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Contaminant Mixing at Pipe Joints: Comparison Between Laboratory Flow Experiments and Computational Fluid Dynamics Models

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Overview

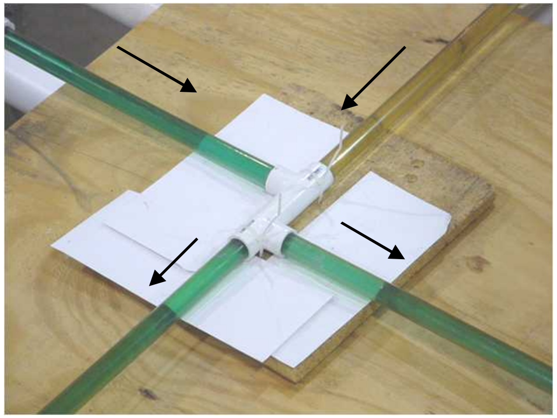
- Introduction
- Experimental Approach
- Modeling Approach
- Results
- Conclusions

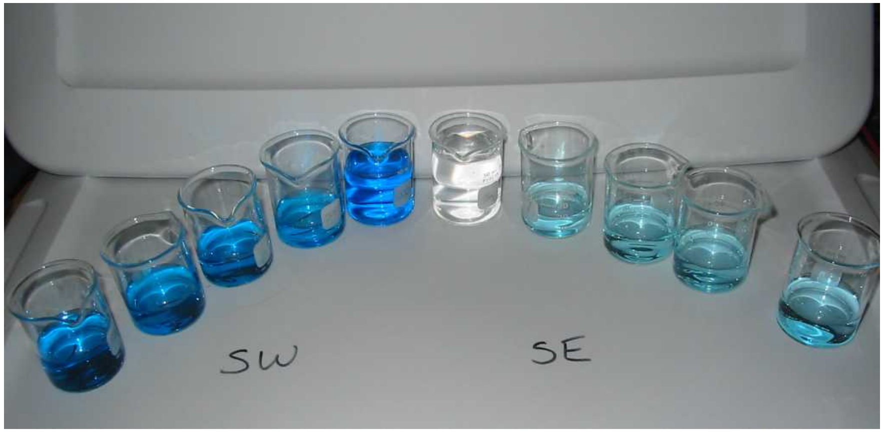
Introduction

- Contaminant transport in water-distribution pipe networks is a growing concern
  - Need to understand and predict contaminant movement
- Need to understand how contaminants mix at pipe junctions
  - Water quality
  - Interpretation of monitoring data
  - Mitigation of contamination events

Problem Statement

- **Many water distribution models (e.g., EPANET) assume complete mixing at pipe junctions**
- **Flow in actual pipe joints yields incomplete mixing**
  - **Orear et al., 2005**
  - **van Bloemen Waanders et al., 2005**



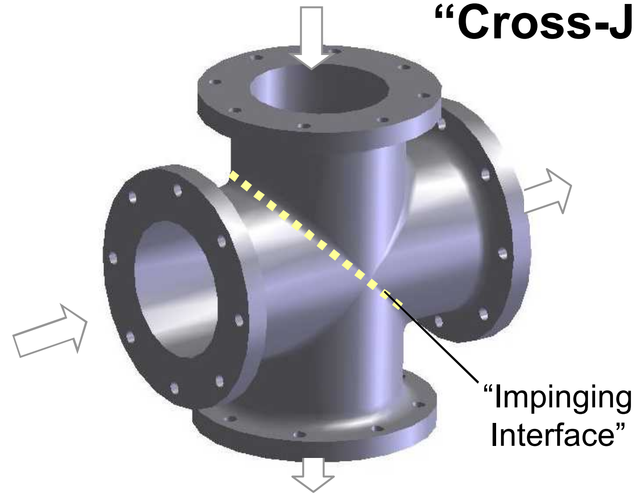


from Orear et al. (2005)

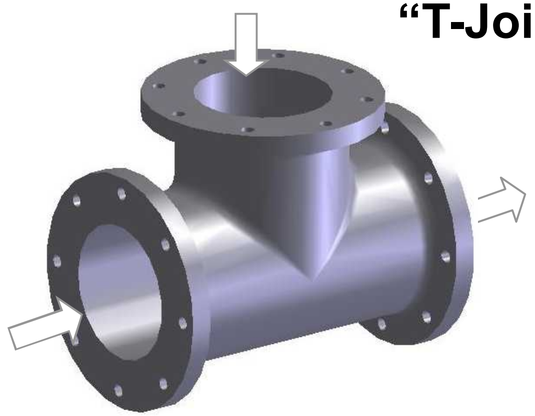
Objectives

- **Conduct physical and numerical simulations of contaminant transport in pipe joints**
- **Understand impact of parameters and processes on mixing behavior**
  - **Different flow rates**
  - **Effective mass transfer at impinging interface**
- **Validate and calibrate models with data from single and multi-joint pipe configurations**

“Cross-Joint”



“T-Joint”



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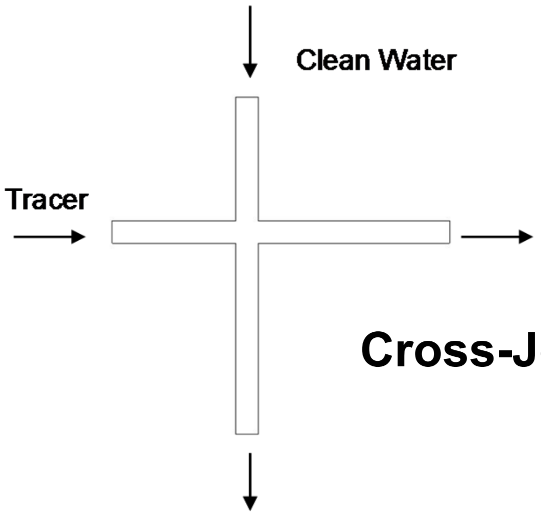
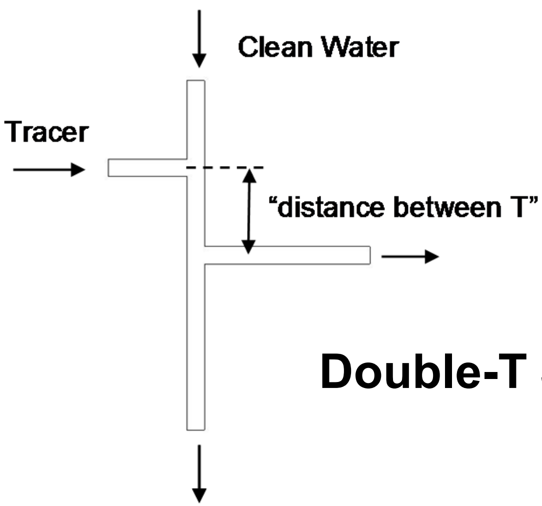
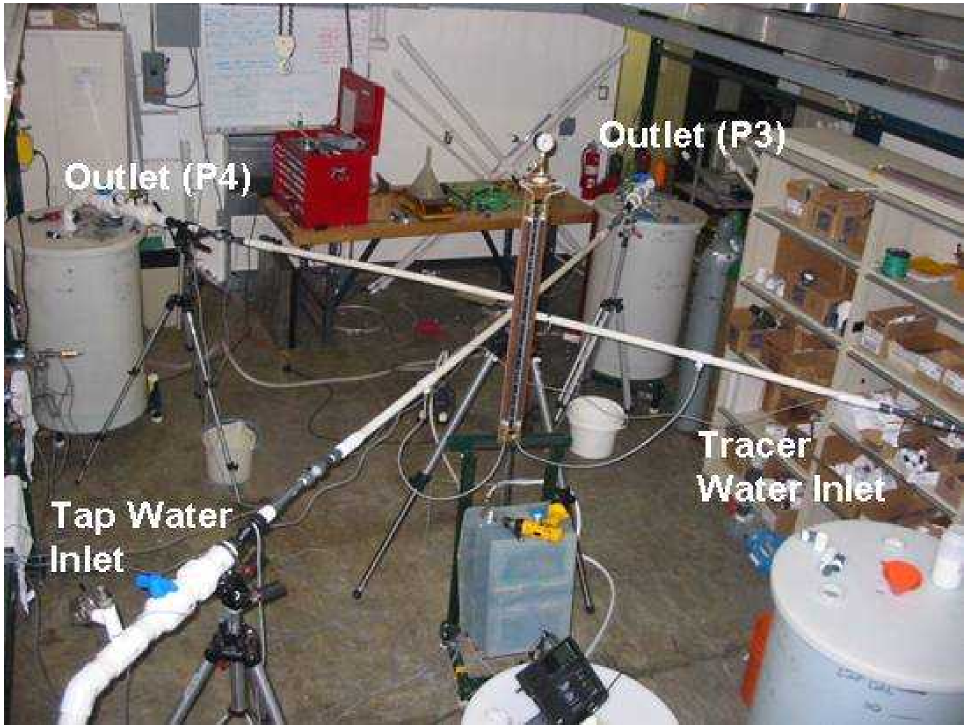
Single-Joint Tests



Cross-Joint

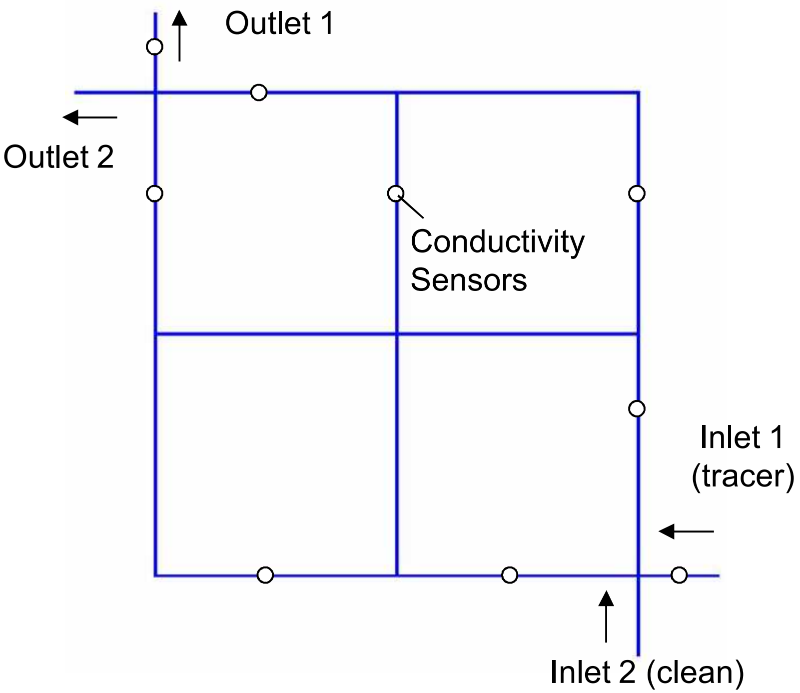


Double-T Joint



- Tracer consists of NaCl solution
- Tracer monitored continuously by electrical conductivity sensors
- Flow rate in each pipe was controlled
- Pipe diameters: 0.5", 1", 2"

Multi-Joint Tests
(Small-Scale Network)



- **3x3 array of cross joints with 3-foot pipe lengths**
- **Flow rates at inlets and outlets controlled**
- **Pipe diameter: 0.5”**

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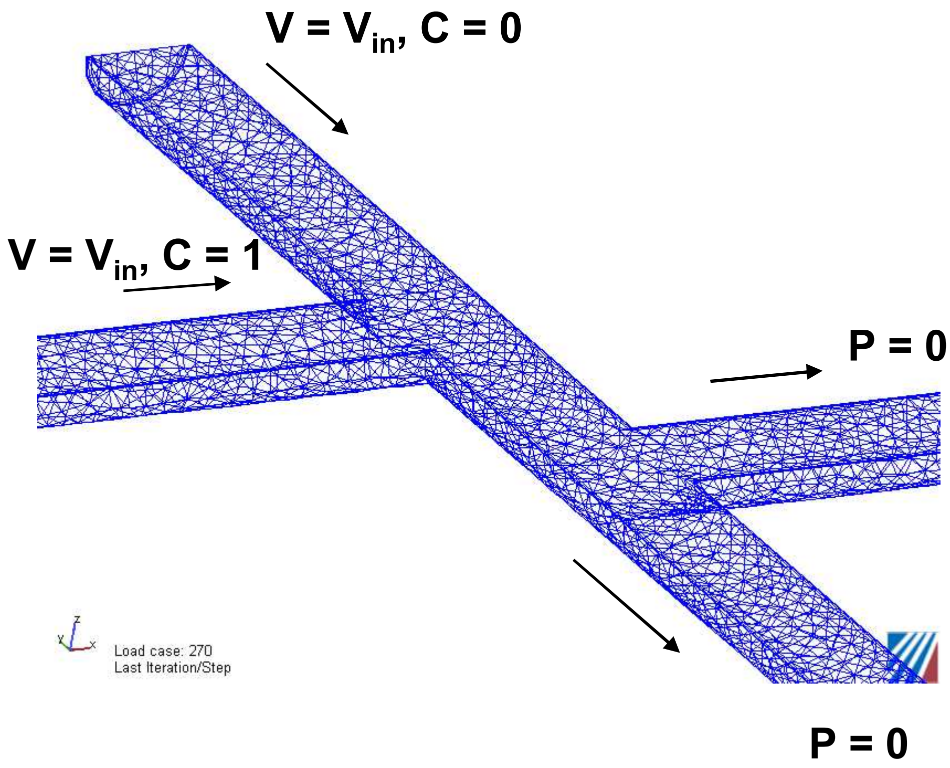
Modeling Approach

- **Finite-element computational fluid dynamics simulations (CFdesign®)**
  - **Mesh refinement: 50,000 to >1M elements**
- **K-ε turbulence model**
  - **Ran turbulent flow to convergence first**
- **Tracer simulation with normalized scalar concentration**
  - **Scalar diffusivity varied**
  - **D = eddy diffusivity = eddy viscosity/Sc**
    - **Turbulent Schmidt number, Sc, varied from 0.001 to 1.0**



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Single-Joint Simulations

All inlet and outlet flows approximately equal

Junction Configuration	Pipe Diameter	Reynolds Number	Velocity Boundary Conditions (*V*)	Turbulent Schmidt Number

*Experiments were run for this configuration

Multi-Joint Simulations

- Two simulations
  - Tracer inlet flow > clean-water inlet flow
  - Tracer inlet flow < clean-water inlet flow

Boundary Conditions				Reynolds Number	Turbulent Schmidt Number
Tracer Inlet Flow (Q_{tracer})	Clean Water Inlet Flow (Q_{clean})	Outlet 1 Flow ($Q_{out,1}$)	Outlet 2 Flow ($Q_{out,2}$)		
38 mL/s* (0.61 gpm)	31 mL/s (0.49 gpm) (P = 0 gage used as B.C.)	33 mL/s (0.52 gpm)	37 mL/s (0.58 gpm)	4,000 – 9,000	0.01, 0.001
28 mL/s** (0.44 gpm) (P = 0 gage used as B.C.)	50 mL/s (0.79 gpm)	32 mL/s (0.50 gpm)	46 mL/s (0.73 gpm)	7,000 – 11,000	0.01, 0.001

*Test period from 19-20 minutes in Orear et al. (2005)
**Test period from 8-9 minutes in Orear et al. (2005)

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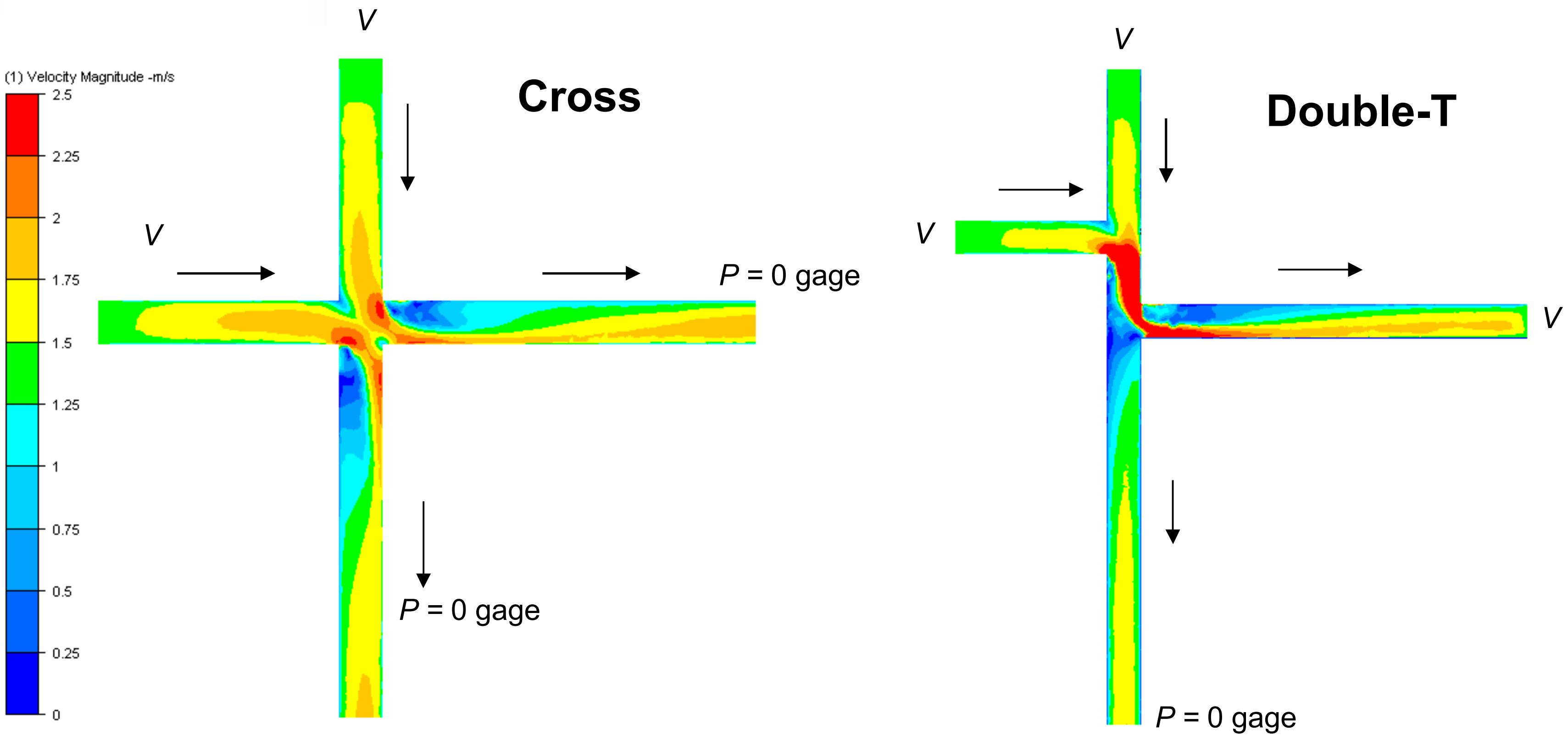
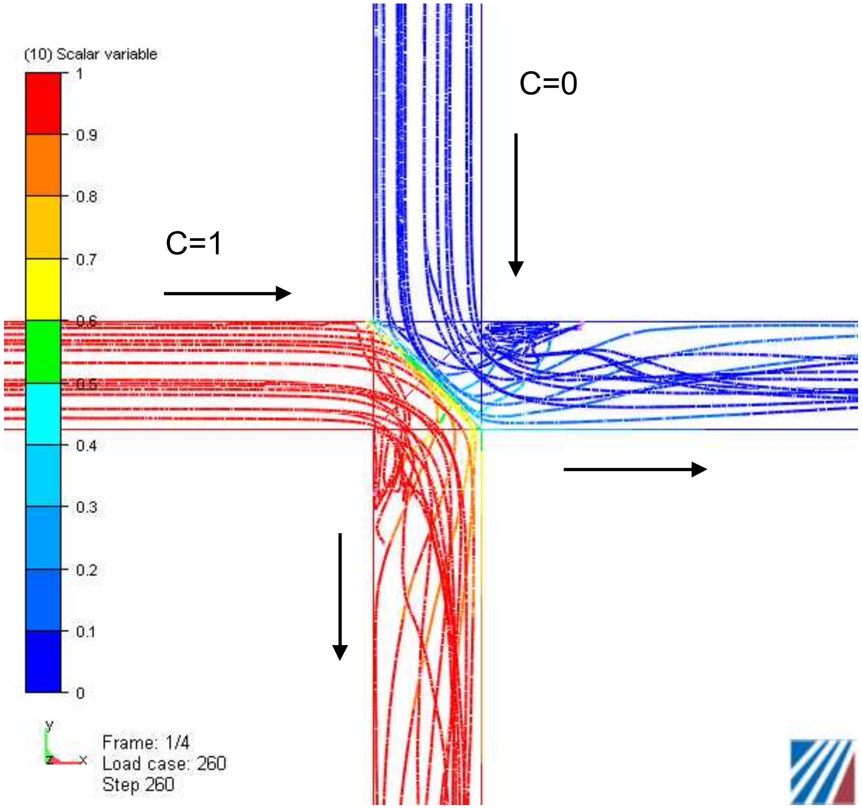
Simulated Velocity Profiles

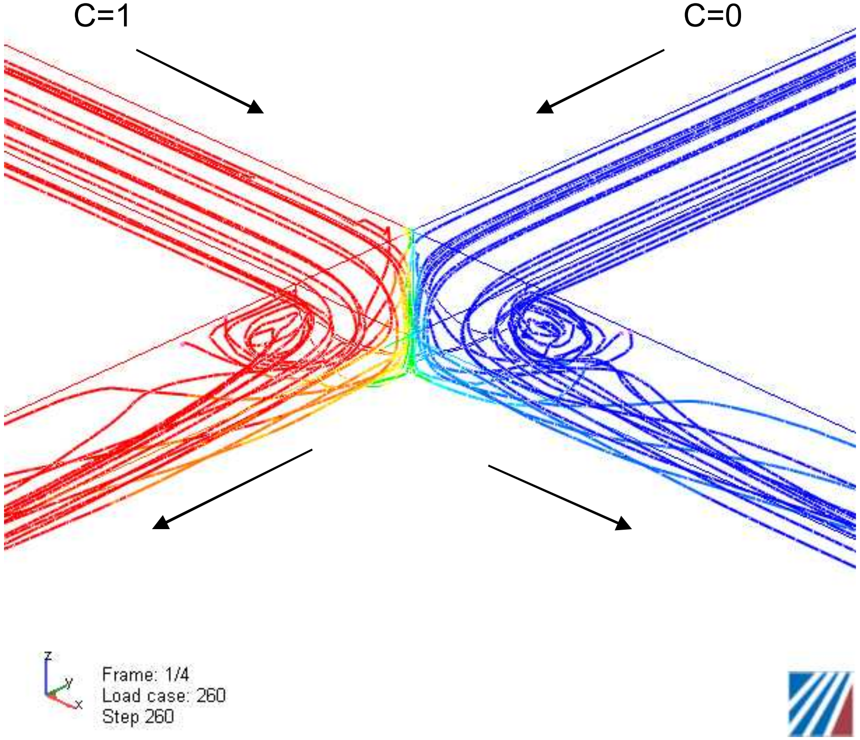


- **Diameter: 0.5”**
- **Re = 20,000**
- **Spacing between double-T joints is 2.5 diameters**

Simulated Mixing

0.5" Cross Joint, Re = 10K, Sc = 1





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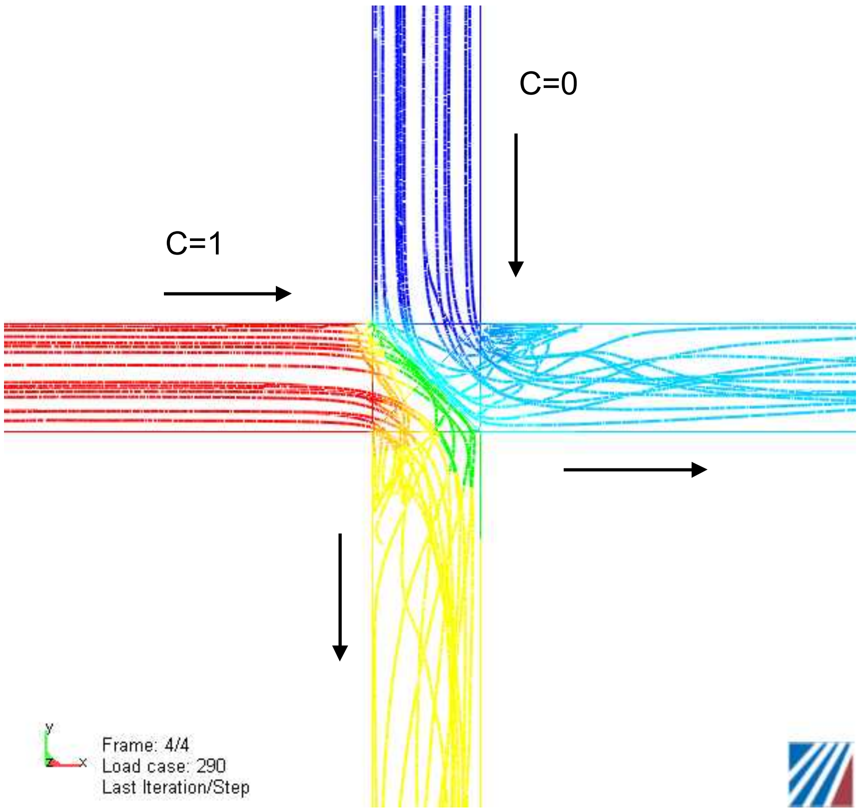
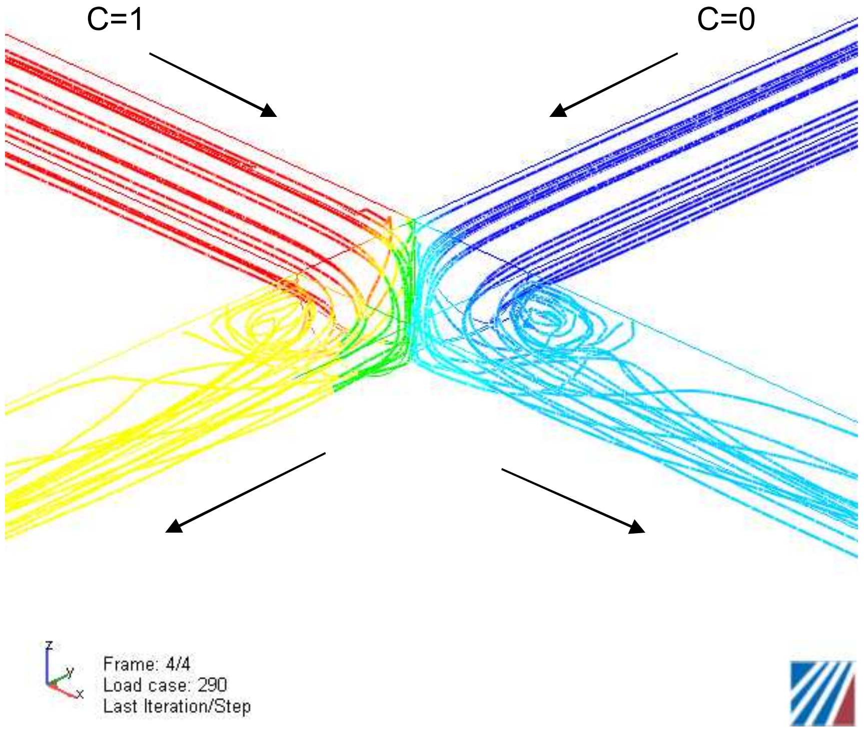
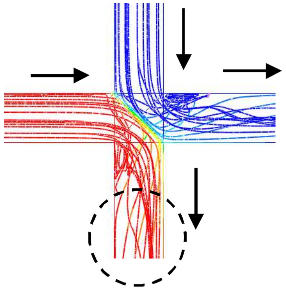
Simulated Mixing

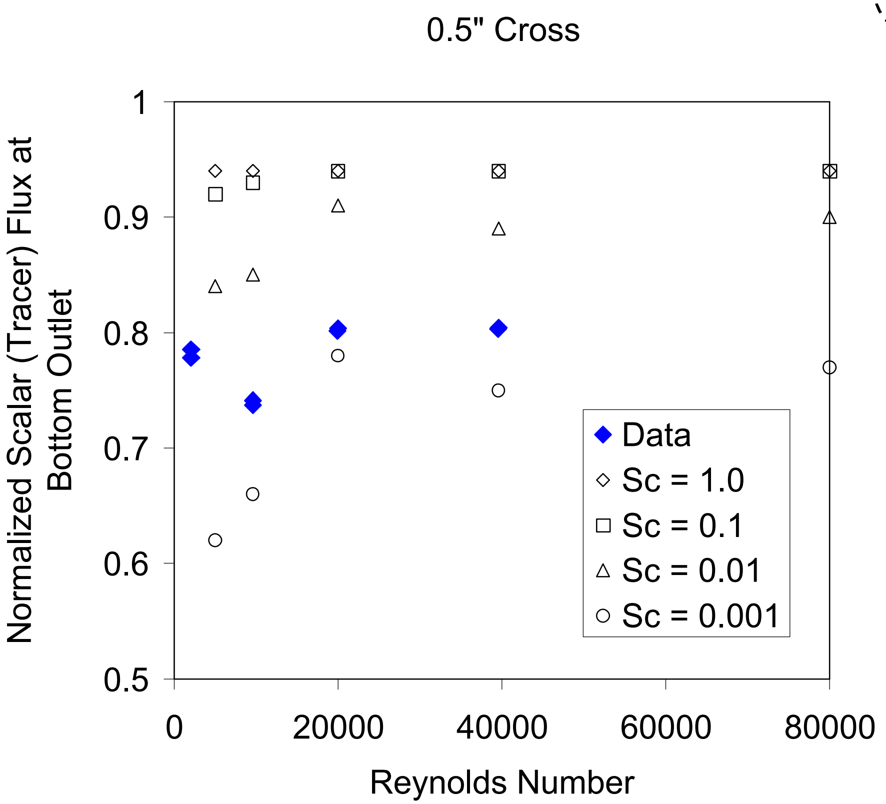
0.5” Cross Joint, Re = 10K, Sc = 0.001

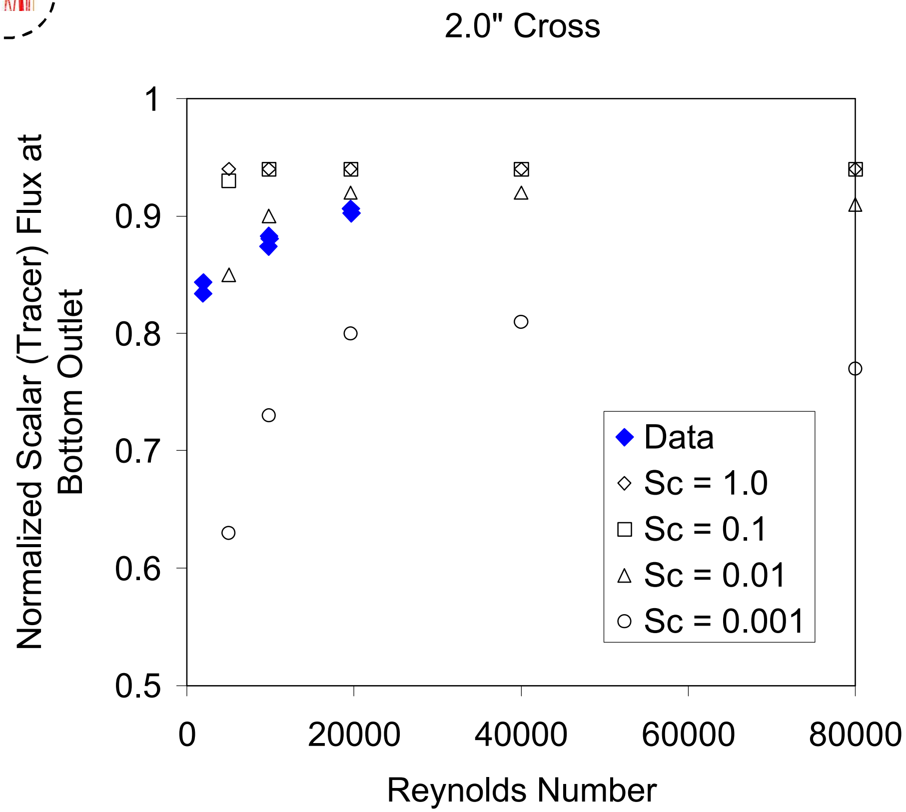




Single-Joint Results







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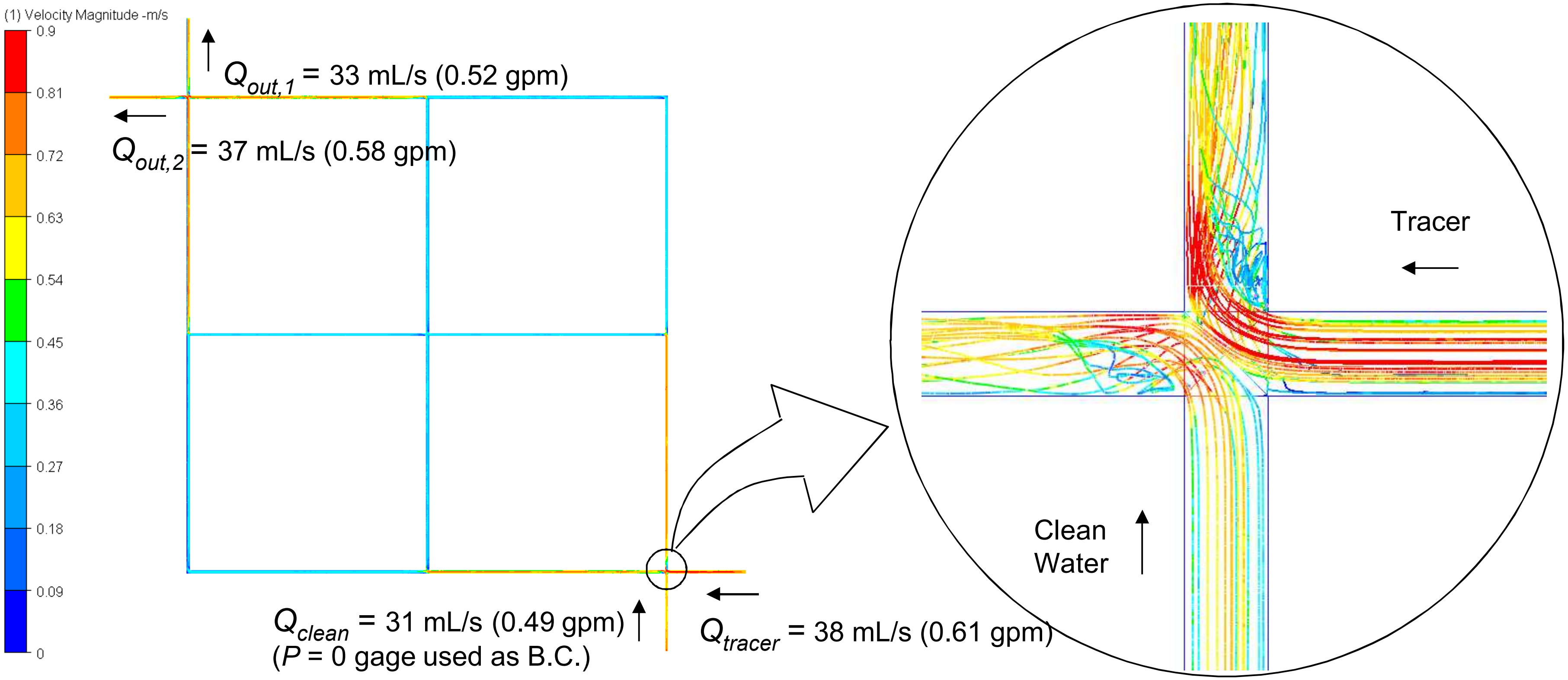
Network Hydraulic Results

$Q_{tracer} > Q_{clean}$



Network Hydraulic Results

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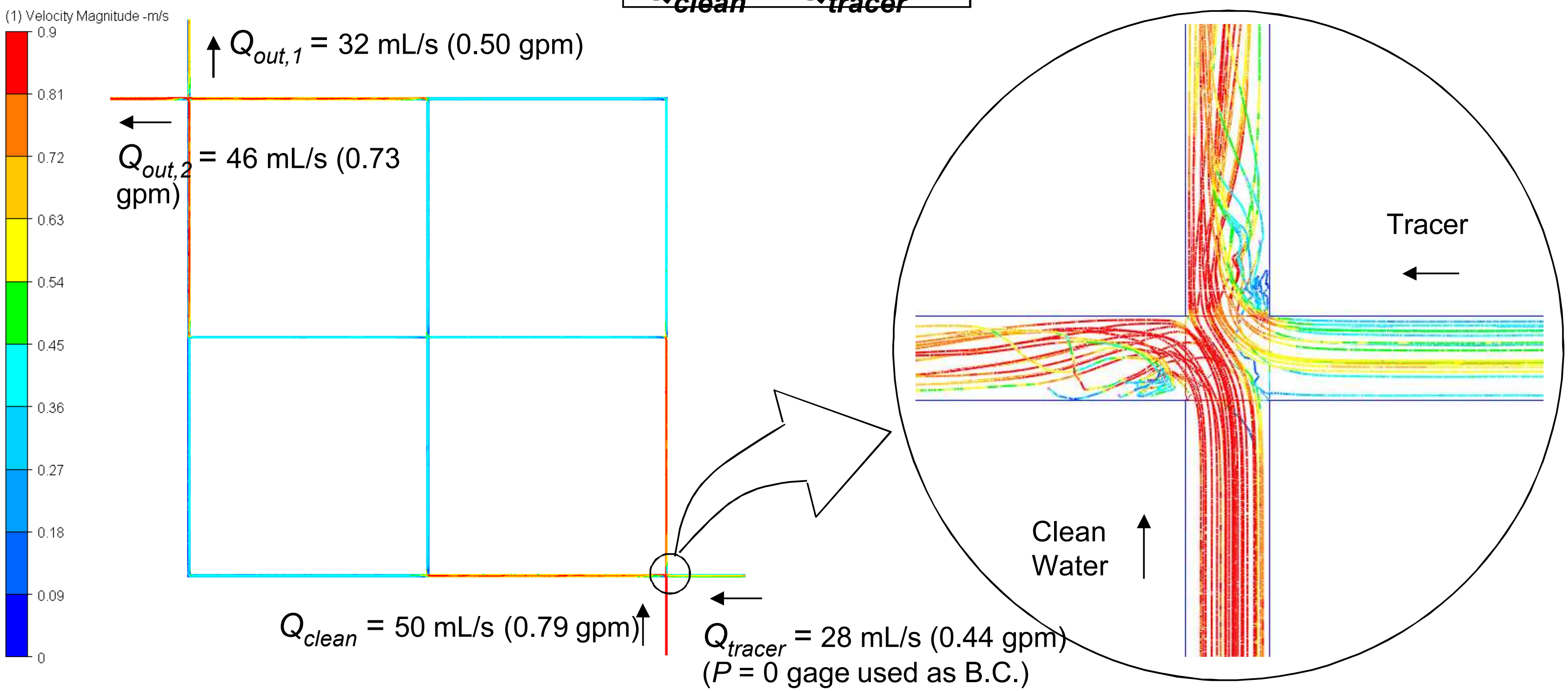
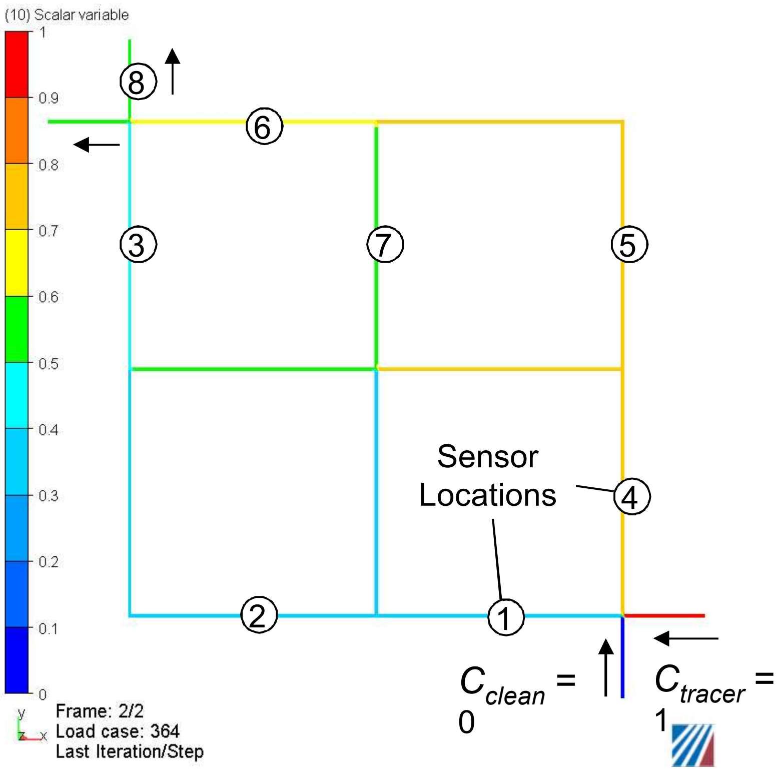
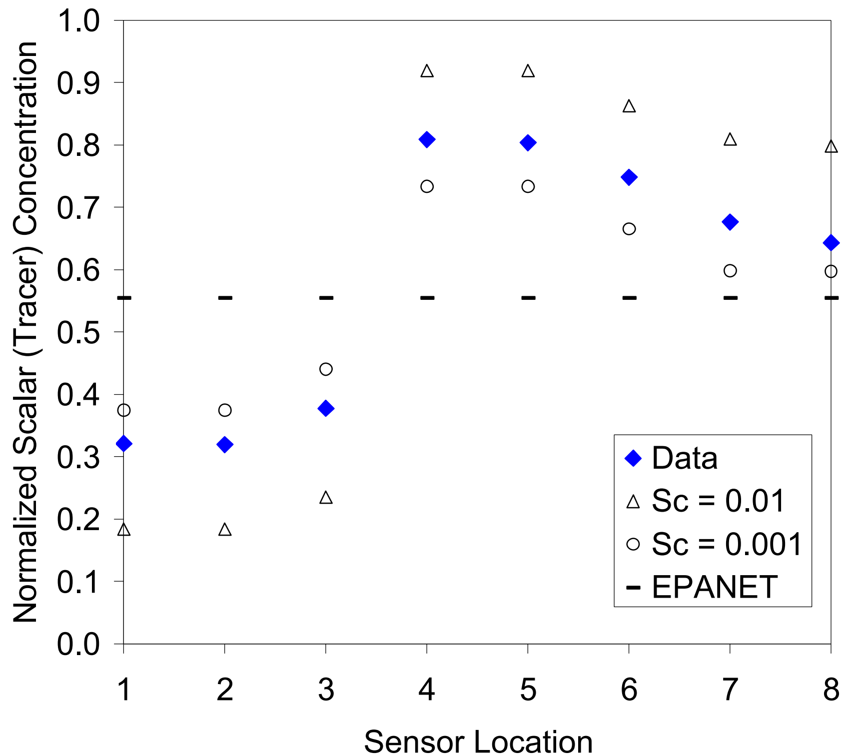


Network Tracer Results

$$Q_{tracer} > Q_{clean}$$





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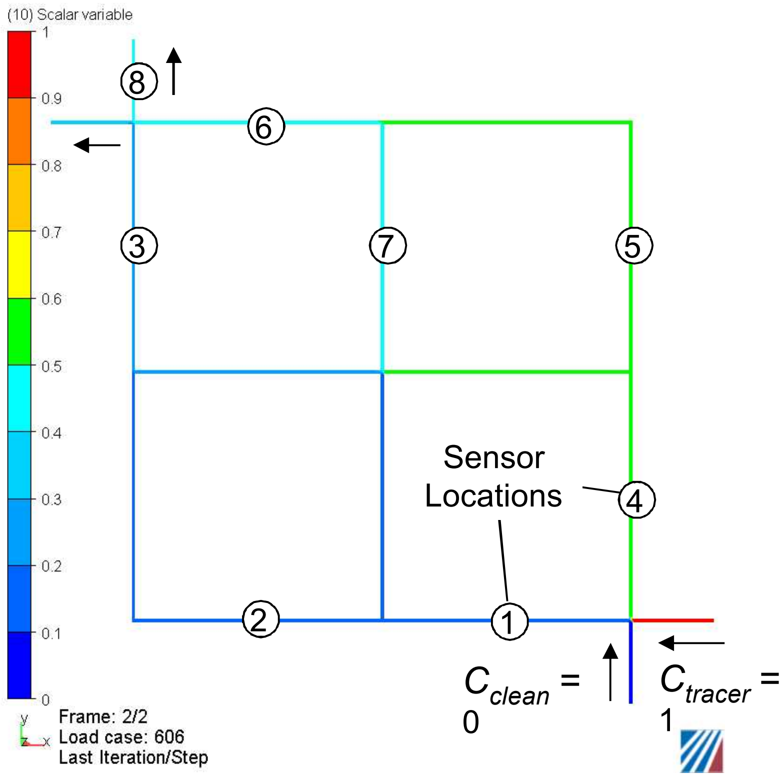

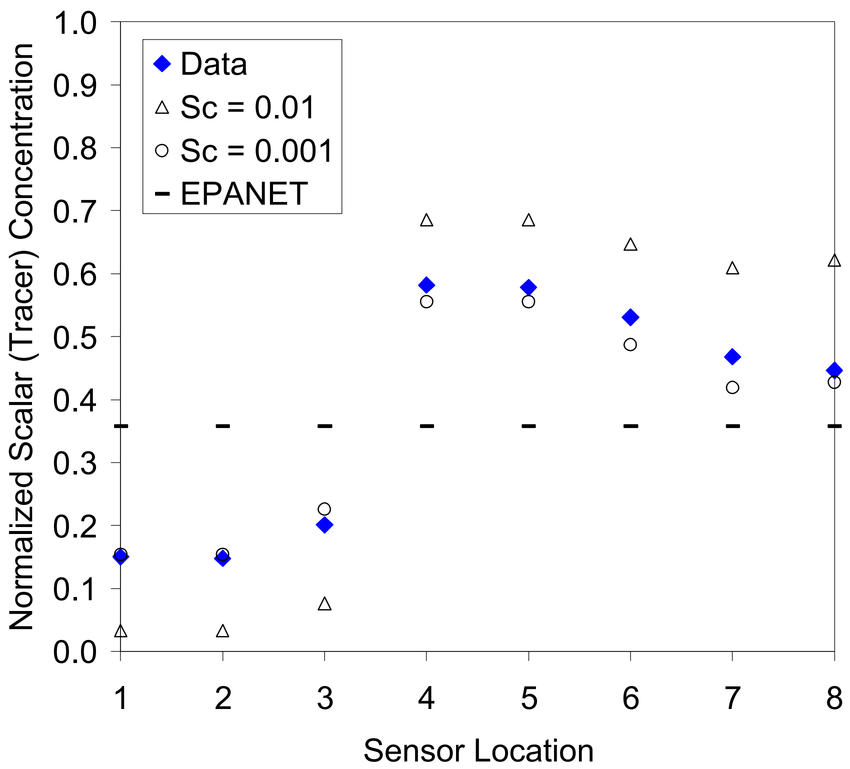

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Conclusions

- Water flow and tracer transport were tested experimentally and simulated using CFD models of turbulent flow
- A turbulent Schmidt number (turbulent diffusivity) was calibrated using single-joint test results
  - $0.001 < Sc < 0.01$
- Mixing in cross joints decreased slightly as the velocity was increased for a fixed diameter pipe ($\sim 10{,}000 < Re < \sim 40{,}000$)
  - Increased momentum and reduced time of contact may dampen and offset the tendency for instabilities to increase mixing at the impinging interface at higher velocities

Conclusions (cont.)

- A small network with 3x3 array of cross joints was tested and simulated
  - Incomplete mixing resulted even after several junctions
  - Unequal inlet flow rates significantly affects mixing
    - Increased momentum from the higher flow-rate inlet allowed some fluid to cross over the junction into the opposite outlet pipe
    - Mixing is caused by both bulk flow (advection) and turbulent diffusion at impinging interface
  - Calibrated turbulent Schmidt numbers yielded good agreement between data and simulations

Next Steps

- Continue physical and numerical simulations
  - Evaluate mixing in more complex configurations and networks
  - Evaluate the effects of transient oscillations and storage on mixing in pipe networks

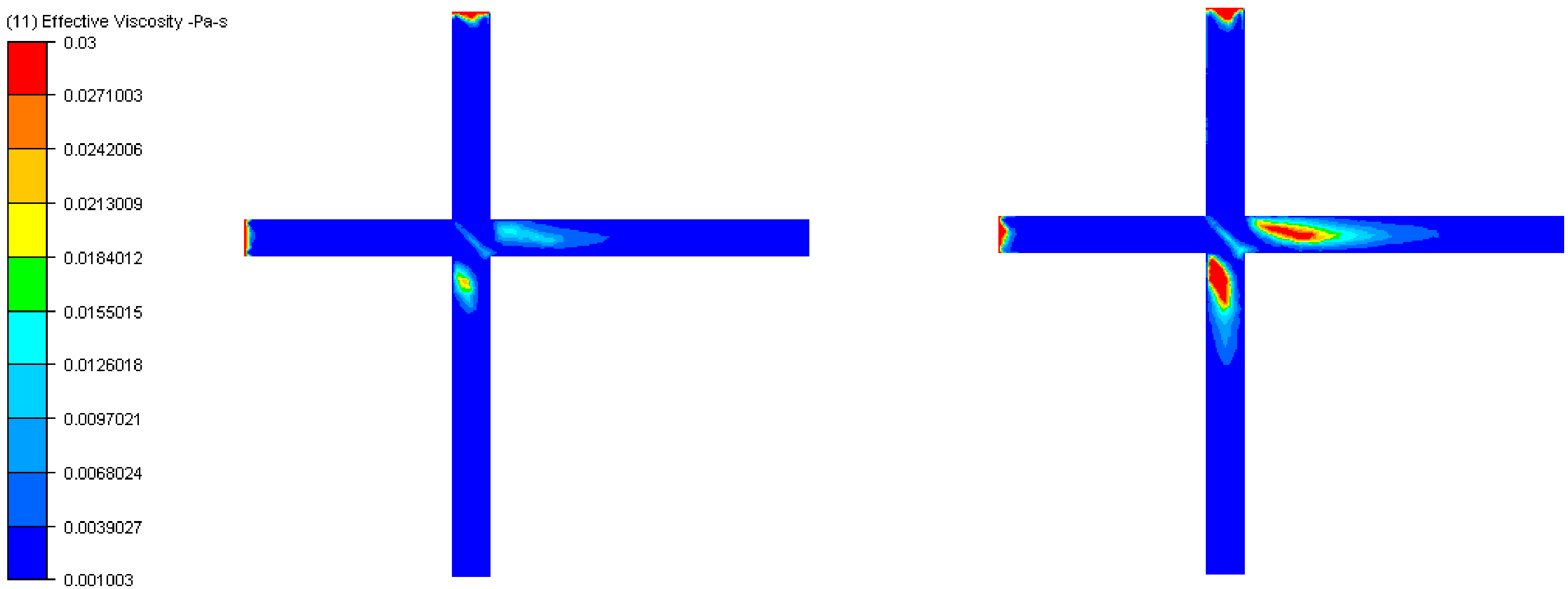
Backup Slides

Mesh Refinement

Model Configuration	Element Size	Number of Elements
Single-Joint Cross 1.27 cm (0.5") diameter pipe	2.5 mm (pipe) 1.5 mm (junction)	46,352
Single-Joint Cross 5.08 cm (2") diameter pipe	10 mm (pipe) 6 mm (junction)	46,352
Single-Joint Double-T 1.27 cm (0.5") diameter pipe 2.5 diameter spacing between T-fittings	2.5 mm (pipe) 1.5 mm (junction)	56,093
Single-Joint Double-T 1.27 cm (0.5") diameter pipe 5 diameter spacing between T-fittings	2.5 mm (pipe) 1.5 mm (junction)	56,382
3x3 Network 1.27 cm (0.5") diameter pipe	2.5 mm (pipe) 1.5 mm (junction)	1,190,163

Simulated Eddy Viscosity

Re=5,000 **Re=10,000**



Simulated effective (eddy) viscosity [Pa-s] distribution for the 1.27 cm (0.5”) diameter cross-joint configuration at two different Reynolds numbers: 5,000 (left) and 10,000 (right)