Implementation of Viscous Effects in RELAP5 – 3D

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Contents

- Background and Motivations
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Background

- *Comparison: RELAP5-3D Systems Analysis Code & Fluent CFD Code Momentum Eq. Formulations,* R5 User’s Group Presentation August 27, 2003
- Laminar velocity profile is the same as turbulent
- Free-Slip wall boundary condition

The Motivations

- More accurate model of laminar flow and wall affects
  - Better agreement with data and analytical calculations
- Better coupling of CFD and RELAP5-3D
- Add options and capabilities to RELAP5-3D
- Add effects without perturbing existing code

Modifying the Liquid Momentum Equation

1)
$$\rho\left(\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_z}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta} + v_z\frac{\partial v_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \rho g_z +$$
$$\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2}\right]$$

1-phase z-dir

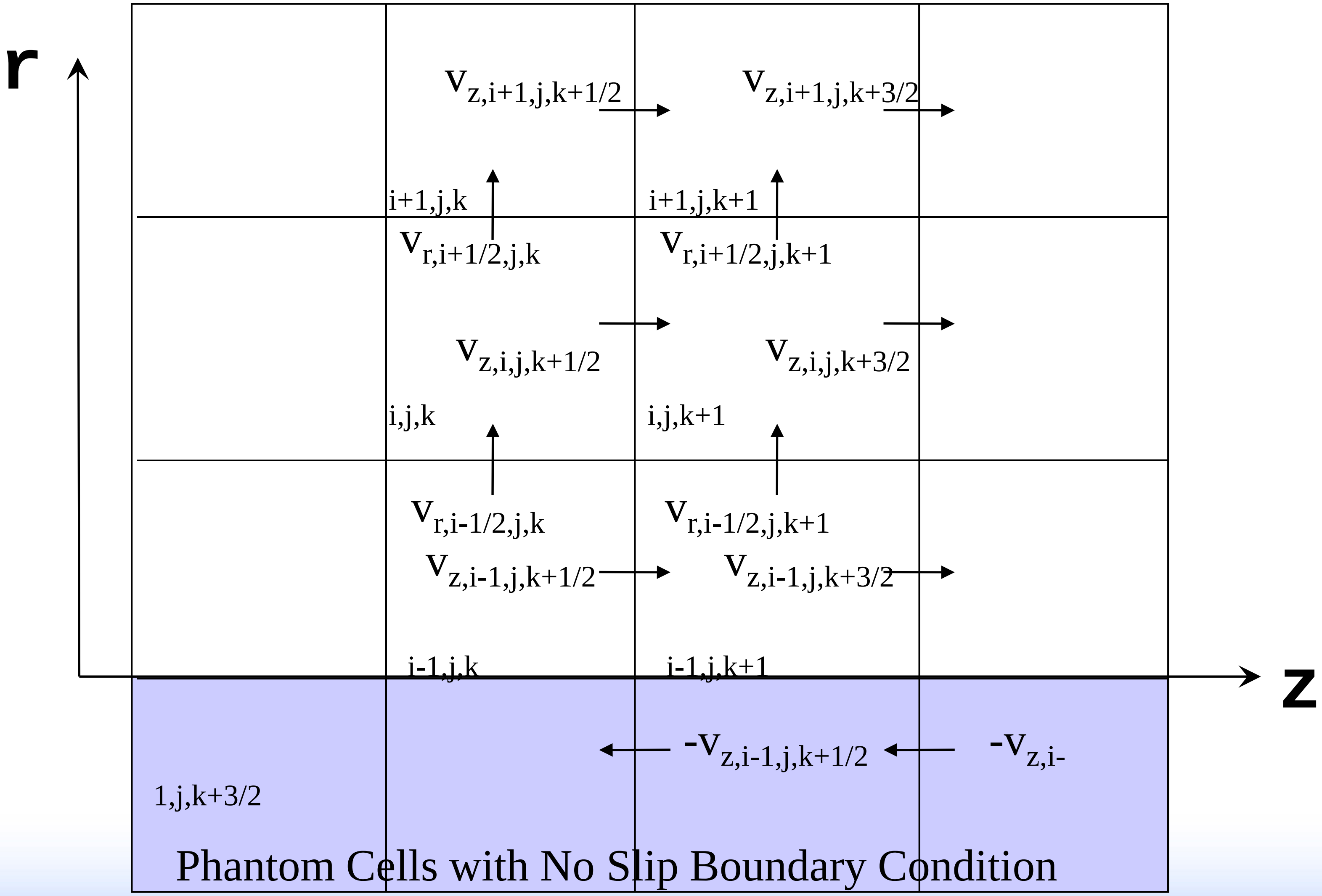
2)
$$\alpha_f \varrho_f A\frac{\partial v_f}{\partial t} + \frac{1}{2}\alpha_f \varrho_f A\frac{\partial v_f^2}{\partial z} =$$
$$-\alpha_f A\frac{\partial P}{\partial z} + \alpha_f \varrho_f B_x A - (\alpha_f \varrho_f A)FWF(v_f) - \Gamma_g A(v_f I - v_f)$$
$$-(\alpha_f \varrho_f A)FIF(v_f - v_g) - C\alpha_f \alpha_g \varrho_m A\left[\frac{\partial(v_f - v_g)}{\partial t} + v_g\frac{\partial v_f}{\partial z} - v_f\frac{v_g}{\partial z}\right]$$

2-phase no viscous term

3)
$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) = \frac{1}{r_i}\left[\frac{r\frac{\partial v_z}{\partial r}\Big|_{i+\frac{1}{2}} - r\frac{\partial v_z}{\partial r}\Big|_{i-\frac{1}{2}}}{\Delta r_i}\right]$$
$$= \frac{1}{r_i}\left(\frac{r_{i+\frac{1}{2}}\left[\frac{v_{z,j+1} - v_{z,j}}{\frac{1}{2}(\Delta r_{j+1} + \Delta r_j)}\right] - r_{i-\frac{1}{2}}\left[\frac{v_{z,j} - v_{z,j-1}}{\frac{1}{2}(\Delta r_j + \Delta r_{j-1})}\right]}{\Delta r_i}\right)$$

Finite difference discretization of one viscous term

R-Z Grid & BC Treatment



r

$V_{z,i+1,j,k+1/2}$ $V_{z,i+1,j,k+3/2}$

i+1,j,k i+1,j,k+1

$V_{r,i+1/2,j,k}$ $V_{r,i+1/2,j,k+1}$

$V_{z,i,j,k+1/2}$ $V_{z,i,j,k+3/2}$

i,j,k i,j,k+1

$V_{r,i-1/2,j,k}$ $V_{r,i-1/2,j,k+1}$

$V_{z,i-1,j,k+1/2}$ $V_{z,i-1,j,k+3/2}$

i-1,j,k i-1,j,k+1

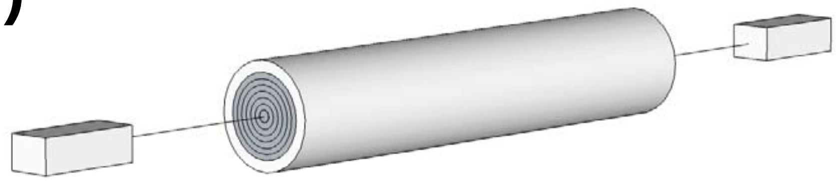
z

$-V_{z,i-1,j,k+1/2}$ $-V_{z,i-1,j,k+3/2}$

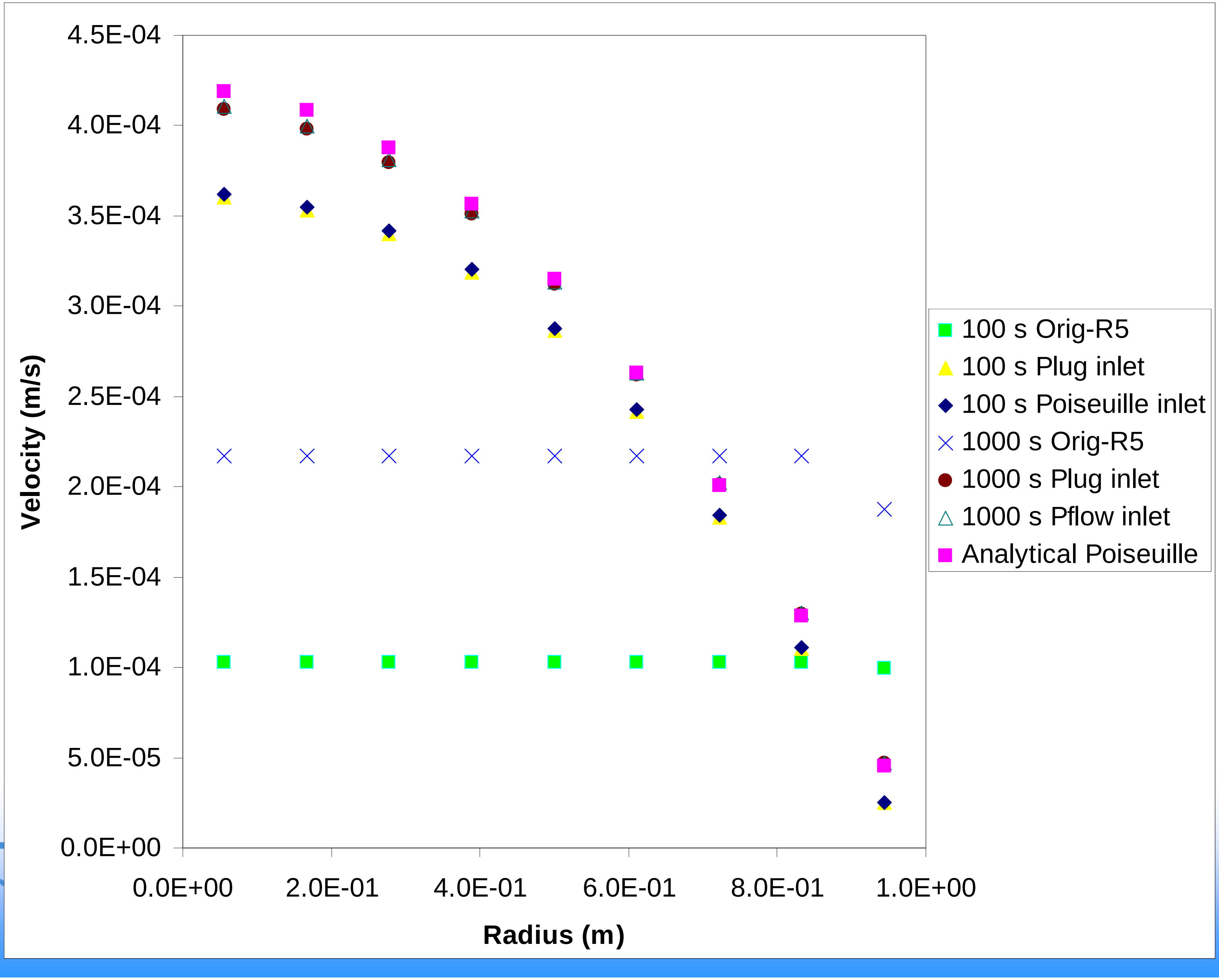
Phantom Cells with No Slip Boundary Condition

Model 1 – Classic Poiseuille Flow

- **Inlet velocity profile: Poiseuille or plug-flow**
- **Friction only in wall radial zone.**
- **25 axial zones (L = 2500 m)**
- **9 radial zones (D = 2 m)**
- **1 azimuthal zone**
- **Laminar flow**

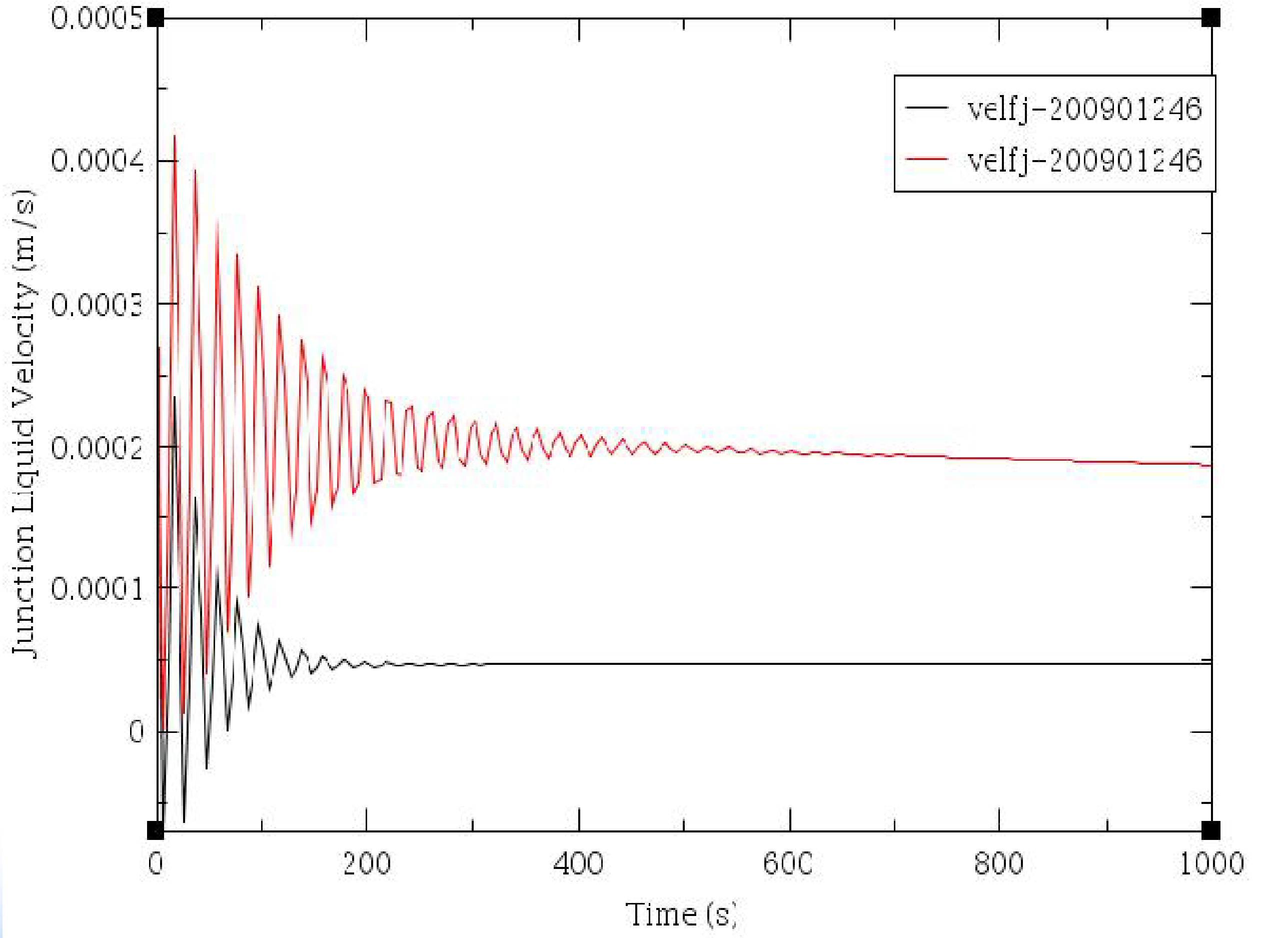


Cylindrical Geometry Axial Flow Velocity



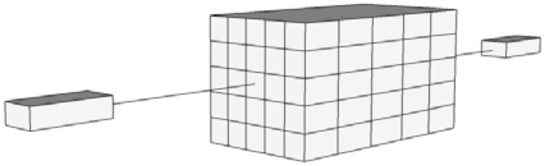
Viscous Effect on Convergence

Poiseuille Flow

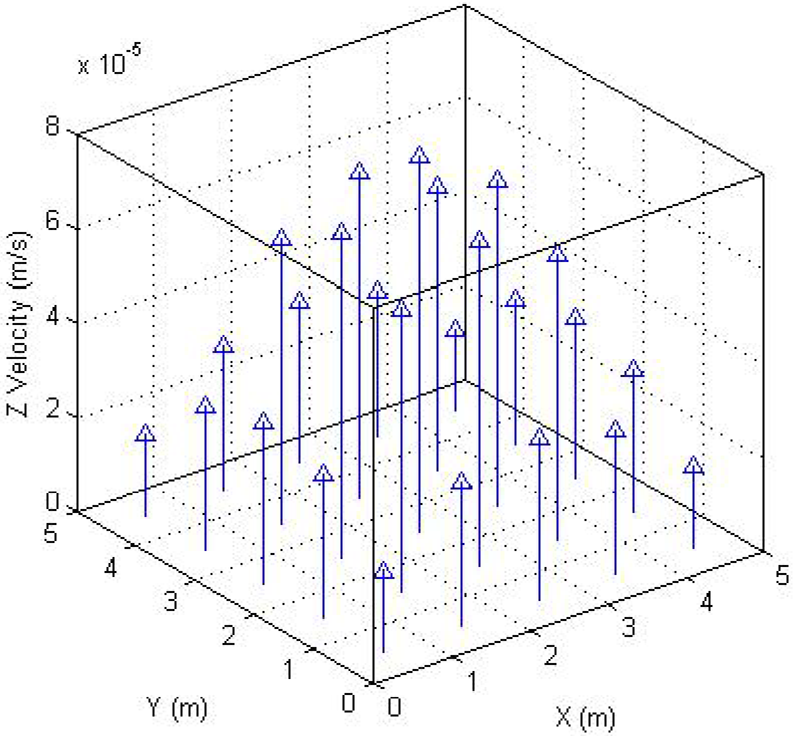


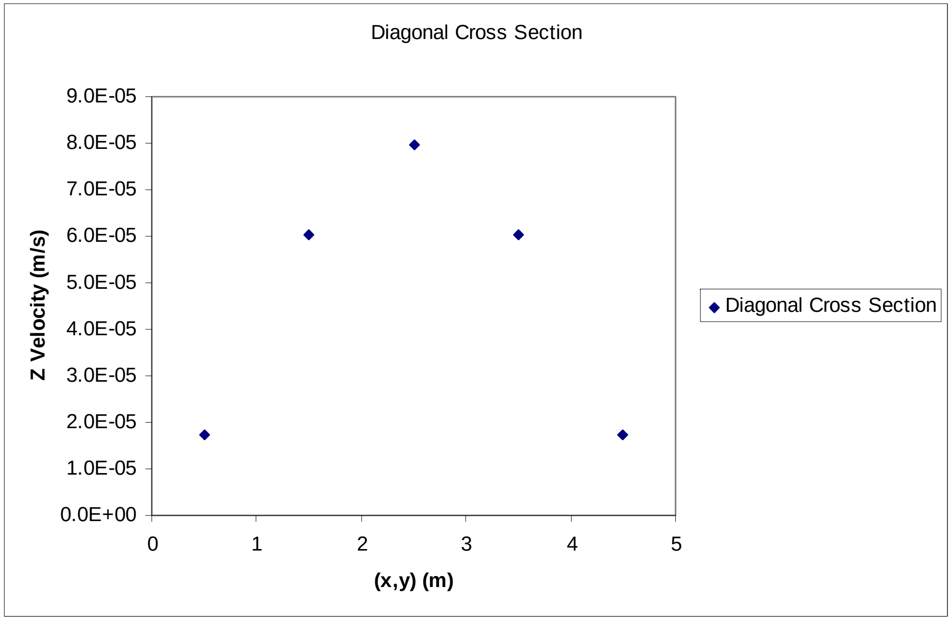
Model 2: Rectangular Duct

- Laminar plug-flow velocity profile inlet
- 5x5 x-y zones (Area = 25 m^2)
- 5 axial zones (L = 500 m)



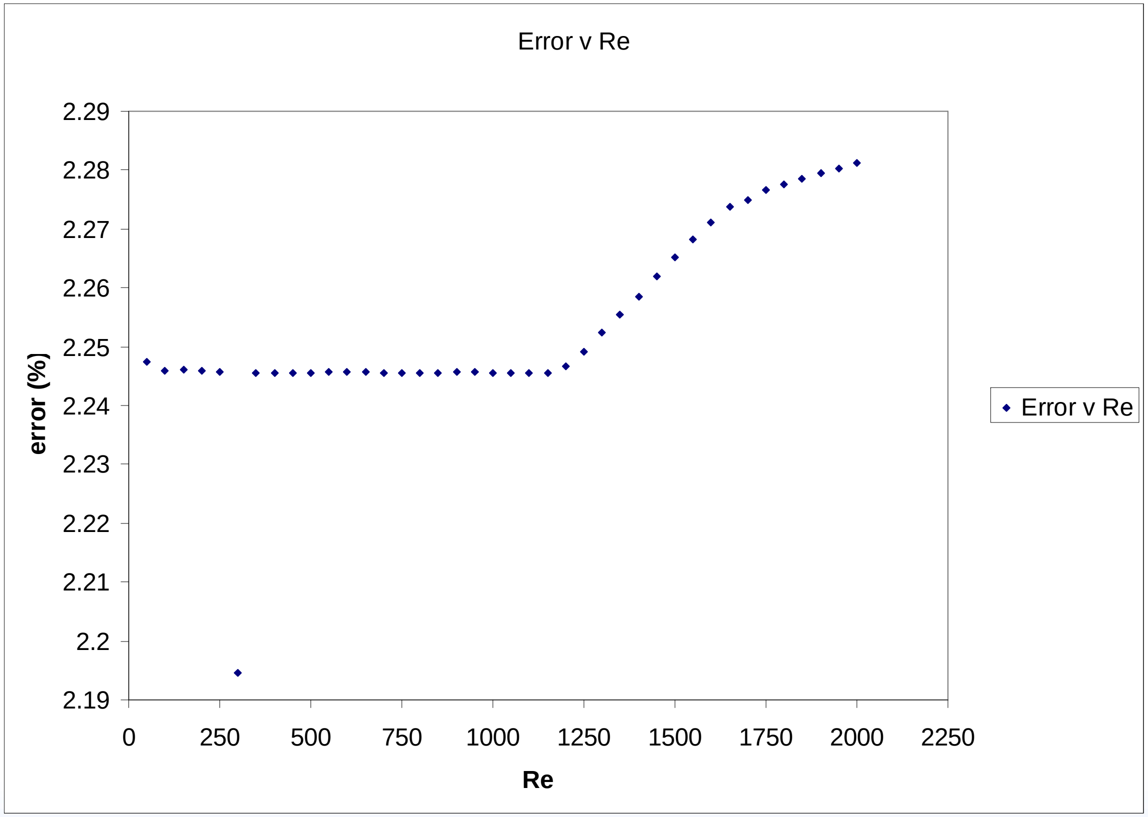
Cartesian 3-D Velocity Profile





Error vs Reynolds Number

- **Error @ 1000 sec @ centermost control volume.**



Coding Update to Version 2.9.3

- Coding changes to subroutines FLUX3D, RCHNG
  - As internal subroutine VISCOUS
  - Unconditionally called from 3 places within FLUX3D
  - Protected by pre-compiler directive, VISCOUST
  - Controlled by user option 31 (card 1 option)
- Two test cases added to run/ directory
  - Pois_xyz.i and pois_cyl.i
  - Script runn augmented to run these two models

Future Work

- Implement viscous effects in Turbulent Regime
  - Several different models
- Implement in Two-Phase
  - Currently only for liquid
- Extend to nearly-implicit advancement

Conclusions

- Viscous Terms added to RELAP5-3D momentum equations
  - Semi-implicit only
  - 3D regions only
  - Liquid phase only
  - Laminar only
  - Cartesian and cylindrical geometries
- Transient approaches steady-state more quickly with viscous terms than without for Poiseuille flow

Conclusions

- Code approaches theoretical Poiseuille flow as transient approaches steady-state in
  - a cylindrical pipe
  - a rectangular duct
- Code error from theoretical @ 1000 sec is under 2.28%
  - It increases with Reynolds number past Re=1250
- Overall improvement in code stability and accuracy for some laminar flow conditions demonstrated.