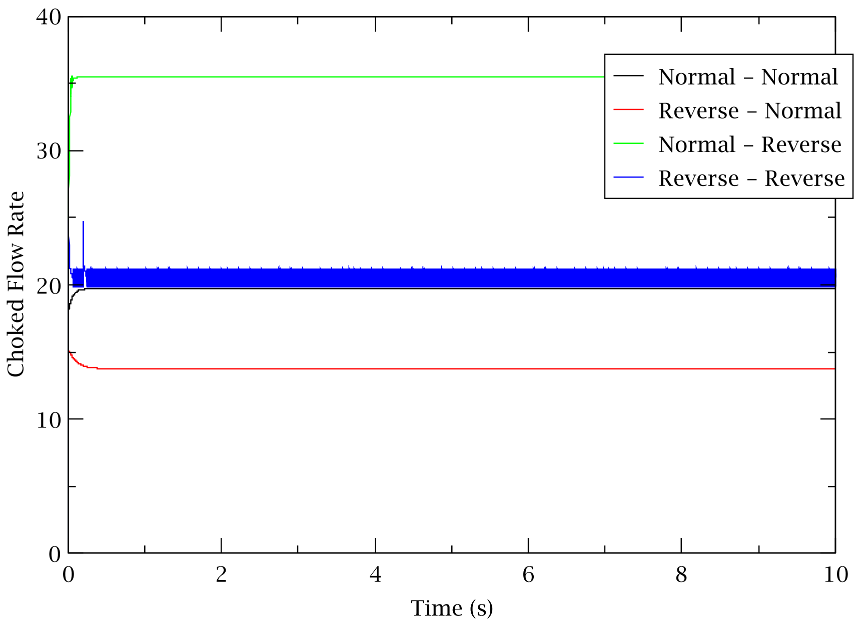
Identification of the Problem

- 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

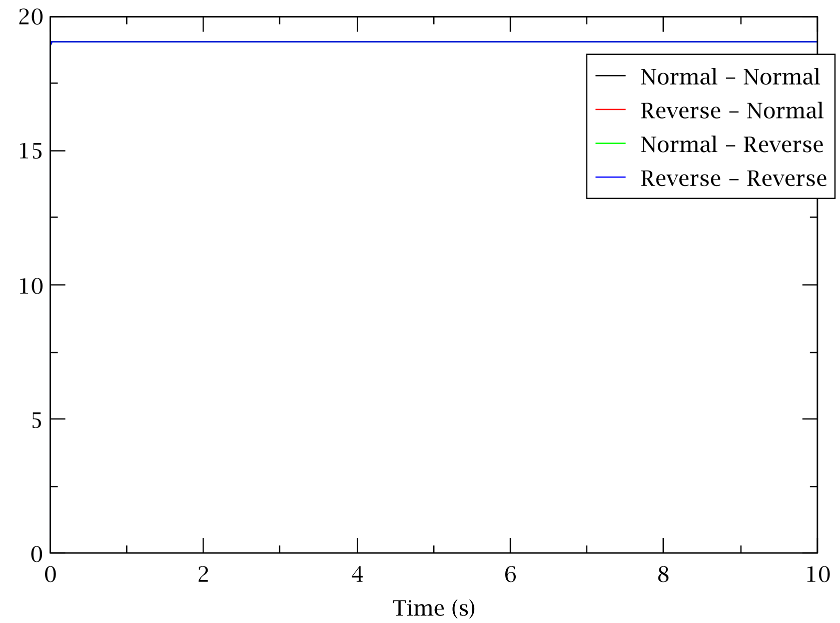
Henry-Fauske

pipe orientation – break orientation



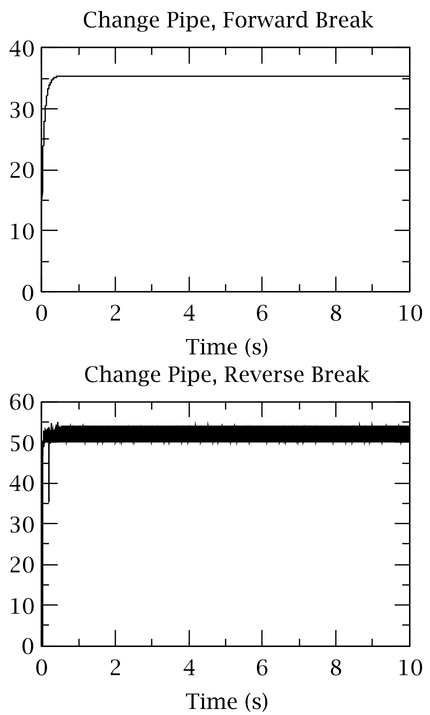
Default

pipe orientation – break orientation

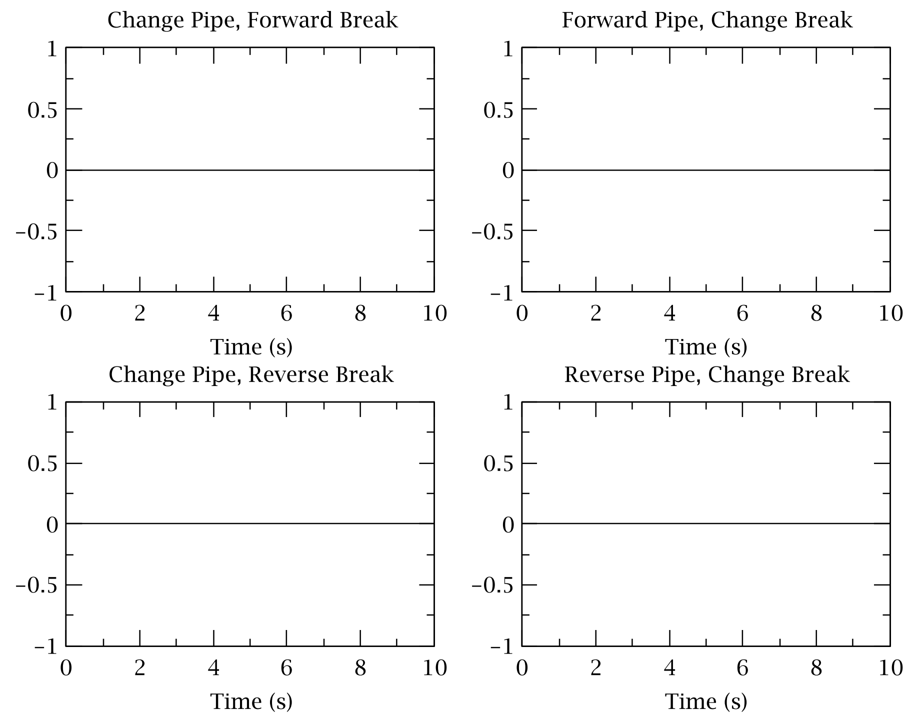


Steady-State Choked Flow

Henry-Fauske



Default

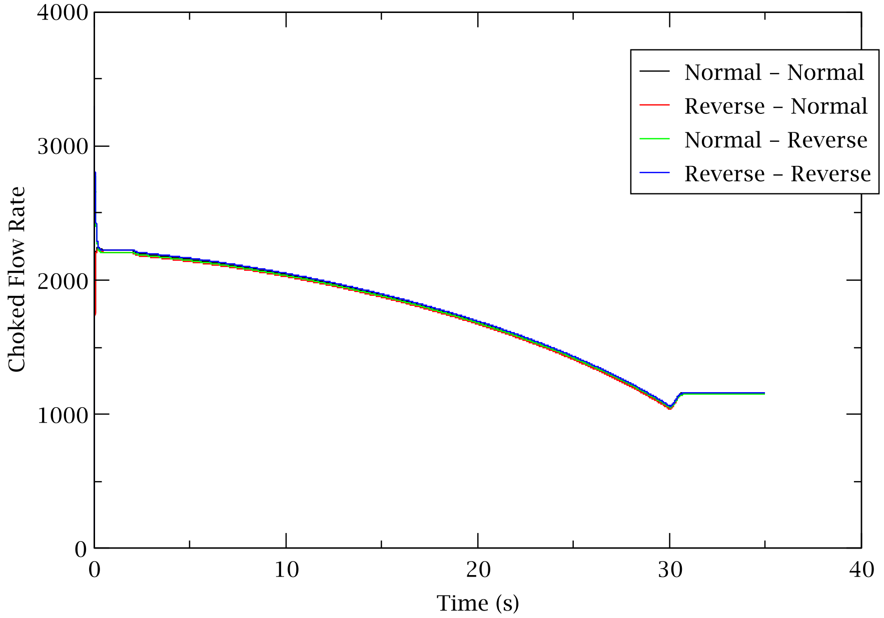


$$Diff = \frac{(\mathcal{M}_1 - \mathcal{M}_2)}{\frac{1}{2}(\mathcal{M}_1 + \mathcal{M}_2)} \times 100$$

Transient Choked Flow

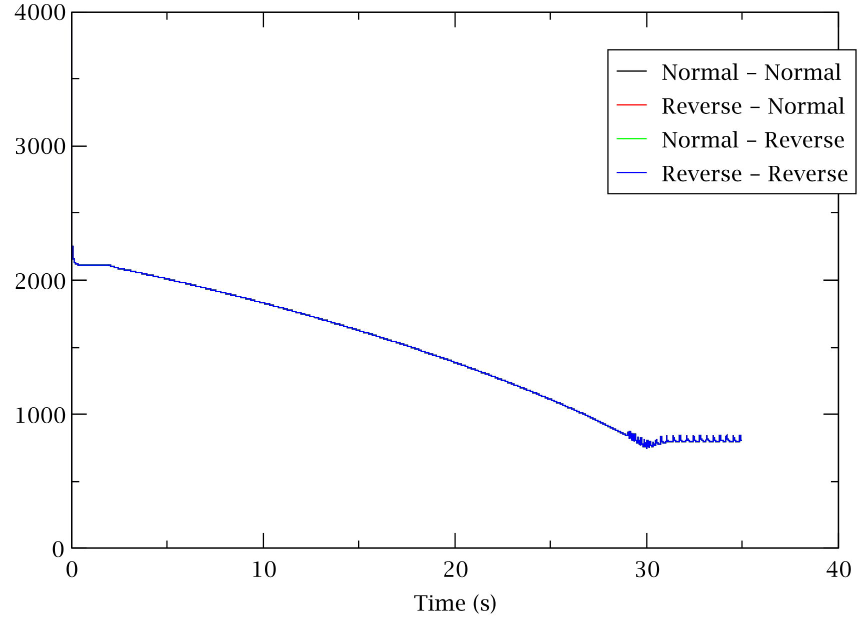
Henry-Fauske

pipe orientation – break orientation



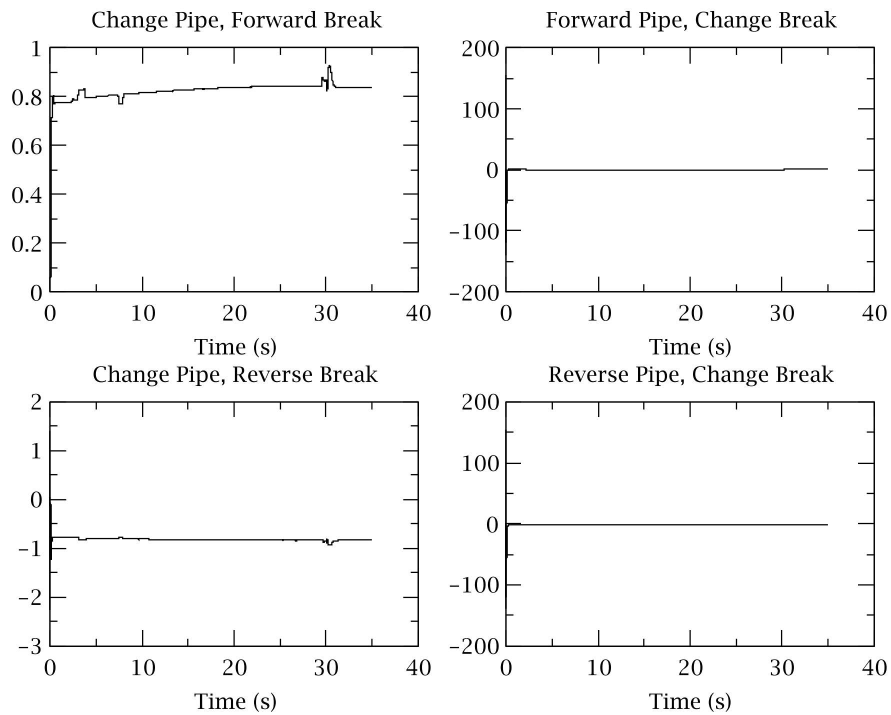
Default

pipe orientation – break orientation

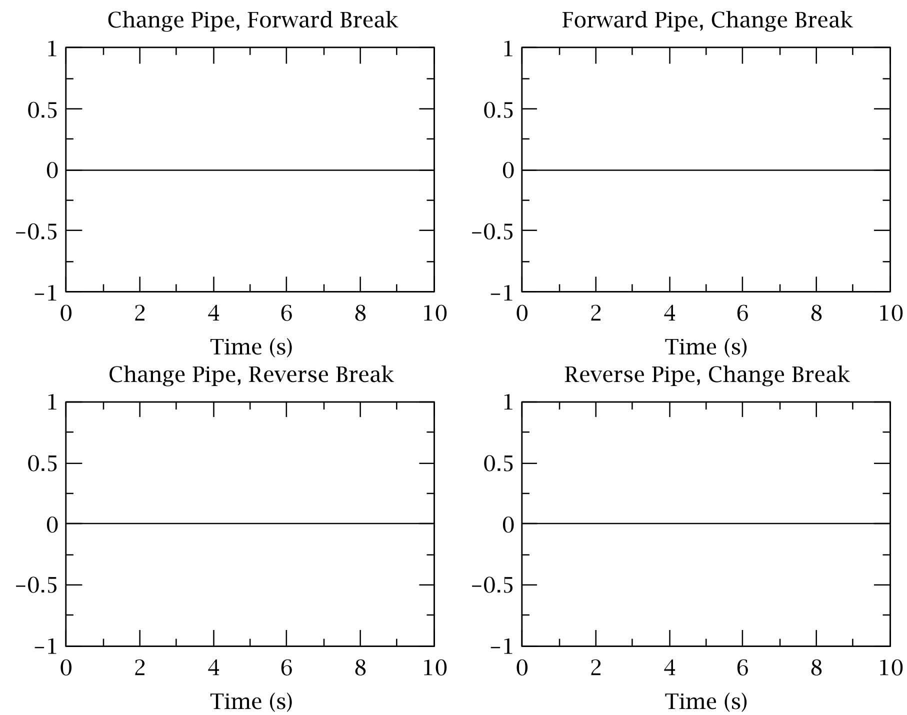


Transient Choked Flow

Henry-Fauske



Default



$$Diff = \frac{(\mathcal{M}_1 - \mathcal{M}_2)}{\frac{1}{2}(\mathcal{M}_1 + \mathcal{M}_2)} \times 100$$

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

$$P_{loss} = 0.5 * \omega_{v,sign}\left(\alpha_{f,j}\rho_{f,j}\left|\mathrm{v}_f\right|\mathrm{v}_f + \alpha_{g,j}\rho_{g,j}\left|\mathrm{v}_g\right|\mathrm{v}_g\right)$$

$$\omega_{v,sign} = SIGN\left(1.0, \mathrm{v}_{f,j}\right)$$

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

$$P_{loss} = 0.5\left|\alpha_{f,j}\rho_{f,j}\left|\mathrm{v}_f\right|\mathrm{v}_f + \alpha_{g,j}\rho_{g,j}\left|\mathrm{v}_g\right|\mathrm{v}_g\right|$$

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

$$P_{loss} = P_{loss} - \omega_{Vol,sign} \Delta x \left(F_{wall,f} \mathrm{v}_f + F_{wall,g} \mathrm{v}_g \right)$$

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

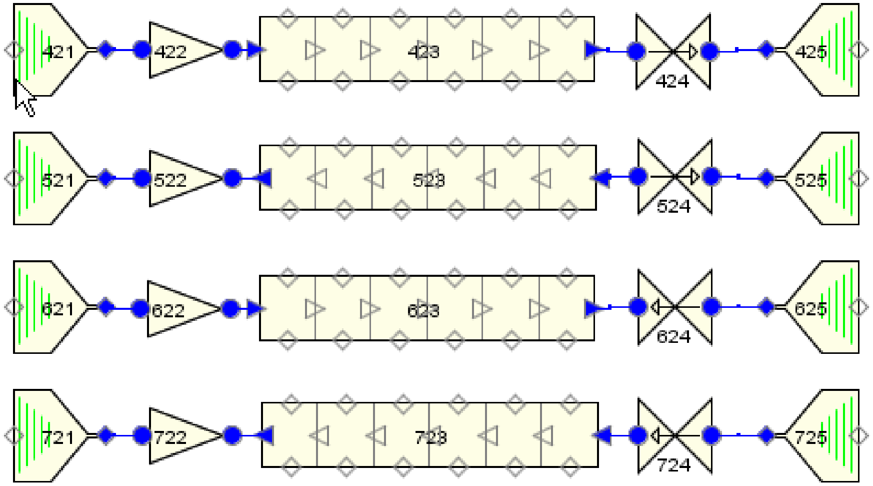
  5. Selection of the weighting factor in the time-smoothing of velocity was done using velocity
     - Corrected by using absolute value of velocity

Verification of Changes

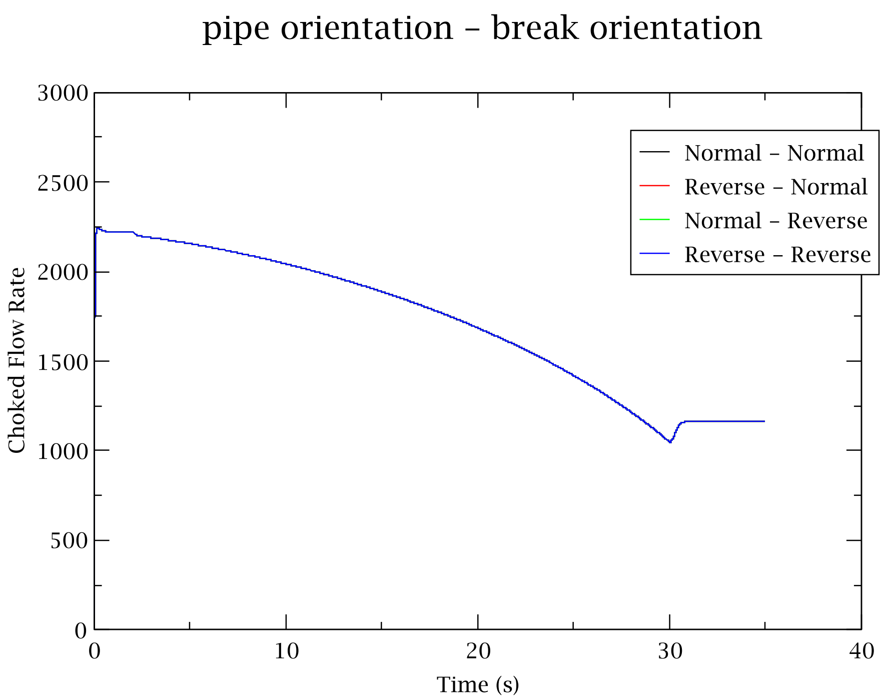
- Four verification problem sets developed
  - One steady-state
  - Three transient
  - Flow in all directions
    - Through junction that is experiencing critical flow
    - In upstream volume
  - Choked flow at all Faces
  - Both semi and nearly-implicit
  - Test all choking options
    - Henry-Fauske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

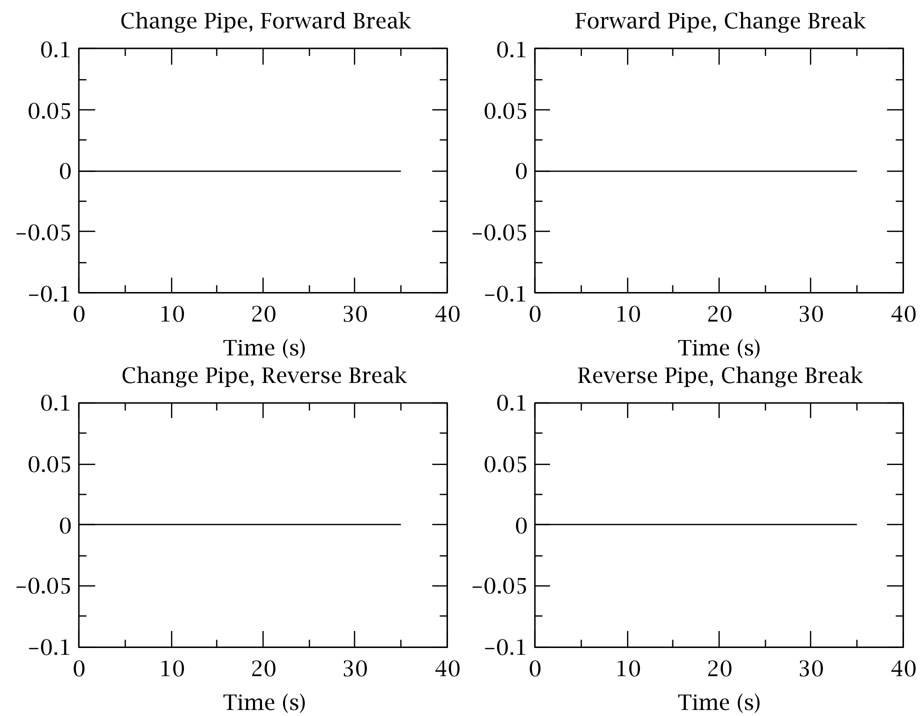
Choked Flow Verification

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



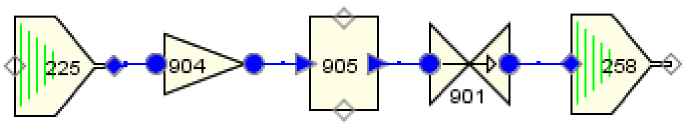
Depressurization Results



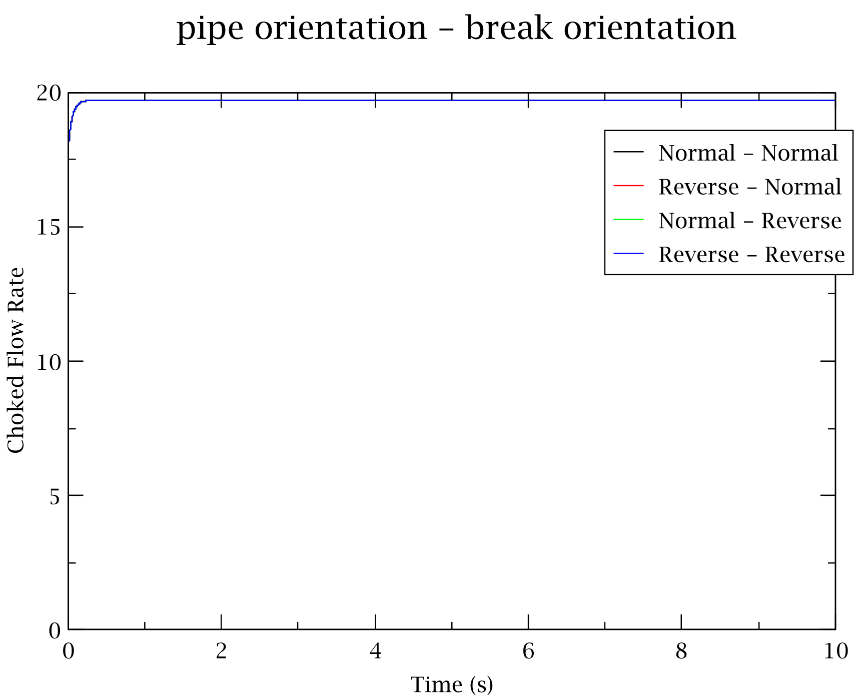


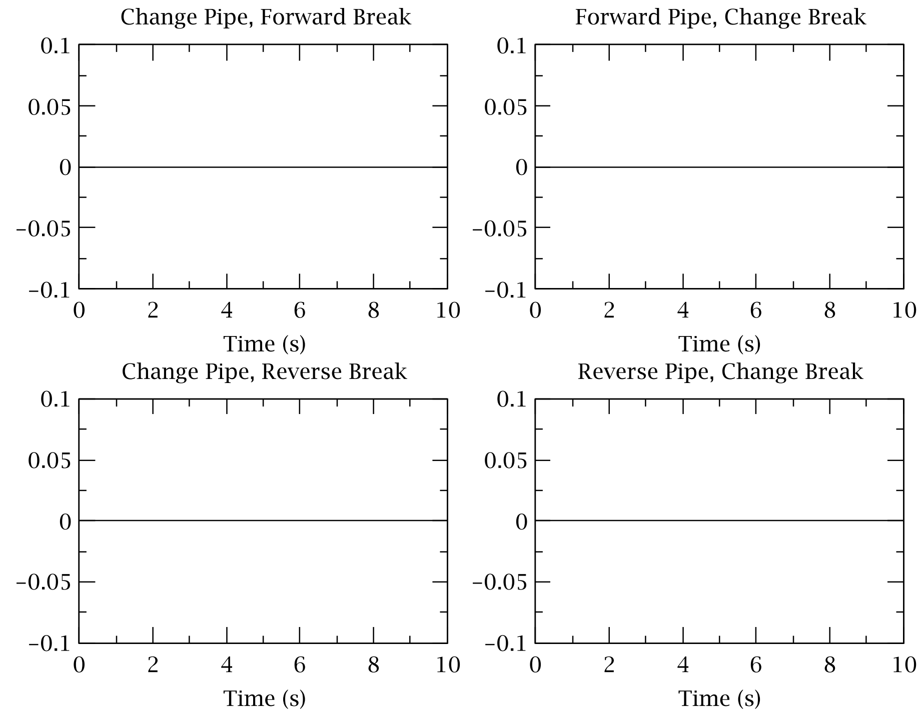
Choked Flow Verification

- 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





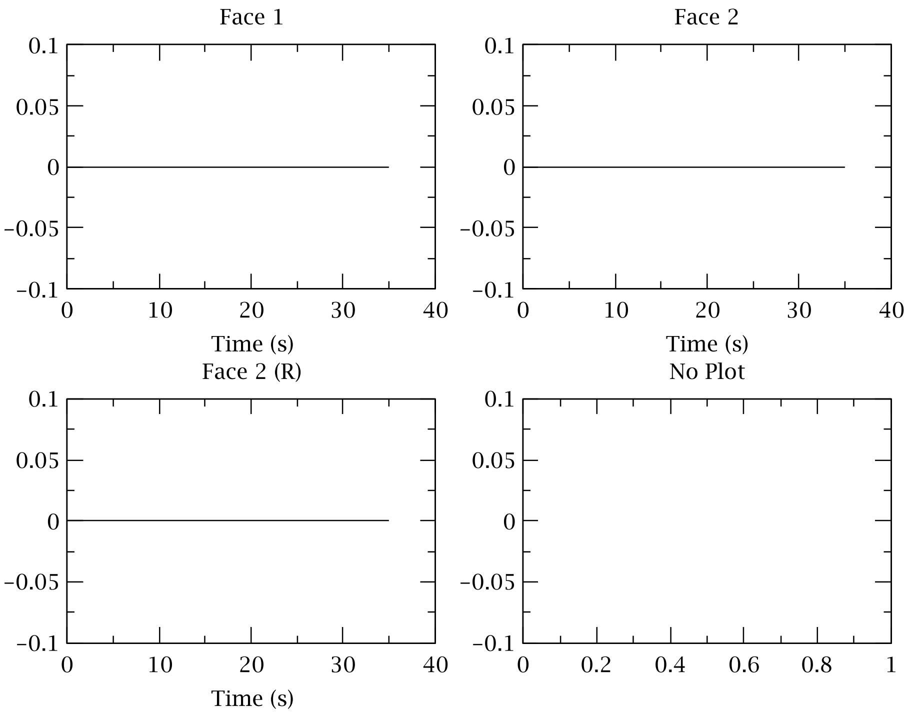
Choked Flow Verification

- 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

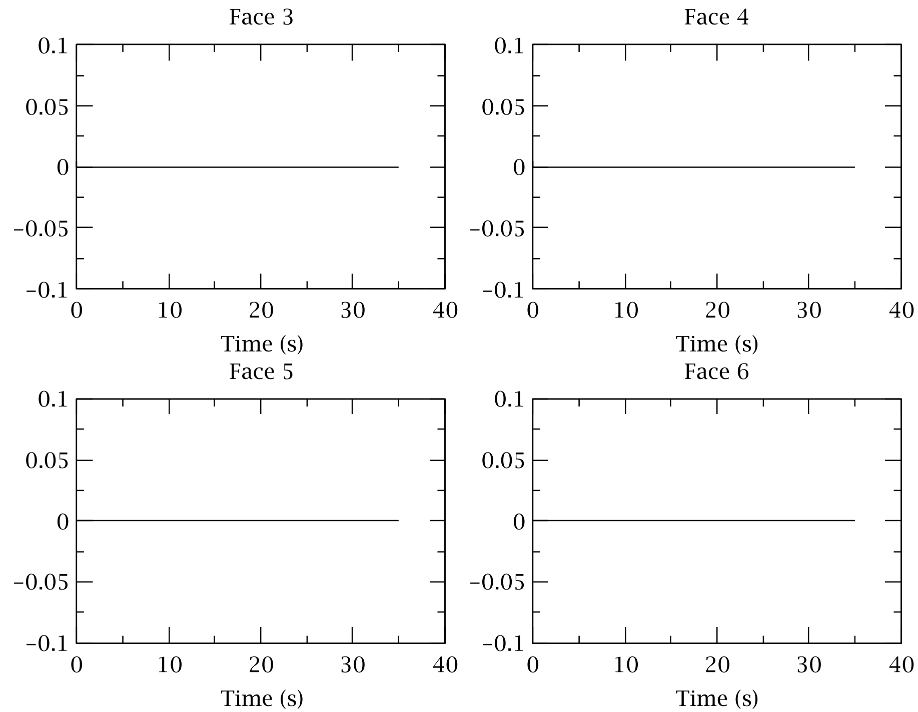
Side-Top-Bottom Results

- Changing break orientation with break located at each of the six faces

Change Break

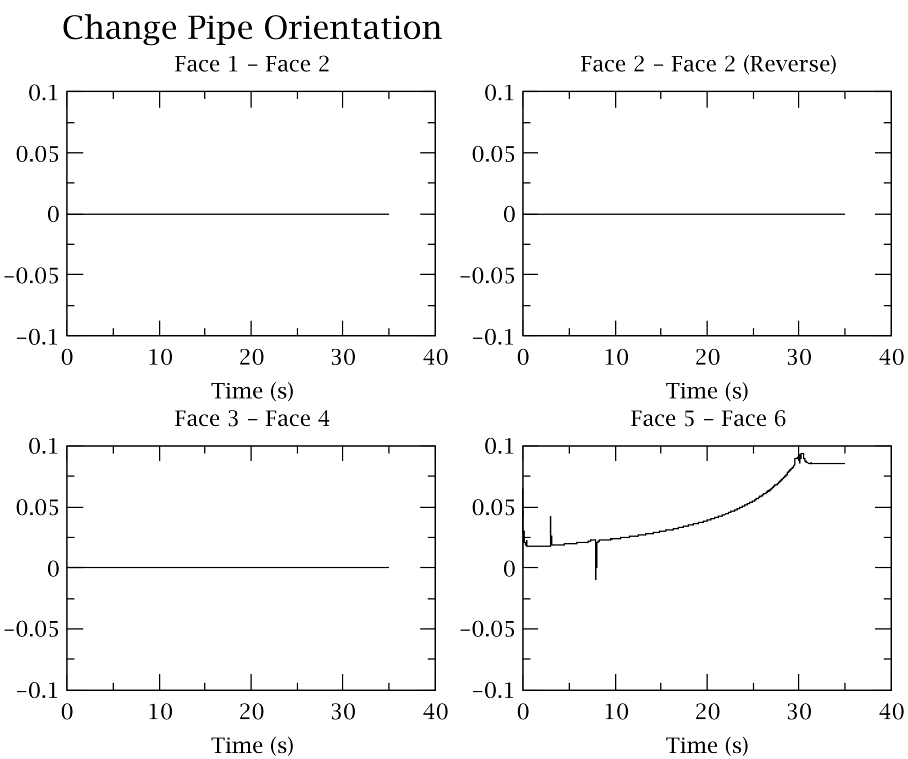


Change Break

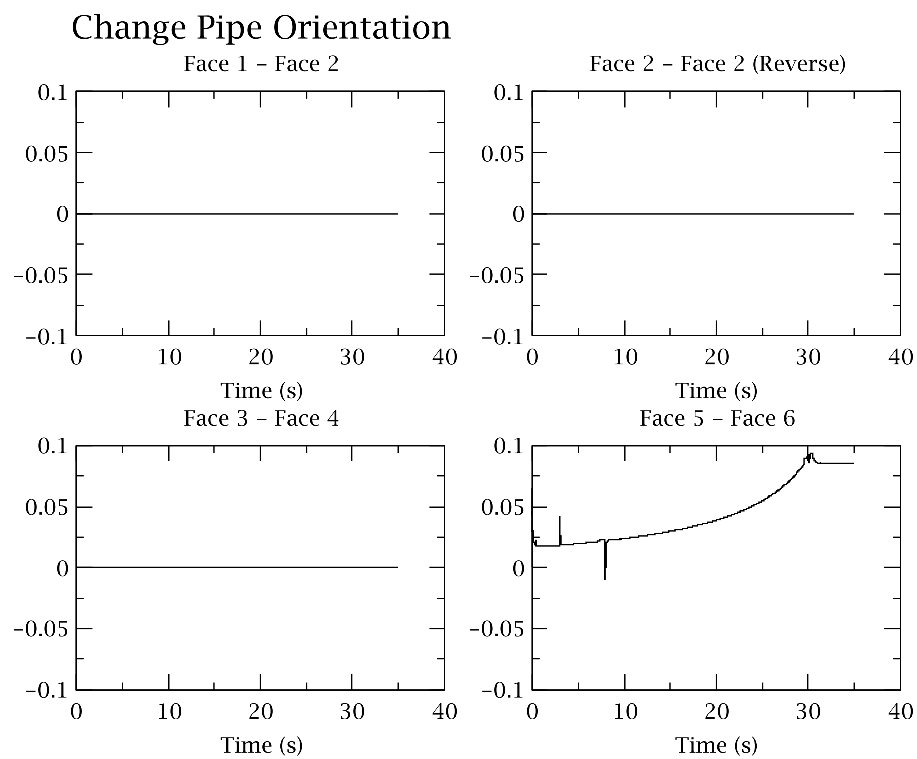


Side-Top-Bottom Results

Changing pipe orientation with break oriented out of the pipe

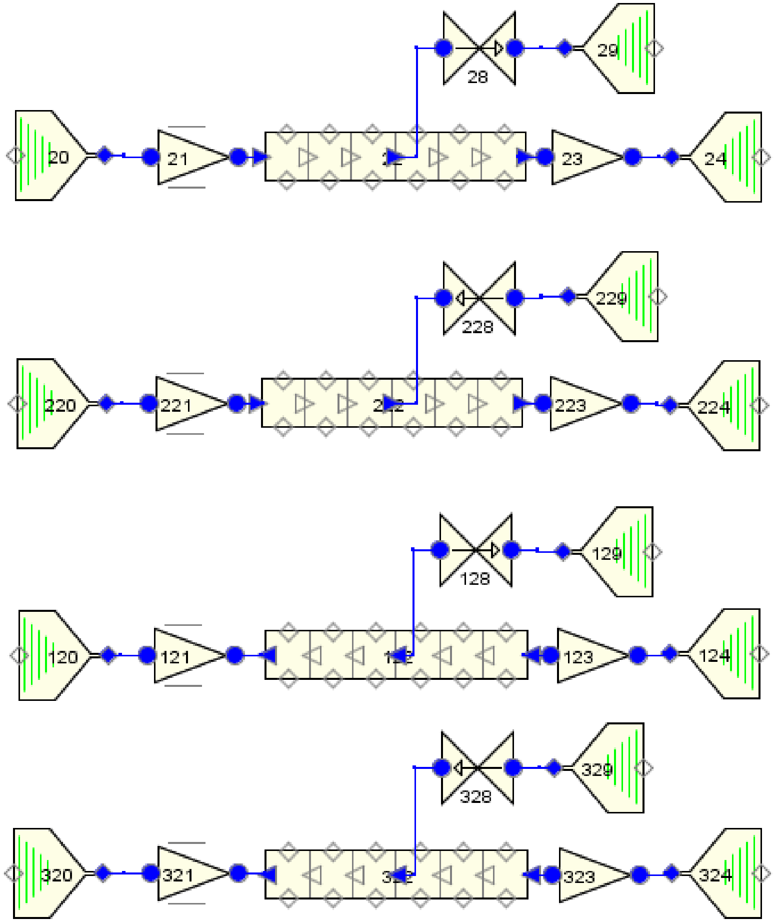


Changing pipe orientation with break oriented into the pipe

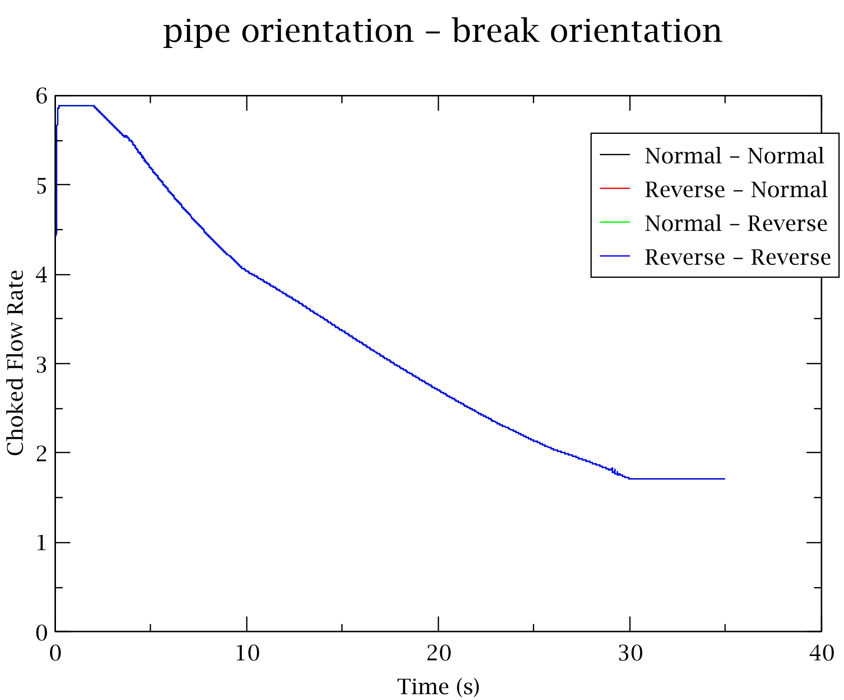


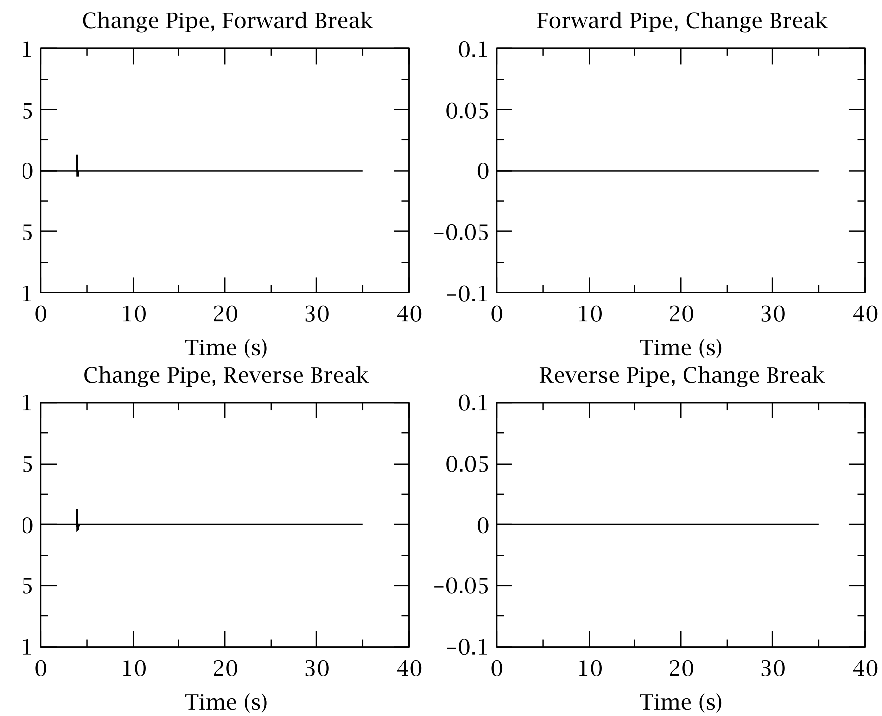
Choked Flow Verification

- 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



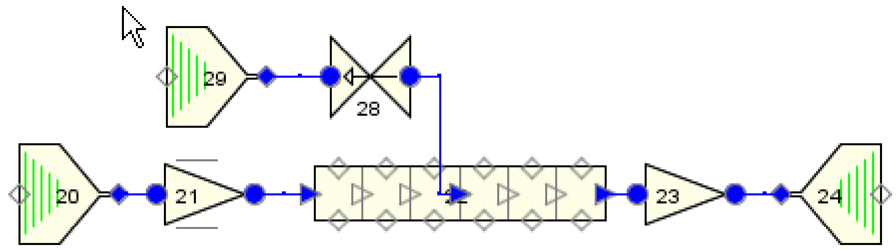
Flow-Past-Break Results



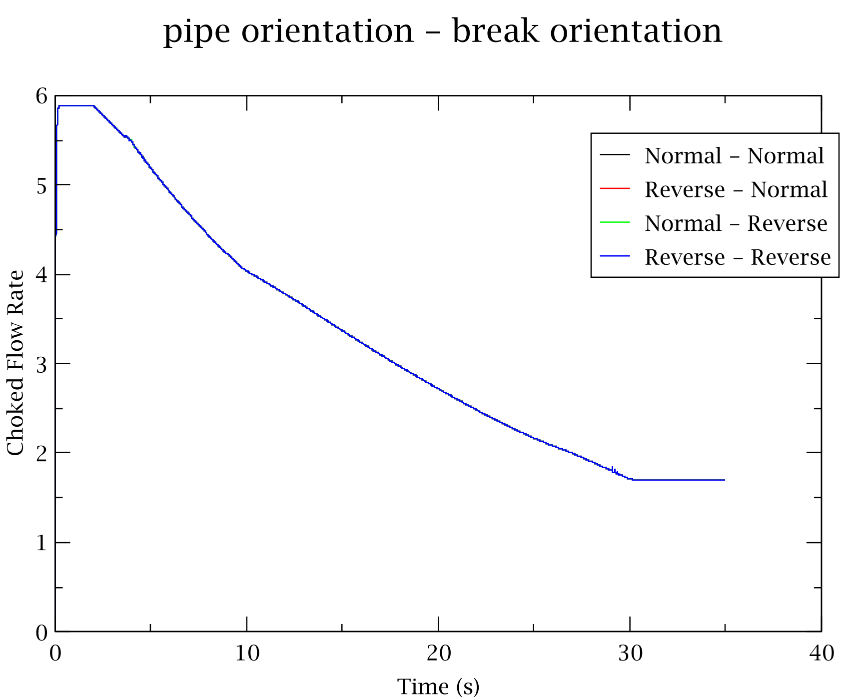


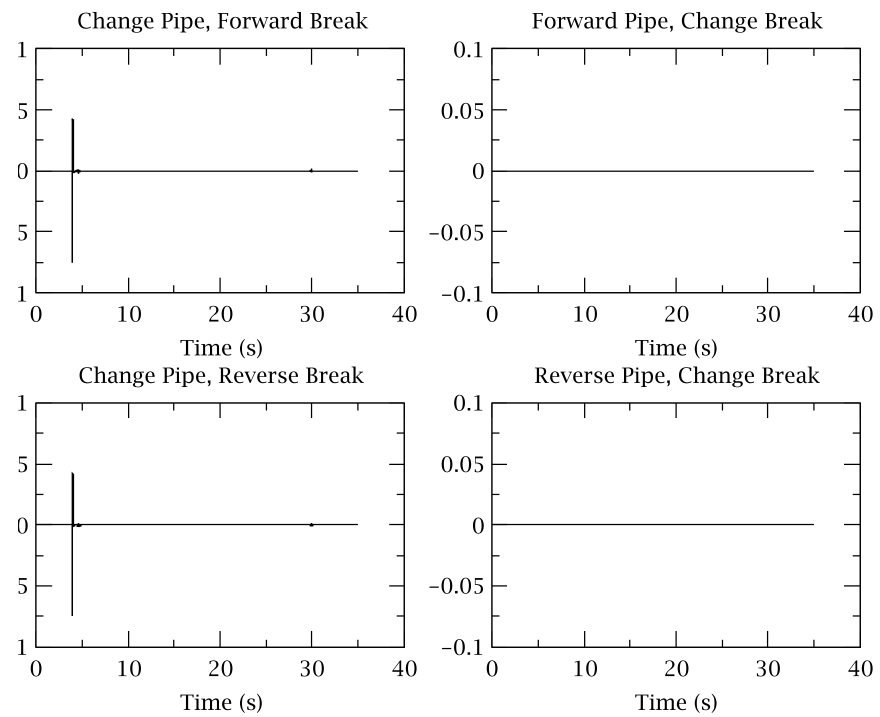
Choked Flow Verification

- 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 **upstream** face of the **fourth** pipe volume
    - Flow out of break is in the **opposite** direction as the flow in the pipe



Flow-Past-RevBreak Results





Flowing Quality

- Ratio of gas field flow rate to total flow rate

$$x_{flow} = \frac{\overline{\mathcal{M}_g}}{\overline{\mathcal{M}_g} + \overline{\mathcal{M}_l}}$$

- Used to calculate the equilibrium quality

$$x_e = \frac{\left[x_{flow} h_g + (1 - x_{flow}) h_f\right] - h_{f,sat}}{h_{g,sat} - h_{f,sat}}$$

- 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
    - Gas

$$\overline{\mathcal{M}_g} = \left[\sum_{N=1}^{N_{exit}} \mathcal{M}_{g,N}^2\right]^{\frac{1}{2}}$$

    - Liquid

$$\overline{\mathcal{M}_l} = \left[\sum_{N=1}^{N_{exit}} \mathcal{M}_{l,N}^2\right]^{\frac{1}{2}}$$

$$x_{flow} = \frac{\overline{\mathcal{M}_g}}{\overline{\mathcal{M}_g} + \overline{\mathcal{M}_l}}$$

Calculating Flowing Quality

- If sum of gas and liquid flow rates is zero
  - Original
    - Use static quality
  - Modified
    - Use volume velocities

$$\overline{\mathcal{M}_g} = \alpha_g \rho_g \left[\left(U_{g,x} A_x\right)^2 + \left(U_{g,y} A_y\right)^2 + \left(U_{g,z} A_z\right)^2 \right]^{\frac{1}{2}}$$

$$\overline{\mathcal{M}_l} = \alpha_l \rho_l \left[\left(U_{l,x} A_x\right)^2 + \left(U_{l,y} A_y\right)^2 + \left(U_{l,z} A_z\right)^2 \right]^{\frac{1}{2}}$$

    - If sum is still zero use static quality

$$x_{flow} = \frac{\overline{\mathcal{M}_g}}{\overline{\mathcal{M}_g} + \overline{\mathcal{M}_l}}$$

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