Critical Flow Model

November 13, 2002
Washington, DC

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Outline

> Self-choking vs. critical flow model
> Subcooled choking implementation
> Two-phase HEM critical flow model implementation
> Single phase vapor sound speed
> Validation examples
> Conclusion

Self-Choking vs. Critical Flow Model

> Self-Choking

- Use fine nodalization to directly calculate the limiting flow rate
- Computationally inefficient (requiring many more nodes and small time-step sizes)
- Not applicable for choking at double-ended breaks because of discontinuous variation of flow area with respect to length

Self-Choking vs. Critical Flow Model *(Continued)*

> Critical Flow Model

- Fluid dynamic and thermodynamic processes for choking are approximated by quasi-steady state flow relations
- Provides boundary conditions for transient solutions
- Eliminates the need for fine nodalization
- In LOCA events, the critical flow is initiated and sustained by the large pressure gradient at the break
  - Friction and heat addition mechanisms are important for gas dynamics, but do not play any role in LOCA

Subcooled Choking Implementation

> The limiting fluid velocity at the throat is calculated as [Equation (5-24)]

$$v_c = \sqrt{v_K^2 + 2\frac{(P_K - P_t)}{\rho_f}}$$

The throat pressure P_t is obtained from the Alamgir-Lienhard-Jones correlation for onset of nucleation

$$P_t = P_{sat} - \Delta P$$

$$\Delta P = 0.258\frac{\sigma^{1.5} T_R^{13.76}\sqrt{1+13.25(\Sigma')^{0.8}}}{\sqrt{k_B T_c}\left(1-\frac{\rho_g}{\rho_f}\right)} - 0.07\left(\frac{A_t}{A}\right)^2(\rho_f v_c^2)$$

- Jones defines "A" as the upstream flow area
- Depressurization rate, Σ, in the correlation is in units of Matm/s

Subcooled Choking Implementation *(Continued)*

- The depressurization rate for steady flow in a nozzle [Equation (5.23)]

$$\Sigma' = \frac{\rho_f v_c^3}{A_t}\left(\frac{dA}{dx}\right)_t$$

is in units of Pa/s. Proper unit conversion is done in the coding

> The area change rate is approximated as [Equation (5.25)]

$$\left(\frac{dA}{dx}\right)_t = \frac{A_K - A_t}{0.5\Delta x_K}$$

for smooth area change option

Subcooled Choking Implementation
(Continued)

and [Equation (5.26)]

$$\left(\frac{dA}{dx}\right)_t = \frac{A_K - A_t}{10D_K}$$

for abrupt-area change option. The approximation has been used since the model was implemented in RELAP5/MOD2

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Subcooled Choking Implementation
(Continued)

> If the velocities calculated by the momentum equations are higher than the limiting fluid velocity, the velocities are replaced by

$$v_g^{n+1} = v_f^{n+1} = v_c = \sqrt{v_K^2 + 2\frac{\left(P_K^{n+1} - P_t\right)}{\rho_f}}$$

> Linearization leads to

$$v_g^{n+1} = v_f^{n+1} = v_c + \frac{\partial v_c}{\partial P_k}\left(P_K^{n+1} - P_K^n\right)$$

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Two-Phase HEM Critical Flow Implementation

> For HEM the choking relation, Equation (5-20)

$$\frac{\alpha_g \rho_f v_g + \alpha_f \rho_g v_f}{\alpha_g \rho_f + \alpha_f \rho_g} = a_{HE}$$

becomes

$$v_f = v_g = a_{HE}$$

The equilibrium sound speed is evaluated at the throat, requiring the computation of thermodynamic state at the throat (junction)

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Two-Phase HEM Critical Flow Implementation *(Continued)*

> Thermodynamic state at the throat is approximated by integrating the steady-state mixture (sum) momentum and energy equations from the volume center to the junction, assuming no phase change and no heat addition along the (short) path

> The mixture energy equation becomes [Equation (5.31)]

$$x_K\left(h_{gK}+\frac{1}{2}v_{gK}^2\right)+(1-x_K)\left(h_{fK}+\frac{1}{2}v_{fK}^2\right)=x_t\left(h_{gt}+\frac{1}{2}v_{gt}^2\right)+(1-x_t)\left(h_{f,t}+\frac{1}{2}v_{f,t}^2\right)$$

Under equal velocity assumption, $v_{g,K}=v_{f,K}$ and $v_{g,t}=v_{f,t}$

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Two-Phase HEM Critical Flow Implementation *(Continued)*

> The steady state mixture (sum) momentum equation is [Equation (5.28) plus friction and gravity terms]

$$\frac{1}{2}\alpha_g\rho_g\frac{\partial v_g^2}{\partial x}+\frac{1}{2}\alpha_f\rho_f\frac{\partial v_f^2}{\partial x}=-\frac{\partial P}{\partial x}+\rho B_x-\alpha_f\rho_f F_f v_f-\alpha_g\rho_g F_g v_g$$

The vapor generation term is not present due to the assumption of equal velocity

> In the integration from the volume center to the the throat, the "$\alpha\rho$" factors for the friction and gravity terms are approximated by the volume center values since their contributions are negligible for short lengths

Two-Phase HEM Critical Flow Implementation *(Continued)*

> The "$\alpha\rho$" factors associated with the momentum flux terms are approximated by average quantities that are adjusted to produce HEM critical flow rate

> If the calculated velocity from the momentum equations is higher than the two-phase equilibrium sound speed, the velocity solution becomes:

$$v_g=v_f=a_{HE}$$

> A transition region from subcooled choking to two-phase choking is implemented to smooth the critical mass flow rate

Single Vapor Sound Speed

> Single phase sound speed is calculated with

$$a^2 = \left(\frac{\partial P}{\partial \rho}\right)_s = -\frac{V^2}{\left(\frac{\partial V}{\partial P}\right)_s}$$

> For two-phase:

$$V = xV_g + (1-x)\,V_f$$

$$\left(\frac{\partial V}{\partial P}\right)_s = x\left(\frac{\partial V_g}{\partial P}\right)_s + (1-x)\left(\frac{\partial V_f}{\partial P}\right)_s + \left(v_g - v_f\right)\left(\frac{\partial x}{\partial P}\right)_s$$

> If the sound speed for single phase vapor is calculated from the two-phase formulation with x = 1, the sound speed is called equilibrium sound speed

Critical Model Validation

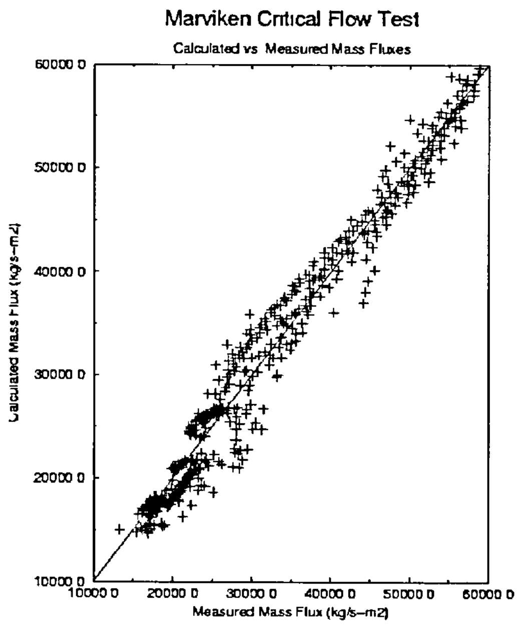
> Nine Marviken critical flow tests are analyzed for the critical flow uncertainty

- Tests 2, 6, 8, 16, 17, 20, 22, 24, 25
- Critical flow multiplier 1±2σ

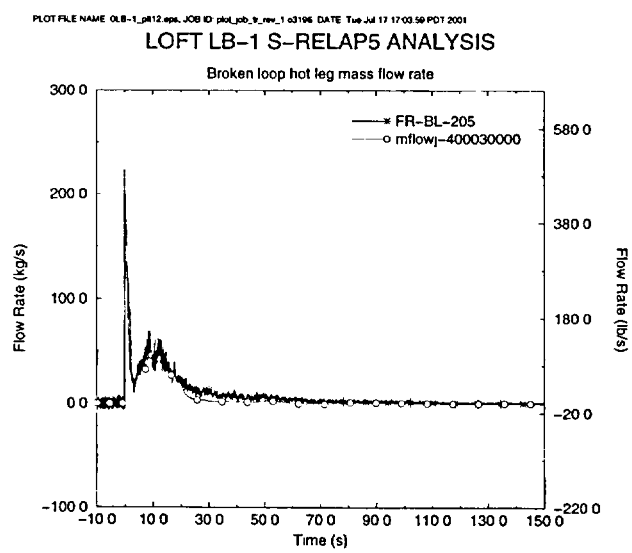
> Additional assessments are performed on four LOFT and two semiscale tests

- LOFT tests L2-3, L2-5, LP-02-6 and LP-LB-1
- Semiscale LBLOCA tests S-06-3 and S-07-1

Calculated and Measured Mass Fluxes for All Nine Marviken Tests



LOFT LP-LB-1



Conclusion

> The presentation provides description of subcooled choking and two-phase HEM critical flow model used in assessment and plant application calculations

> The model uncertainty is obtained from assessment of nine Marviken critical flow tests

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Statistical Resolution

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Statistical Resolution

> Issue: The NRC request to report the PCT, maximum nodal oxidation, and total oxidation as a joint probability

Statistical Resolution

> Original Proposed RLBLOCA Methodology

- Reports an individual 95/95 value for each of the criteria: PCT, maximum nodal oxidation, and total oxidation
- Joint probability not addressed

Statistical Resolution

> Resolution:

- Regulatory Guide 1.157 indicates:

"The revised paragraph 50.46(a)(1)(i) requires that it be shown with a high probability that none of the criteria of paragraph 50.46(b) will be exceeded, and is not limited to the peak cladding temperature criterion. However, since the other criteria are strongly dependent on peak cladding temperature, explicit consideration of the probability of exceeding the other criteria may not be required if it can be demonstrated that meeting the temperature criterion at the 95% probability level ensures with an equal or greater probability that the other criteria will not be exceeded."

Statistical Resolution

> Resolution:

- Based on this, Framatome-ANP has agreed to amend the proposed methodology to only report the 95/95 PCT case and its associated maximum nodal oxidation and total oxidation

General RELAP5 Questions

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General Response

> Topics

- Transient discharge of mass and energy
- Propagation flows
- Forces on piping and structures
- Selection of node size

Transient Discharge of Mass and Energy

Please describe how the discharge mass flow rate is obtained for the postulated instantaneous rupture of a long pipe before the quasi-steady blowdown rate is reached. The pipe is attached to a pressure vessel

Concern:

The earliest RELAP calculations for this case sometimes resulted in flow rates exceeding critical flows. Too much mass lost

Transient Discharge of Mass and Energy

Background

> Numerical Considerations

- Using fine nodalization and small time-steps, RELAP5 codes have demonstrated the ability to mechanistically capture the choke flow phenomenon
- This approach is computationally intensive and undesirable
- To achieve fast execution speed, implicit evaluation is used for those terms responsible for the sonic wave propagation time step. This allows a maximum stable time step to approach the Courant limit

Transient Discharge of Mass and Energy

> Subcooled Choke Flow Model

- Alamgir-Lienard-Jones used to determine throat pressure and choke velocity (discussion in Section 5.1.2.1 of EMF-2100) using local conditions
- When (Bernoulli) calculated velocity exceeds the choke velocity, velocity is set to the choke velocity

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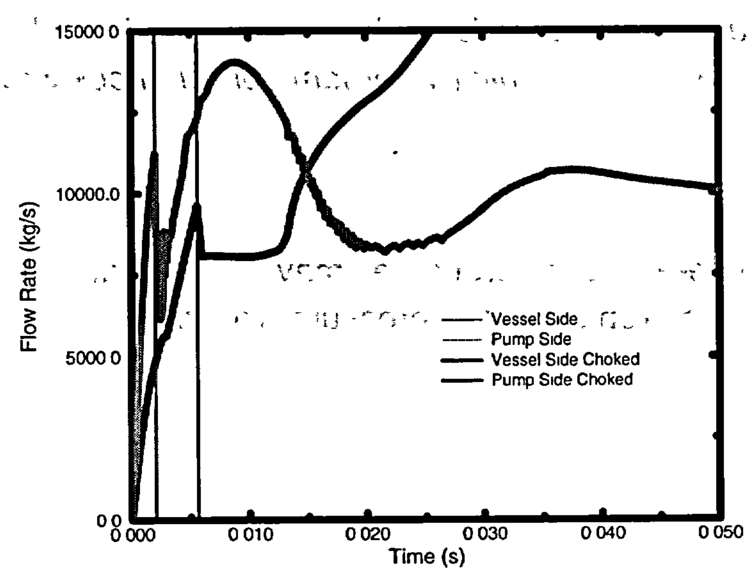
Transient Discharge of Mass and Energy

Choke Model Timing



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Transient Discharge of Mass and Energy

> Conclusion

- May for a very short period (< 0.002 s), over predict flow
- Still use small time steps
- Short period of over prediction is inconsequential and conservative for LOCA

Propagative Flows

Please describe how moving pressure or velocity disturbances can be tracked by the code as they propagate through a subsystem either as sonic (waterhammer) or shock waves

Concern:

Volume/time-averaged properties may distort spatial gradients that drive the propagation of pressure waves

Propagation Flows

Background

> Pressure waves velocity will typically range below 1000 m/s

> Most RCS loops are less than 50 m

> S-RELAP5 implicitly simulates the dynamics of short wavelength phenomena (small time constant), including pressure wave disturbances (not Courant limited)

> No formal effort is made to track the propagation of pressure waves in S-RELAP5; however, sound speed is calculated

Propagation Flows

Framatome Experience

> Small disturbance are imperceptible in plant analysis

> Break provides the singular large disturbance in LOCAs

- Begins to dampen when choke model is applied

> Initiation of ECC may induce a pressure disturbance; however, this is also imperceptible in LBLOCA

Conclusion

> Generally not important for LOCA applications

Forces on Piping and Structures

Please describe how transient properties from S-RELAP5 calculations are employed to predict forces on stationary solid surfaces, such as pipes, containing walls, and submerged structures

Concern:

Miscalculations of forces

Forces on Piping and Structures

> Realistic LBLOCA has not been developed to address this type of calculation

Selection of Node Size

Please describe how various node sizes are selected in a given system, providing assurance that the dominant phenomena are predicted, representative of the actual system response being analyzed

Concern:

Coarse nodalization may mask important phenomena

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Node Size

Quotes from "Quantifying Reactor Safety Margins"

> *"The plant model must be nodalized* ***finely enough*** *to represent both the important phenomena and design characteristics of the NPP but coarsely enough to* ***remain economical.****"*

> *"Thus, the preferred path is to establish a* ***standard NPP nodalization*** *for the subsequent analysis. This minimizes or removes nodalization, and the freedom to manipulate noding, as a contributor to uncertainty."*

> *"Therefore, a nodalization selection procedure defines the* ***minimum noding needed to capture the important phenomena.****"*

> *"This procedure starts with analyst experience in* ***previous code assessment*** *and application studies and any documented nodalization studies. Next, nodalization studies are performed during the simulation of separate- and integral-effects code data comparisons. Finally, an iterative process using the NPP model is employed to determine sufficiency of the NPP model nodalization."*

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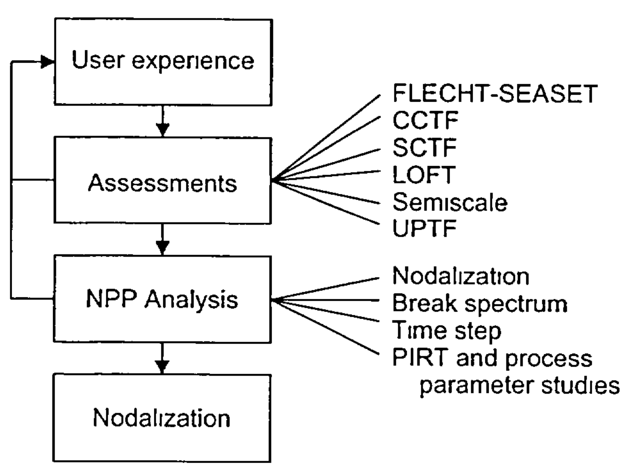
Node Size

> Necessary Conditions (and method of resolution)

- Discriminate key structure characteristics (drawings)
- Obtain acceptable steady-state agreement with plant (shakedown)
- *Preserve dominant phenomena* (code models, shakedown)
- Maintain reasonable computational economics (shakedown)
- Maintain scalability (assessments)
- Preserve accuracy, numerical stability, and convergence

Issue	Evaluation
Accuracy	Assessment
Stability	Semi-Implicit Numerics
Convergence	Time Step

Node Size



Node Size

> Conclusions

- Initial nodalization based on experience
- Revised based on plant studies and assessment results
- Final nodalization validated through the performance of final assessments

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Discussion of Momentum Equations

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Introduction

> Purpose of the presentation is to address momentum equation issues raised by ACRS member comments. Several comments concerned application of the S-RELAP5 momentum equation in the solution of flows in a typical NPSS system.

- Will provide discussion of several momentum equation terms
- Will apply S-RELAP5 to several problems and discuss dominate terms
- Will address specific questions

Momentum Conservation Equations

> Contents

- Definitions
- Conventions
- Momentum Discussion
- Example Problems
- Response to Comments
- Question Resolution

> Example Problems

- Straight Pipe
- 180° Bend
- Area Change
- Tee
- Plenums
  - simple example
- 2-D Problems

Definitions

> Control Volume
  - Volume where integration performed (cell)

> Hydrodynamic Volume
  - Represents space containing fluid (node, volume)

> Junction
  - Connection between hydrodynamic volumes
  - Center of the momentum control volume

> Components
  - Collection of hydrodynamic volumes and/or junctions
    - Automation tool for generating input
    - Specialized processes (i.e., pumps, separators, etc)

Definitions (cont.)

> "Old-time" (n) and "new-time" (n+1) are used to designate current time level and the time level at which the solution is being obtained

> Cross-Flow
  - Orthogonal junction connections
    - Special momentum treatment that yields no dissipation

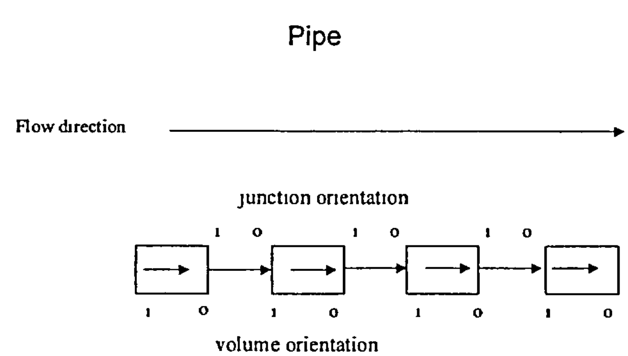
Conventions

> Hydrodynamic volume and junction orientation (1-D)

- Volumes have a designated inlet side and outlet side
  - Flow is assumed to be positive from inlet to outlet
  - Inclination angle is formed from inlet to outlet
    - Implies gravity effects not a second dimension
    - All 1-D nodes are in the 'x-direction'
  - Multi-volume components arrange volume order from inlet to outlet
- Junctions have a designated inlet side and outlet side
  - called 'from' and 'to' in the manual
  - Logic tables keep track of orientation for use in volume velocity calculation

Conventions (cont.)

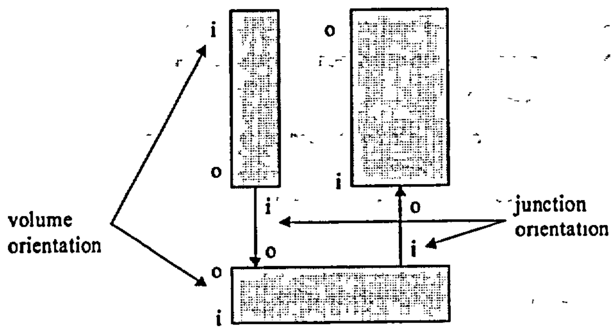
> Hydrodynamic volume and junction orientation (1-D)



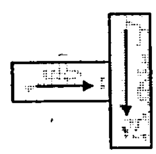
Conventions (cont.)

> Hydrodynamic volume and junction orientation (1-D)

Simple Lower Plenum



Conventions (cont.)



> Cross-flow junction connects to midpoint of hydrodynamic volume

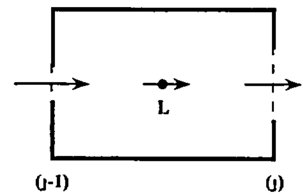
- Flow across junction orthogonal to flow in connected volume

> Areas

- Volume flow area constant throughout node
  - Must satisfy V=AL
  - Length and volume should be preserved
- Junction area defaults to minimum of adjacent volume flow areas or user defined
- Smooth or abrupt can be specified

Conventions (cont.)

> Volume Average Velocity

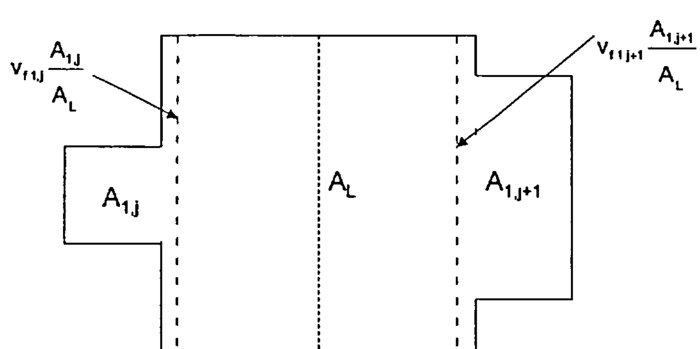


- What is it used for?
  - Wall friction factors
  - Wall-fluid convective heat transfer
  - Difference formulation of the momentum flux terms
- Why is it needed?
  - Value needed for velocity at center of mass/energy cell and the face of momentum control volumes
  - Need to account for possibility of multiple junctions on a cell face
- How does it work?
  - Averages phasic flows at cell faces and uses area ratio to translate junction values to a mass/energy volume value

Conventions (cont.)

> Volume Average Velocity' for simple, single-phase junction connections in coordinate direction 1

$$(v_f)_{L,1,in} = v_{f,1,j}\frac{A_{1,j}}{A_L} \qquad (v_f)_{L,1,out} = v_{f,1,j+1}\frac{A_{1,j+1}}{A_L} \qquad (v_f)_{L,1} = \frac{(v_f)_{L,1,in} + (v_f)_{L,1,out}}{2}$$



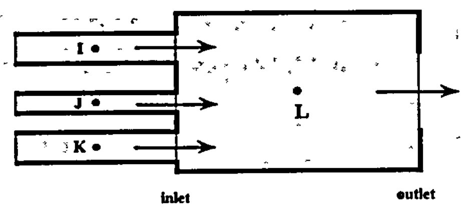
Conventions (cont.)

> Volume Average Velocity' for complex two phase junction connections

- Get average velocity for all junctions connected to the inlet face of the mass/energy control volume

$$(v_f)_{L,J,in} = \left(\frac{\sum_{jin} (\dot{\alpha}_f \dot{\rho}_f v_f)_{i,jin} A_{i,jin}}{\sum_{jin} (\dot{\alpha}_f \dot{\rho}_f)_{i,jin} A_{i,jin}} \right) \left(\frac{\sum_{jin} A_{i,jin}}{A_L} \right)$$

where $\sum_{jin}$ is the summation over all junctions on the inlet face



Momentum Equation Discussion

> Momentum Equation

- Field Equation Question
- RLBLOCA Nodalization
- Momentum Equation Discussion
  - Control Volume - 1D
  - 1D Spatial Discretization
  - Example Problems
- Control Volume - 2D
  - 2-D Spatial Discretization
  - 2-D Finite Difference Equations
  - 1-D to 2-D Connections
  - Example problems
- Response to Comments
- Question Resolution

> Example Problems

- Straight Pipe
- Simple Elbow
- 180° Bend
- Area Change
- Tee
- Plenums
  - Simple Example
- 2-D

Momentum Equation Question

> Draw some control volumes to which Equations 2.3 and 2.4 from EMF-2100 apply, explaining the meaning of the various terms

> Equations 2 3 and 2 4 are the liquid and vapor field equations and are expressed in differential format using vector notation

> Should be reduced to the 1D and 2D spatial discretization form before discussion

- Show nodalization of system model and relate portions of plant model to momentum effects
- Show field equation and spatial discretized form
- 'Nodalization-to-control volume' mapping and discussion

RLBLOCA Nodalization

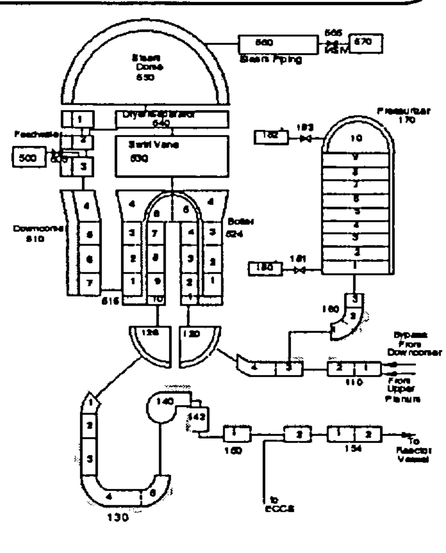
Loop Nodalization

> 1-D is sufficient to model the primary system

- Pump overwhelms losses from inertial effects
- Limited inertial effects by design

> Secondary system is a quasi-steady boiler

- Inertial effects limited to separator
- 1-D is sufficient to model the secondary system

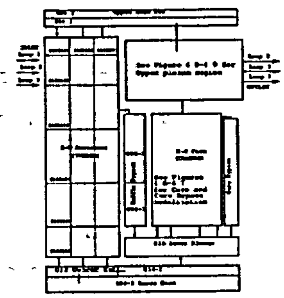


RLBLOCA Nodalization (cont.)

> Significant inertial effects at cold leg to downcomer and lower plenum
- Overwhelmed by pump
- Effects diminish after blowdown

> Significant multi-dimensional effects in downcomer and lower plenum
- Exacerbated in downcomer during blowdown
  - Downcomer requires multi-dimensional modeling
  - 2-D sufficient
- Effects diminish in lower plenum after blowdown
  - 2-D may not be required

Vessel Nodalization



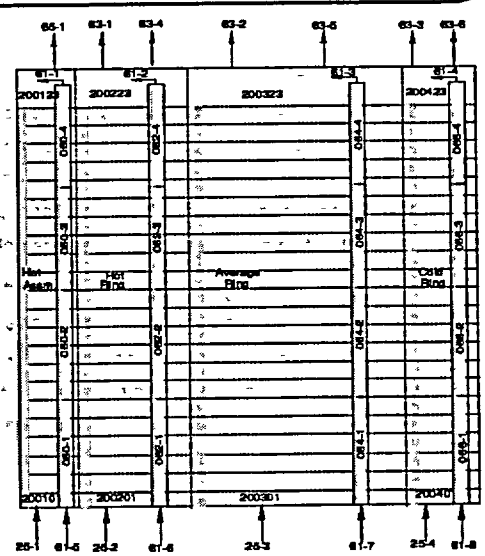
RLBLOCA Nodalization (cont.)

Core Nodalization

> No significant inertial effects

> No significant multi-dimensional flow effects

> Significant radial temperature profile effects
- Effects intensify after blowdown begins
- Multi-dimensional modeling required
- 2-D sufficient



RLBLOCA Nodalization (cont.)

> Summarizing

- The primary and secondary systems do not have significant multi-dimensional effects nor significant inertial effects
- The downcomer and core regions have significant multi-dimensional effects during blowdown
  - The multi-dimensional effects in the lower plenum diminish during the transient
- The downcomer region initially has significant inertial effects which diminish during the LOCA transient
  - The inertial effects in the lower plenum diminish during the blowdown transient

Momentum Equation Discussion

> Assumption

- For reactor safety analysis applications using thermal-hydraulic system codes, the conservation of mass and energy is of paramount importance The conservation of momentum is considered to be of secondary importance and a less rigorous approach can be used (providing, of course, that this simplified treatment does not seriously degrade the solution).
- Consequently, in the formulation and discretization of the momentum equations, approximations are made to
  - Accommodate volumes with multiple junctions on a cell face
    - e g , the downcomer to lower plenum connection
  - Render the equations easier to solve numerically
  - Ensure the stability of the numerical solution

Momentum Equation Discussion (cont.)

> Momentum Field Equations

- The phasic conservation of momentum equations are used in an expanded form and in terms of momenta per unit volume using the phasic primitive velocity variables v_g and v_f
- The primary reason for use of the expanded form is that is it more convenient for the development of the numerical scheme
- The guiding principle used in the development of the S-RELAP5 momentum formulation is that momentum effects are secondary to mass and energy conservation in reactor safety analysis and a less exact formulation (compared to mass and energy conservation) is acceptable, especially since nuclear reactor flows are dominated by large sources and sinks of momentum

Momentum Equation Discussion (cont.)

> Equations 2.3 and 2.4 are the liquid and vapor field equations in differential format

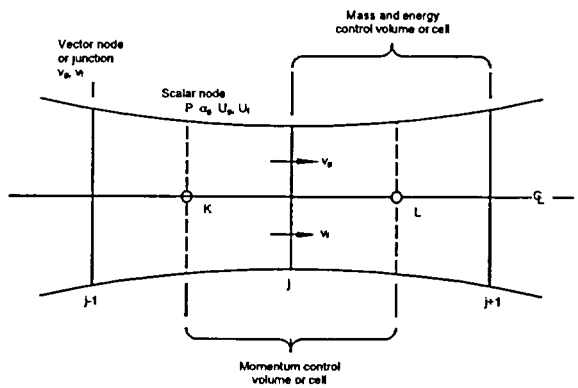
$$\alpha_f \rho_f \frac{\partial v_f}{\partial t} + \alpha_f \rho_f v_f \cdot \nabla v_f = -\alpha_f \nabla P + \alpha_f \rho_f B - \alpha_f \rho_f FWF v_f - \Gamma_g (v_I - v_f) - \alpha_f \rho_f FIF (v_f - v_g) - C \alpha_f \alpha_g \rho \frac{\partial}{\partial t}(v_f - v_g)$$

and

$$\alpha_g \rho_g \frac{\partial v_g}{\partial t} + \alpha_g \rho_g v_g \cdot \nabla v_g = -\alpha_g \nabla P + \alpha_g \rho_g B - \alpha_g \rho_g FWG v_g + \Gamma_g (v_{gI} - v_g) - \alpha_g \rho_g FIG (v_g - v_f) - C \alpha_f \alpha_g \rho \frac{\partial}{\partial t}(v_g - v_f)$$

Control Volume 1-D

Generalized Momentum Control Volume



Field Equation Reduction to 1-D

> The field equations are rewritten in terms of the primary direction for 1-D

- Decomposing the vector notation into it's components

$$\alpha_f \rho_f \frac{\partial v_{x,f}}{\partial t} + \alpha_f \rho_f \frac{1}{2}\frac{\partial v_{xf}^2}{\partial x} = -\alpha_f \frac{\partial P}{\partial x} + \alpha_f \rho_f g_x$$
$$-\alpha_f \rho_f FWF_x v_{x,f} - \Gamma_g \left(v_{xfi} - v_{x,f}\right)$$
$$-\alpha_f \rho_f FIF_x \left(v_{xf} - v_{xg}\right) - C\alpha_f \alpha_g \rho \frac{\partial}{\partial t}\left(v_{xf} - v_{xg}\right)$$

Field Equation Reduction to 1-D, Single-Phase

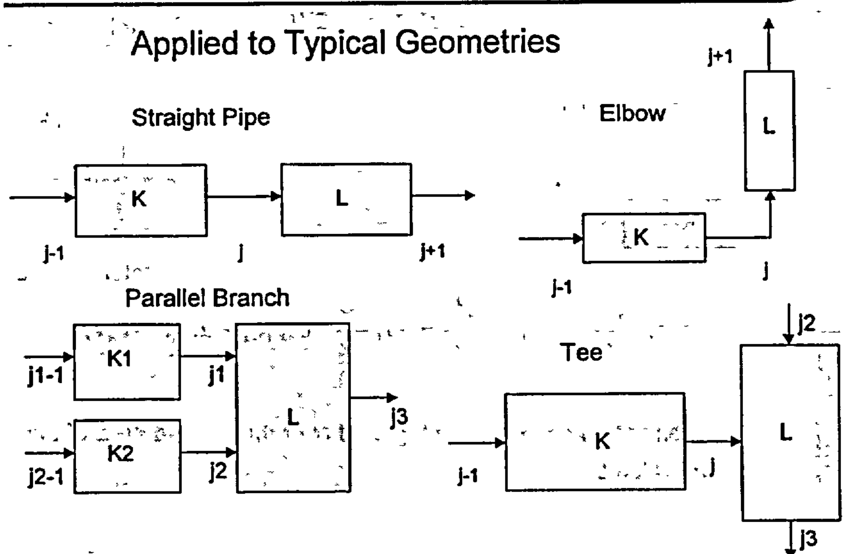
> The field equations are rewritten in terms of the primary direction for 1-D

- Decomposing the vector notation into it's components for single-phase liquid
  - Void fractions have been left in place

$$\alpha_f \rho_f \frac{\partial v_{x,f}}{\partial t} + \alpha_f \rho_f \frac{1}{2}\frac{\partial v_{x,f}^2}{\partial x} = -\alpha_f \frac{\partial P}{\partial x} + \alpha_f \rho_f g_x - \alpha_f \rho_f FWF_x v_{x,f}$$

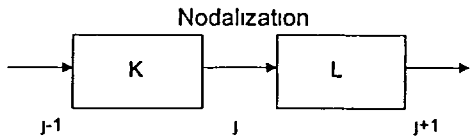
Reduced Single-Phase Field Equation

Applied to Typical Geometries

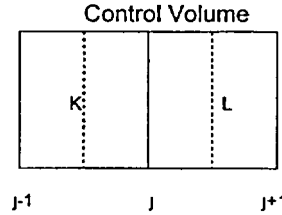


Reduced Single-Phase Field Equation (cont.)

Straight Pipe



Control Volume



= 0 if horizontal

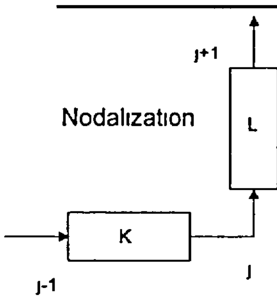
$$\alpha_f \rho_f \frac{\partial v_{x,f}}{\partial t} + \alpha_f \rho_f \frac{1}{2}\frac{\partial v_{x,f}^2}{\partial x} = -\alpha_f \frac{\partial P}{\partial x} + \alpha_f \rho_f g_x - \alpha_f \rho_f FWF_x v_{x,f}$$

≠ 0 if vertical

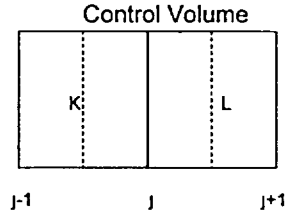
The momentum equation is integrated over the shaded area of the control volume

Reduced Single-Phase Field Equation (cont.)

90° Bend (elbow)



Control Volume



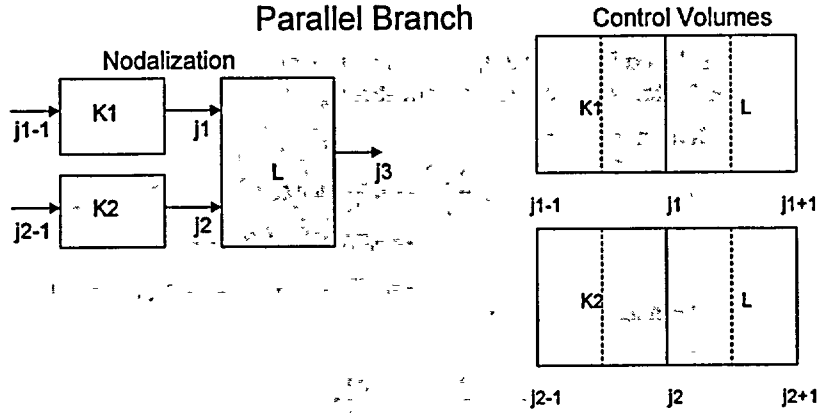
= total elevation head

$$\alpha_f \rho_f \frac{\partial v_{x,f}}{\partial t} + \alpha_f \rho_f \frac{1}{2}\frac{\partial v_{x,f}^2}{\partial x} = -\alpha_f \frac{\partial P}{\partial x} + \alpha_f \rho_f g_x - \alpha_f \rho_f FWF_x v_{x,f}$$

The momentum equation is integrated over the shaded area of the control volume

Reduced Single-Phase Field Equation (cont.)

Parallel Branch

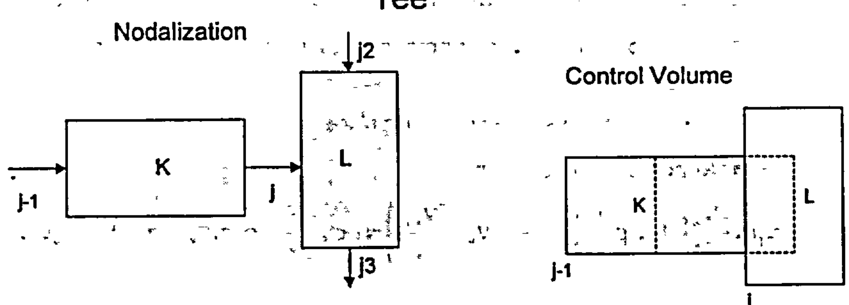


$$\alpha_f\rho_f\frac{\partial v_{x,f}}{\partial t}+\alpha_f\rho_f\frac{1}{2}\frac{\partial v_{x,f}^2}{\partial x}=-\alpha_f\frac{\partial P}{\partial x}+\alpha_f\rho_f g_x-\alpha_f\rho_f FWF_x v_{x,f}$$

The momentum equation is integrated individually over the two shaded areas of the control volumes

Reduced Single-Phase Field Equation (cont.)

Tee



$$\alpha_f\rho_f\frac{\partial v_{x,f}}{\partial t}+\alpha_f\rho_f\frac{1}{2}\frac{\partial v_{x,f}^2}{\partial x}=-\alpha_f\frac{\partial P}{\partial x}+\alpha_f\rho_f g_x-\alpha_f\rho_f FWF_x v_{x,f}$$

The momentum equation for a Tee is integrated from the center of 'K' to the center of 'L' using the cross-flow model to define the 'L' limits of integration. Control volumes centered at 'j2' and 'j3' use straight pipe formulation.

Field Equation Reduction to 2-D

> Considering Equation 2.3, rewrite in terms of the spatial 'x-y' coordinates and expand the derivatives

- X-momentum equation

$$\alpha_f\rho_f\frac{\partial v_{x,f}}{\partial t}+\alpha_f\rho_f\left(\frac{1}{2}\frac{\partial v_{x,f}^2}{\partial x}+v_{y,f}\frac{\partial v_{x,f}}{\partial y}\right)=-\alpha_f\frac{\partial P}{\partial x}+\alpha_f\rho_f g_x$$
$$-\alpha_f\rho_f FWF v_{x,f}-\Gamma_g\left(v_{x,i}-v_{x,f}\right)$$
$$-\alpha_f\rho_f FIF\left(v_{x,f}-v_{x,g}\right)-C\alpha_f\alpha_g\rho\frac{\partial}{\partial t}\left(v_{x,f}-v_{x,g}\right)$$

- Y-momentum equation

$$\alpha_f\rho_f\frac{\partial v_{y,f}}{\partial t}+\alpha_f\rho_f\left(\frac{1}{2}\frac{\partial v_{y,f}^2}{\partial y}+v_{x,f}\frac{\partial v_{y,f}}{\partial x}\right)=-\alpha_f\frac{\partial P}{\partial y}+\alpha_f\rho_f g_y$$
$$-\alpha_f\rho_f FWF v_{y,f}-\Gamma_g\left(v_{y,i}-v_{y,f}\right)$$
$$-\alpha_f\rho_f FIF\left(v_{y,f}-v_{y,g}\right)-C\alpha_f\alpha_g\rho\frac{\partial}{\partial t}\left(v_{y,f}-v_{y,g}\right)$$

Field Equation Reduction to 2-D, Single-Phase

> The field equations are rewritten in terms of the primary direction for 2-D

- Decomposing the vector notation into it's components for single-phase liquid
  - Void fractions have been left in place
- X-momentum equation

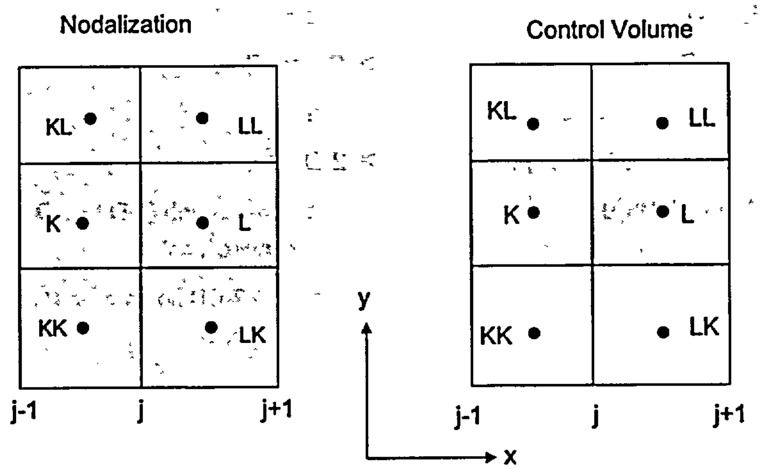
$$\alpha_f\rho_f\frac{\partial v_{x,f}}{\partial t}+\alpha_f\rho_f\left(\frac{1}{2}\frac{\partial v_{x,f}^2}{\partial x}+v_{y,f}\frac{\partial v_{x,f}}{\partial y}\right)=-\alpha_f\frac{\partial P}{\partial x}+\alpha_f\rho_f g_x-\alpha_f\rho_f FWF_x v_{x,f}$$

- Y-momentum equation

$$\alpha_f\rho_f\frac{\partial v_{y,f}}{\partial t}+\alpha_f\rho_f\left(\frac{1}{2}\frac{\partial v_{y,f}^2}{\partial y}+v_{x,f}\frac{\partial v_{y,f}}{\partial x}\right)=-\alpha_f\frac{\partial P}{\partial y}+\alpha_f\rho_f g_y-\alpha_f\rho_f FWF_y v_{y,f}$$

Reduced Single-Phase Field Equation

Applied to Typical 2-D Geometry



Momentum Field Equation Summary

- > Several control volumes representing plant component nodalizations have been shown
- > How specific terms from the momentum field equations are applied to those control volumes was shown
  - ■ Reduced to single phase 1-D and 2-D for clarity
- > Now going to apply the momentum equations to simple problems with nodalizations similar to a plant model
  - ■ Consider single phase frictional-less flow for clarity
  - ■ Will use the 1-D and 2-D spatial discretized form of the momentum equations
    - will compare with either analytic solutions or CDF code calculations

Momentum Equation Simple Problems

- > Straight Pipe
- > Elbow
- > 180° Bend
  - S-RELAP5 solution
  - STAR-CD solution
- > Area Change
  - smooth
  - abrupt
- > Multiple Connections
  - simple lower plenum
- > Cross-Flow
  - Tee
- > 2-D
  - flow-through (1-D to 2-D connections)
  - STAR-CD flow visualisation of vessel

1-D Spatial Discretization

Single-Phase Liquid

> The reduction steps from the field equations to the numerical solution formulation have been previously presented. Thus, consider the sum momentum equation (Equation 2-120) applied to single-phase liquid.

$$\overbrace{(\alpha_g\rho_g)_j^n}^{0}\left(v_g^{n+1}-v_g^n\right)_j\Delta x_j+(\alpha_f\rho_f)_j^n\left(v_f^{n+1}-v_f^n\right)_j\Delta x_j+\frac{1}{2}\overbrace{(\dot{\alpha}_g\rho_g)_j^n}^{0}\left[(\dot{v}_g)_L^n(v_g)_L^n-(v_g)_K^n(v_g)_K^n\right]\Delta t$$

$$+\tfrac{1}{2}(\alpha_f\rho_f)_j^n\left[(v_f)_L^n(v_f)_L^n-(v_f)_K^n(v_f)_K^n\right]\Delta t$$

$$=-(P_L-P_K)^{n+1}\Delta t+\Big[\rho_j^n B_x-\overbrace{(\alpha_g\rho_g)_j^n}^{0}v_{g,j}^{n+1}\,FWG_j^n$$

$$-(\alpha_f\rho_f)_j^n v_{f,j}^{n+1}\,FWF_j^n+\overbrace{(\Gamma_g)_j^n}^{0}(v_f-v_g)_j^{n+1}\Big]\Delta x_j\Delta t$$

1-D Spatial Discretization (cont.)

> Add form loss term and assume single-phase steady flow without wall friction, the momentum equation:

$$(\alpha_f\rho_f)_j^n\overbrace{\left(v_f^{n+1}-v_f^n\right)_j}^{0}\Delta x_j+\frac{1}{2}(\dot{\alpha}_f\dot{\rho}_f)_j^n\left[(\dot{v}_f)_L^n(v_f)_L^n-(\dot{v}_f)_K^n(v_f)_K^n\right]\Delta t+\frac{K_{loss}}{2}(\dot{\alpha}_f\dot{\rho}_f)_j^n\left(v_f^{n+1}\left|v_f^n\right|\right)_j$$

$$=-(P_L-P_K)^{n+1}\Delta t+\left[\rho_j^n B_x-\underbrace{(\alpha_f\rho_f)_j^n v_{f,j}^{n+1}\,FWF_j^n}_{0}\right]\Delta x_j\Delta t$$

can be simplified to

$$\frac{1}{2}(\rho_f)_j^n\left[(\dot{v}_f)_L^n(v_f)_L^n-(\dot{v}_f)_K^n(v_f)_K^n\right]+\frac{K_{loss}}{2}(\rho_f)_j^n\left(v_f^{n+1}\left|v_f^n\right|\right)_j$$

$$=-(P_L-P_K)^{n+1}+g\left(\rho_K^n\frac{h_K}{2}+\rho_L^n\frac{h_L}{2}\right)$$

1-D Spatial Discretization (cont.)

> Volume Average Velocity in the i[th] direction:

x-direction ⇒ i = 1, y-direction ⇒ i = 2, cross-flow ⇒ i = 3

$$(v_f)_{L,I}=\frac{(v_f)_{L,I,in}\sum_{jin}(\dot{\alpha}_f\dot{\rho}_f A)_{i,jin}+(v_f)_{L,I,out}\sum_{jout}(\dot{\alpha}_f\dot{\rho}_f A)_{i,jout}}{\sum_{jin}(\dot{\alpha}_f\dot{\rho}_f A)_{i,jin}+\sum_{jout}(\dot{\alpha}_f\dot{\rho}_f A)_{i,jout}}$$

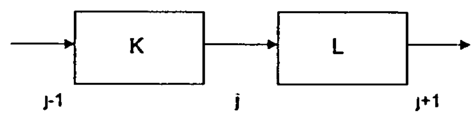
gives

$$(v_f)_{L,I,in}=\frac{\sum_{jin}(\dot{\alpha}_f\dot{\rho}_f v_f)_{i,jin}A_{i,jin}}{\sum_{jin}(\dot{\alpha}_f\dot{\rho}_f)_{i,jin}A_{i,jin}}\,\frac{\sum_{jin}A_{i,jin}}{A_L}\qquad (v_f)_{L,I,out}=\frac{\sum_{jout}(\dot{\alpha}_f\dot{\rho}_f v_f)_{i,jout}A_{i,jout}}{\sum_{jout}(\dot{\alpha}_f\dot{\rho}_f)_{i,jout}A_{i,jout}}\,\frac{\sum_{jout}A_{i,jout}}{A_L}$$

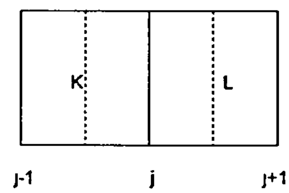
Straight Pipe Problem

> Straight pipe with uniform single-phase liquid and steady flow

- Nodalization



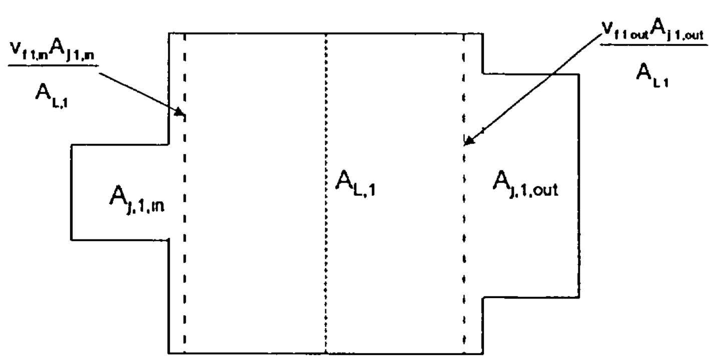
- Control Volume



Straight Pipe Problem (cont.)

> Nodalization of hydrodynamic volume ' L '

x-direction ⇒ i = 1, y-direction ⇒ i = 2, cross-flow ⇒ i = 3



Straight Pipe Problem (cont.)

> From the assumption of uniform single-phase liquid with steady flow and with single inlet and outlet, the volume average velocity is

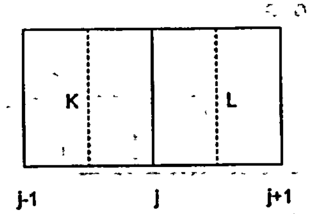
$$(v_f)_{L,1,in}=\frac{(v_f)_{1,in}A_{j,1,in}}{A_{L,1}} \qquad (v_f)_{L,1,out}=\frac{(v_f)_{1,out}A_{j,1,out}}{A_{L,1}}$$

and

$$(v_f)_{L,1}=\frac{(v_f)_{L,1,in}+(v_f)_{L,1,out}}{2}$$

Straight Pipe Problem (cont.)

> Straight pipe control volume

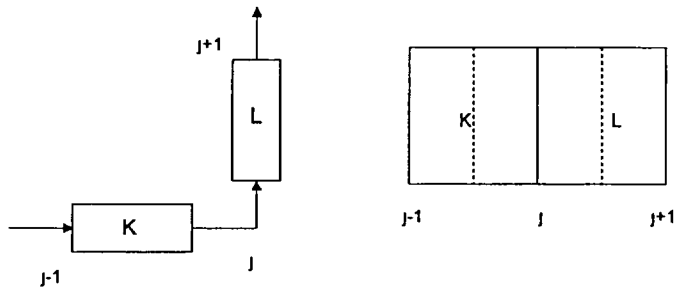


yields no change in momentum

$$\frac{1}{2}(\dot\alpha_f\dot\rho_f)_j^n\left[\cancelto{0}{(\dot v_f)_L^n(v_f)_L^n-(\dot v_f)_K^n(v_f)_K^n}\right]+\cancelto{0}{\frac{K_{loss}}{2}}(\dot\alpha_f\dot\rho_f)_j^n\left(v_f^{n+1}|v_f^n|\right)_j$$
$$=-\cancelto{0}{(P_L-P_K)^{n+1}}+g\left(\dot\rho_K^n\frac{h_K}{2}+\cancelto{0}{\rho_L^n\frac{h_L}{2}}\right)$$

Simple Elbow Problem

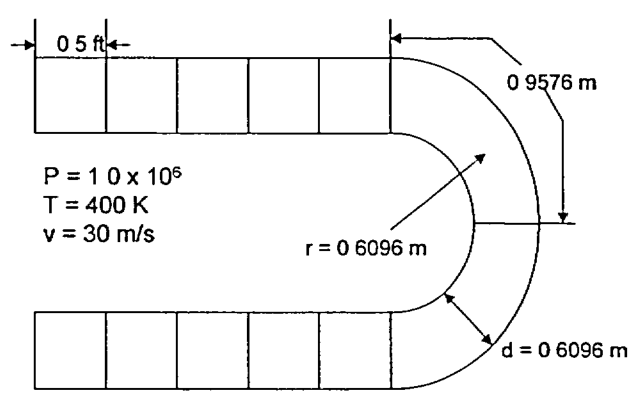
> Horizontal to vertical nodalization and control volume



$$\frac{1}{2}(\alpha_f\rho_f)_j^n\left[\cancelto{0}{(\dot{v}_f)_L^n(v_f)_L^n - (\dot{v}_f)_K^n(v_f)_K^n}\right] + \frac{K_{loss}}{2}(\alpha_f\rho_f)_j^n\left(v_f^{n+1}\left|v_f^n\right|\right)_j$$
$$= -(P_L - P_K)^{n+1} + g\left(\cancelto{0}{\rho_K^n\frac{h_K}{2}} + \rho_L^n\frac{h_L}{2}\right)$$

180° Bend Problem

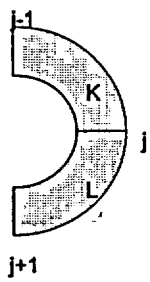
> Horizontal 180° bend nodalization with dimensions and boundary conditions



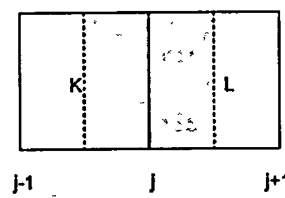
180° Bend Problem (cont.)

>Nodalization is 1-D

- Control volume shown with junction ' j ' at midpoint of bend



- Use form loss from Crane
  - -Kloss = 0 354



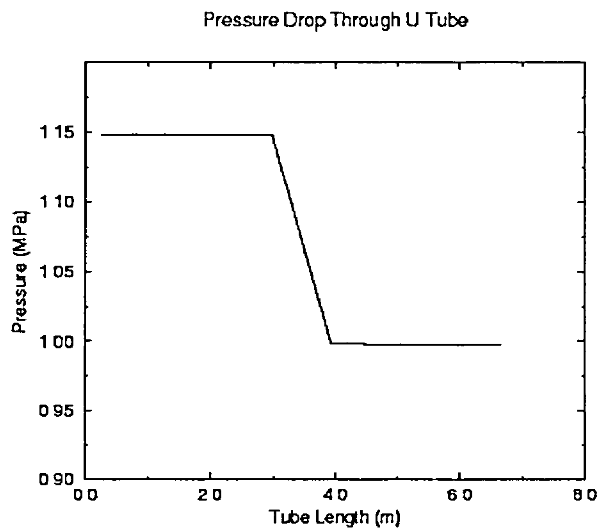
180° Bend Problem (cont.)

> Momentum equation

$$\frac{1}{2}(\dot{\rho}_f)_j^n\left[\cancelto{0}{(\dot{v}_f)_L^n(v_f)_L^n-(\dot{v}_f)_K^n(v_f)_K^n}\right]+\frac{K_{loss}}{2}(\dot{\rho}_f)_j^n\left(v_f^{n+1}\left|v_f^n\right|\right)_j$$
$$=-(P_L-P_K)^{n+1}+g\,\cancelto{0}{\left(\rho_K^n\frac{h_K}{2}+\rho_L^n\frac{h_L}{2}\right)}$$

> S-RELAP pressure change is 0.1502 MPa

180° Bend Problem (cont.)



CFD Application to 180° Bend

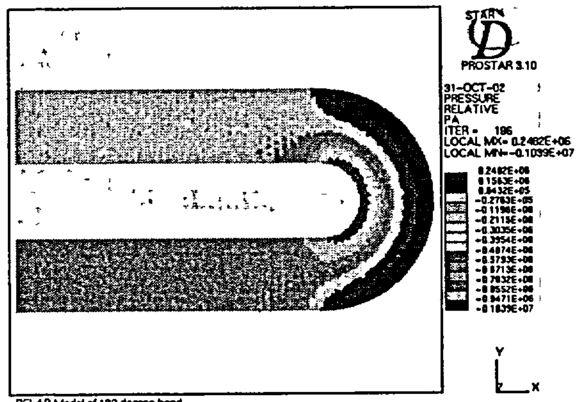
> STAR-CD was used to model the same U bend as previously discussed

> Model was built using hexahedral cells with smaller cells next to walls

> The assumptions for the problem were
- High Re k-ε turbulence model
- No wall friction nor buoyancy forces
- Inlet velocity of 30 meters/sec

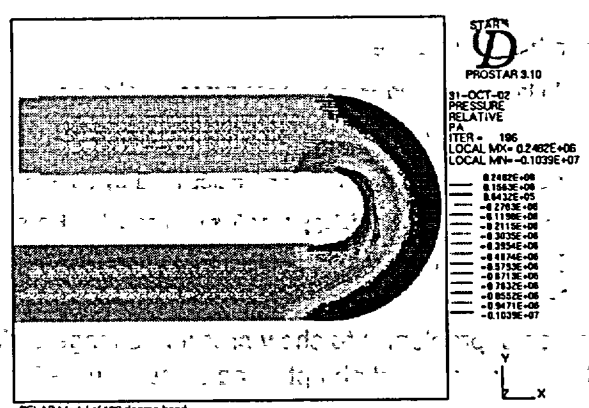
> Resultant pressure drop is 0.1505 Mpa
- Resultant pressure distribution and velocity vectors are shown
- Cross-section view of velocity vectors at bend midpoint

Pressure Distribution



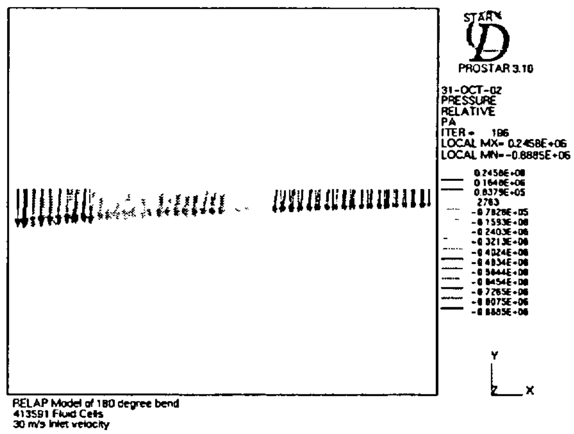
RELAP Model of 180 degree bend
413591 Fluid Cells
30 m/s inlet velocity

Velocity Vectors Overlaid on Pressure Distribution



RELAP Model of 180 degree bend
413591 Fluid Cells
30 m/s inlet velocity

Velocity Vectors in Center of U Bend



Area Change Problem

> Smooth area change

- No loss assumed ⇒ reversible pressure change

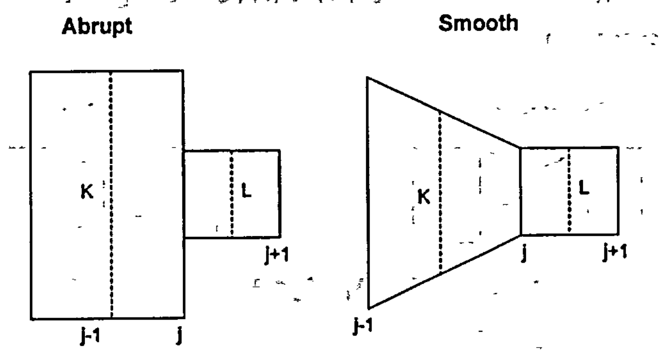
> Abrupt area change

- Irreversible loss assumed and calculated by code or user
  - RLBLOCA methodology specifies user calculated loss
- Orifice area (if modeled) applies to junction area in the volume average velocity calculation

> Purpose of problem is to show pressure change variation between smooth and abrupt using same volume flow areas

Area Change Problem (cont.)

> Nodalization examples with control volumes overlaid



Area Change Problem (cont.)

> The volume average velocity for the ' K ' volume (both cases) is

$$(v_f)_{K,1,in} = \frac{(v_f)_{j-1} A_{j-1}}{A_K} \qquad (v_f)_{K,1,out} = \frac{(v_f)_j A_j}{A_K}$$

and

$$(v_f)_{K,1} = \frac{(v_f)_{K,1,in} + (v_f)_{K,1,out}}{2}$$

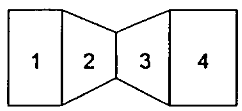
Area Change Problem (cont.)

> The differences are from the form loss used in the abrupt case

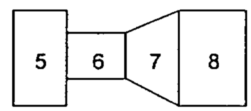
- Area change is 2:1 ⇒ form loss from Crane $K_{loss} = 0\ 25$

> Nodalization

Smooth-Smooth

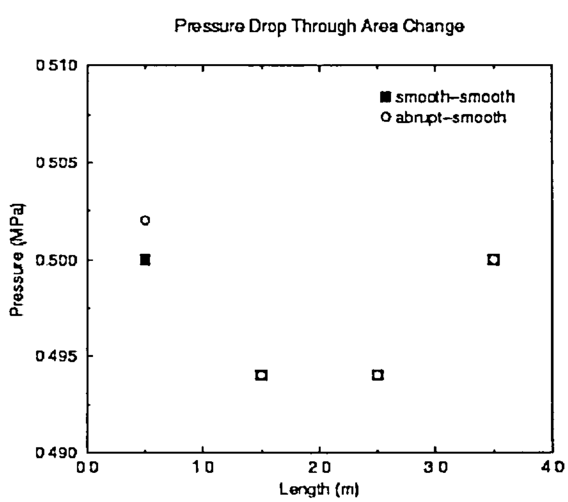


Abrupt-Smooth



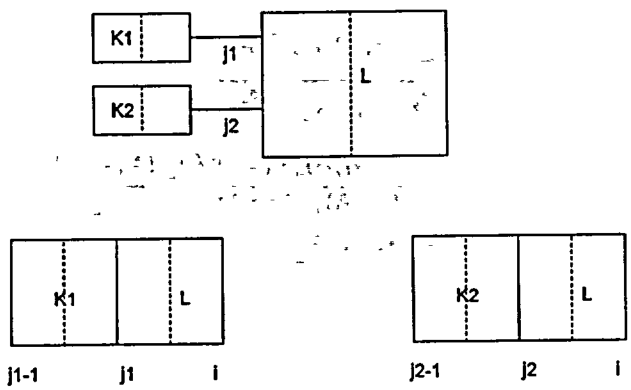
- nodalizations have $A_1 = A_4 = A_5 = A_8$ and $A_2 = A_3 = A_6 = A_7$

Area Change Problem (cont.)



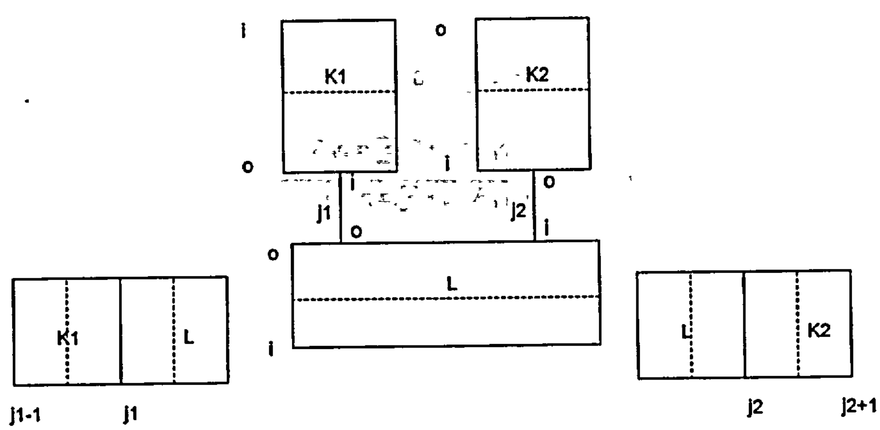
Multiple Junctions

> Nodalization and control volumes



Multiple Junctions (cont.)

> Simple lower plenum model nodalization and control volumes



Multiple Junctions (cont.)

> Simple lower plenum model, volume velocity - inlet side

$$
\begin{aligned}
(v_f)_{L,jn} &= \frac{\sum_{jin}(\alpha_f \rho_f v_f)_{jin} A_{jin}}{\sum_{jin}(\dot{\alpha}_f \rho_f)_{jin} A_{jin}} \frac{\sum_{jin} A_{jin}}{A_L} \\
&= \frac{\left(\alpha_f \rho_f (-v_f) A\right)_{j1} + \left(\alpha_f \dot{\rho}_f v_f A\right)_{j2}}{\left(\alpha_f \rho_f A\right)_{j1} + \left(\alpha_f \rho_f A\right)_{j2}} \frac{\left(A_{j1} + A_{j2}\right)}{A_L} \\
&= \frac{-v_{j1} A_{j1} + v_{j2} A_{j2}}{A_L} \\
&= 0
\end{aligned}
$$

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Multiple Junctions (cont.)

> Simple lower plenum model, volume average velocity

$$
(v_f)_{L,in} = 0, \text{ and } (v_f)_{L,out} = 0
$$

$$
\begin{aligned}
(v_f)_L &= \frac{0 \ \sum_{jin}(\alpha_f \rho_f A)_{i,jin} + 0 \cdot \sum_{jout}(\dot{\alpha}_f \rho_f A)_{i,jout}}{\sum_{jin}(\alpha_f \rho_f A)_{i,jin} + \sum_{jout}(\dot{\alpha}_f \rho_f A)_{i,jout}} \\
&= 0
\end{aligned}
$$

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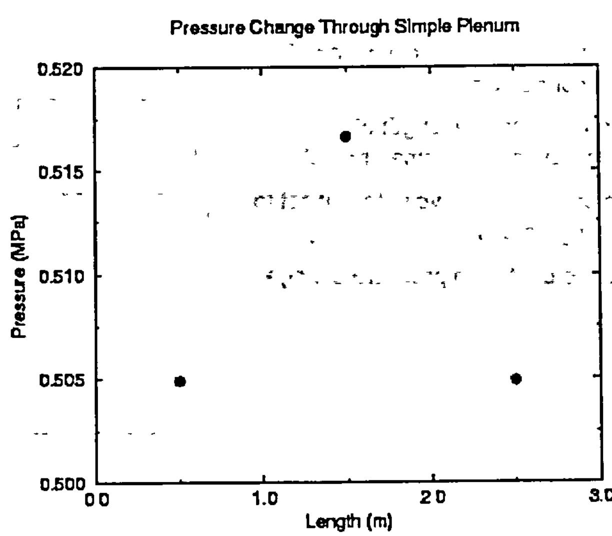
Multiple Junctions (cont.)

$$\frac{1}{2}(\dot{\alpha}_f\dot{\rho}_f)_j^n\left[(\dot{v}_f)_L^n(v_f)_L^n-(\dot{v}_f)_K^n(v_f)_K^n\right]+\cancelto{0}{\frac{K_{loss}}{2}(\dot{\alpha}_f\dot{\rho}_f)_j^n\left(v_f^{n+1}\left|v_f^n\right|\right)_j}$$
$$=-(P_L-P_K)^{n+1}+g\left(\rho_K^n\frac{h_K}{2}+\rho_L^n\frac{h_L}{2}\right)$$

> Since the ' L ' velocity is zero, a pressure rise is expected
- Reversible pressure rise since dissapation terms are neglected

Simple Lower Plenum



Cross-Flow

> Cross-flow junctions are used to model pressurizer and ECC surge line connection to the primary loops and used for the hot/cold leg connections to the vessel

> Flow directions of connecting hydrodynamic volumes are orthogonal (transverse momentum not modeled)

> Cross flow junction connects at mid-length or inlet/outlet ends of hydrodynamic volume

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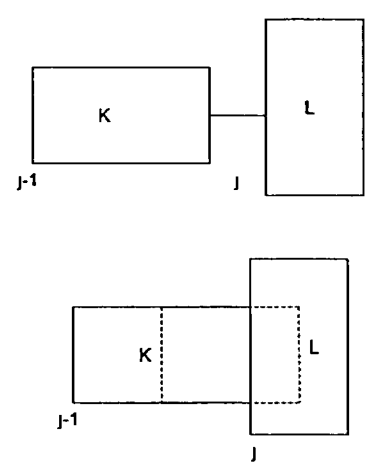
Cross-Flow (cont.)

> Nodalization and control volume of typical connection

> Control volume cell length of downstream set to diameter of 'L'

> Geometry at control volume exit set to junction 'j' values

> Yields no upstream pressure change



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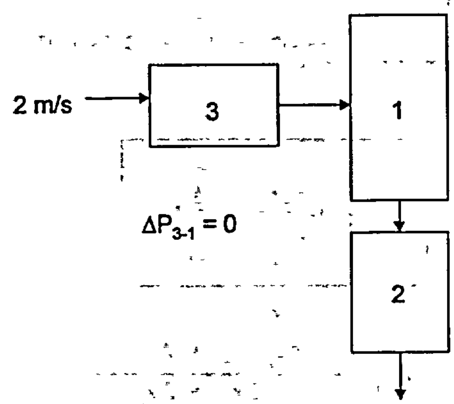
Cross-Flow (cont.)

> Demonstration calculation nodalization



2-D Momentum Equations

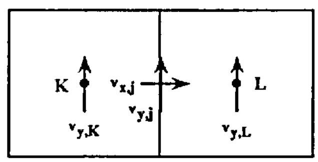
> Spatial Discretization

- 2-D Noding
  - Orthogonal coordinate systems used
  - One coordinate is always vertically aligned
- 2-D Momentum Equations
  - Equations are identical to 1-D formulation except for the introduction of the cross-product momentum flux terms
  - The normal momentum flux terms (e.g., axial convection of axial momentum) are differenced as for the 1-D component
  - Interfacial friction and wall drag are considered separable
    - i e , they are computed for each flow direction independently

2-D Momentum Equations (cont.)

> Spatial Discretization

- Cross-Product Momentum Flux Terms
  - Step 1
    - For junction j, calculate a volume averaged axial (z-direction) velocity for the momentum control volume



(j)

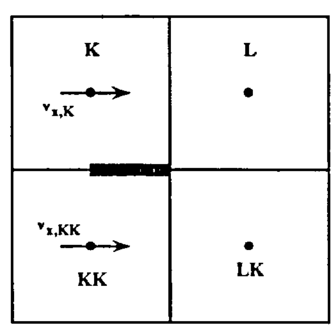
$$(\bar{v}_y)_j = \frac{\Delta x_K v_{yK} + \Delta x_L v_{yL}}{\Delta x_K + \Delta x_L}$$

2-D Momentum Equations (cont.)

Cross-Product Momentum Flux Terms

> Step 2: Decide on the donoring for the axial velocity gradient

- If the junction axial velocity is positive, the velocity gradient will be computed across the bottom face of the momentum control volume
- Conversely, if the junction axial velocity is negative, the velocity gradient will be computed across the top face of the momentum control volume



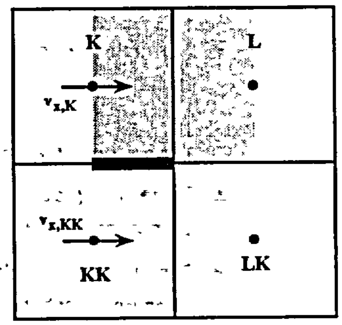
$(\bar{v}_y)_j \geq 0$

2-D Momentum Equations (cont.)

Cross-Product Momentum Flux Terms

> Step 3: Evaluate the axial velocity gradient for the *K* half-volume:

$$\rightarrow \frac{(v_{x,K})_{out} - (v_{x,KK})_{out}}{\frac{1}{2}(\Delta z_K + \Delta z_{KK})}$$



> Step 4: Repeat Step 3 for *L* half volume

> Step 5: Add the contributions from the two half volumes:

$$\left(\frac{\Delta \dot{v}_x}{\Delta y}\right)_j = \frac{1}{2}\left[\frac{(v_{x,K})_{out} - (v_{x,KK})_{out}}{\frac{1}{2}(\Delta y_K + \Delta y_{KK})} + \frac{(v_{x,L})_{in} - (v_{x,LK})_{in}}{\frac{1}{2}(\Delta y_L + \Delta y_{LK})}\right]$$

2-D Momentum Equations (cont.)

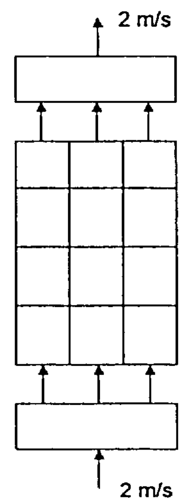
> Two Model Options

- Downcomer defaults to z-θ coordinates and internally connects first and last theta nodes
  - x-direction maps to the vertical coordinate (z)
  - y-direction maps to the azimuthal coordinate (θ)
- Core defaults to z-r coordinates
  - x-direction maps to the vertical coordinate (z)
  - y-direction maps to the radial coordinate (r)

1-D to 2-D Connections

> Momentum treatment for 1-D to 2-D end connections

- 2-D nodes connected via external junctions to 1-D nodes are treated as a 1-D to 1-D connection
  - e g. straight pipe control previously shown
- Same 1-D process applied for 2-D to 2-D connections using external junctions
- Demonstration calculation shows same pressure distribution between TWODEE-A (downcomer), TWODEE (core), and three parallel pipes
  - P = 55862 Pa for each case



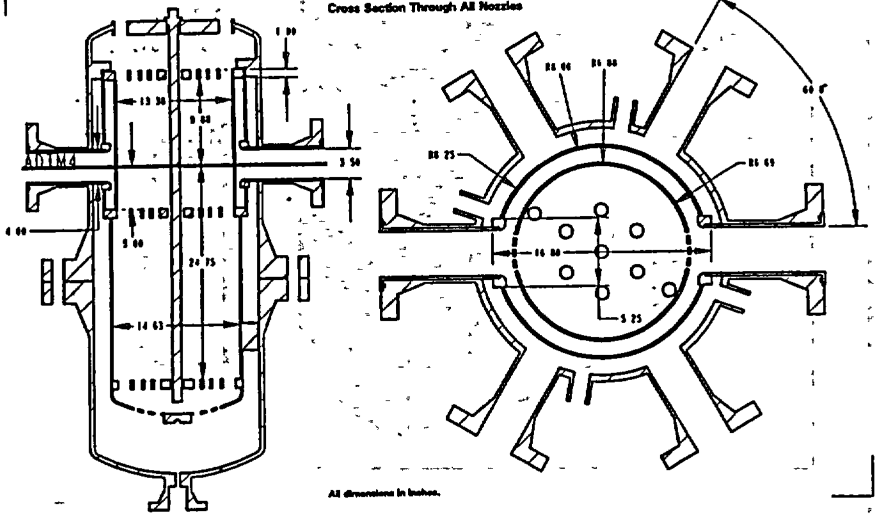
2-D Momentum Equation

> Flow Visualization study using STAR-CD CFD code

- Flow path simulated for study consists of cold leg, downcomer, lower plenum, and core entrance (lower core support plate)
- Vessel model was developed for ISP-43 simulation
  - Rapid Boron-Dilution Transient Tests using 1/5 scale B&W 2x4 vessel
  - Boundary conditions modified for flow visualization study
    - 9 m/s inflow
    - 1 MPa
    - 400 K
- Test facility schematic
- Flow patterns in downcomer and lower plenum

2-D Momentum Equation (cont.)

FIGURE 2
Longitudinal Cross Section Through Hot Leg Nozzles and Horizontal Cross Section Through All Nozzles



All dimensions in inches.

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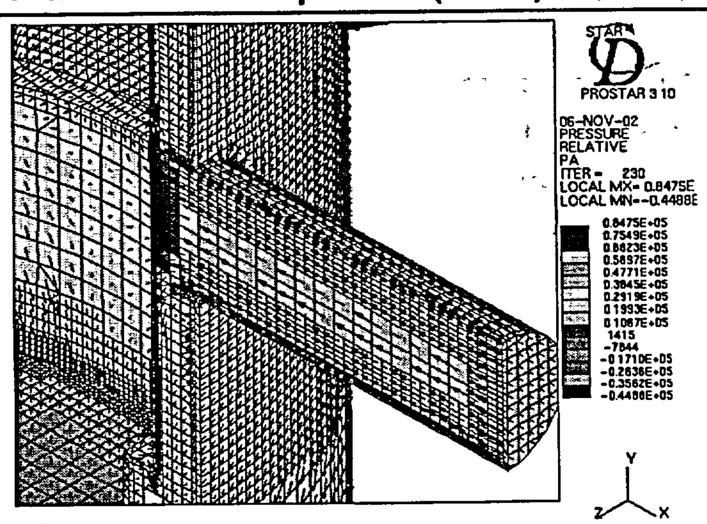
2-D Momentum Equation (cont.)



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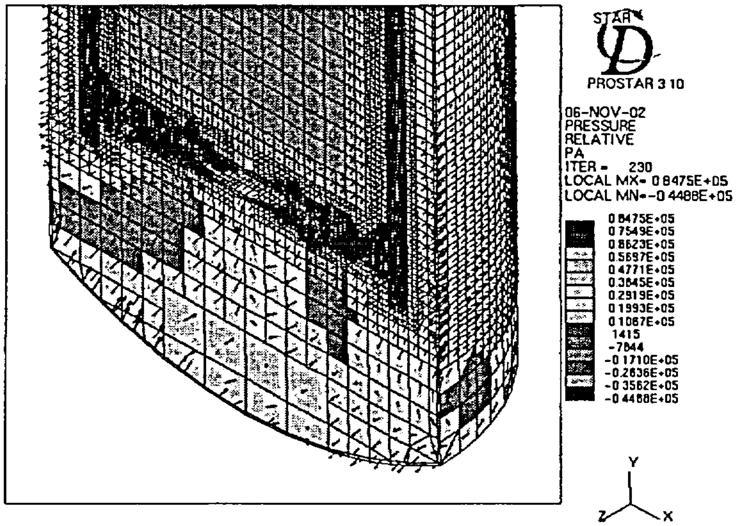
2-D Momentum Equation (cont.)



Question Resolution

> Remaining questions:

- Pump head
- Added mass

Pump Head

> Pump head is added explicitly to momentum equation

> Requires two control volumes (e.g. two junctions)

- inlet side has half of the pump head added
- outlet side has remaining half of the pump head added

Virtual Mass

> Interphase drag consists of steady (FI) and dynamic (FA) drag

- FA is the added mass or virtual mass force

$$FA = -C\alpha_f\alpha_g\rho\left[\frac{\partial}{\partial t}(v_g - v_f) + v_f\frac{\partial v_g}{\partial x} - v_g\frac{\partial v_f}{\partial x}\right]$$

- Spatial terms neglected in field equations
- Temporal terms have the effect of slowing down the rate of change of the relative velocity

$$C = \frac{1.5}{\max(\alpha_f, \alpha_g)} - 1 \quad (C = 0 \text{ for horizontal stratified flow})$$

  - ρ is the mixture density
    - ρ should be the density of the continuous phase
  - $C\alpha_f\alpha_g\rho$ is not flow regime dependent
    - $C\alpha_f\alpha_g\rho$ should be flow regime dependent

Momentum Exchange from Mass Transfer

> Mass times velocity at interface

$$v_{fi} = v_{gi} = v_i$$

$$v_i = \lambda v_g + (1 - \lambda v_f)$$

- setting $\lambda = \frac{1}{2}$ implies the process is reversible
- use a donor formulation

$$\lambda = 0 \quad \Gamma_g \geq 0$$

$$\lambda = 1 \quad \Gamma_g < 0$$

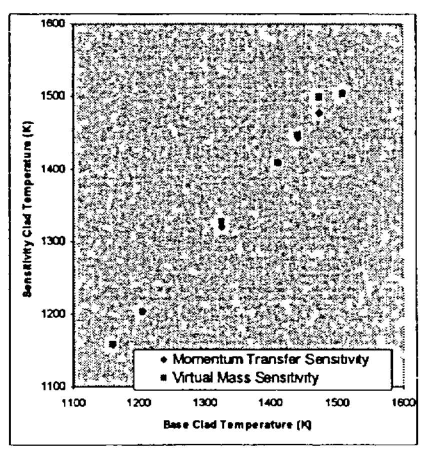
  - dissipative

> Sensitivities were made to show effects under important two phase conditions

- used FLECHT-SEASET assessment cases

Added Mass Sensitivity

> Sensitivity calculations show the effects of virtual mass and momentum transfer due to mass transfer are quite small



Conclusions

> Discussed momentum equation terms
> Shown how momentum control volumes are mapped to nodalization used for plant analysis
> Shown how various terms in momentum equation are applied to plant specific components
> Shown flow visualizations of important geometries with the CFD code STAR-CD
> Addressed momentum equation questions, either directly or indirectly

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Framatome ANP RLBLOCA Methodology

ACRS Thermal-Hydraulic Subcommittee Meeting
November 13 and 14, 2002
Washington, DC

FRAMATOME ANP

Agenda - November 13

> Introduction (Holm)

> Momentum Equation (Carlson)

- Straight pipe
- Bends/elbows
- Area change
- Multi-junctions
- Cross-flow
- 2-D model
- Cold leg/downcomer connection
- Downcomer/lower plenum connection
- Pump
- Added mass

> General RELAP5 Questions (Martin)

> Selection of Node Size (Martin)

> Critical Flow (Carlson)

> Statistical Analyses (O'Dell)

Agenda - November 14

Morning

> Summary of RLBLOCA Methodology (O'Dell)

- Requirements and capabilities
  - Changes to RELAP5 to create S-RELAP5
- Assessment and ranging of parameters
- Sensitivity and uncertainty analyses