Modeling of Laminar Flow Static Mixers

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Introduction

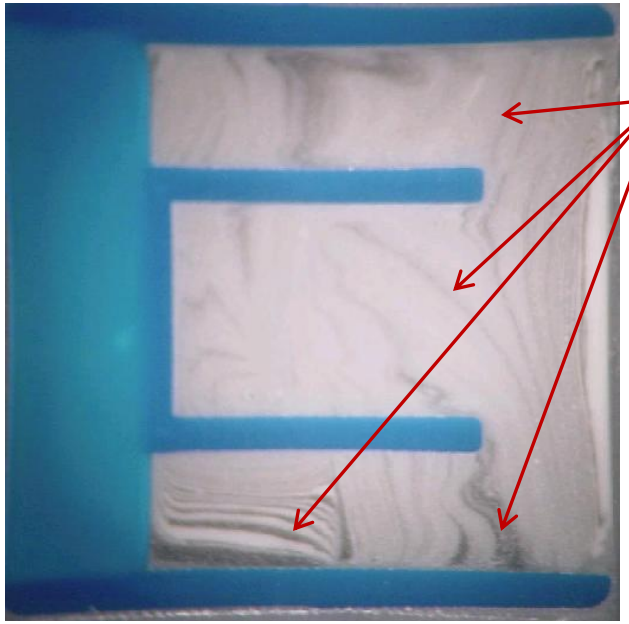
- Laminar flow static mixers are inexpensive and suitable for wide range of industrial applications
- There is very limited diffusion in between the mixed fluids
  - Mixing must involve dividing and recombining fluids

Image courtesy of Nordson EFD

Introduction

- Multiphase CFD simulation cannot be used by itself to predict mixing quality due to numerical diffusion

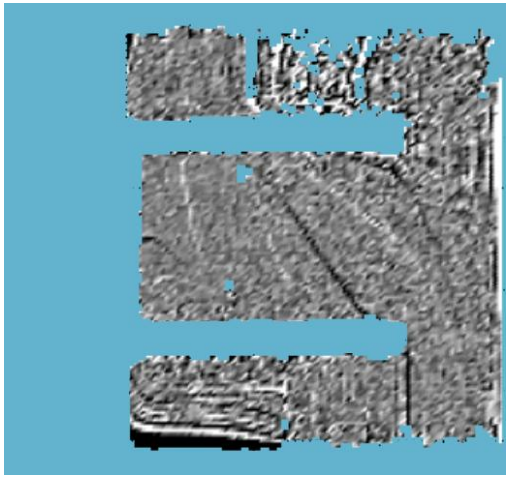
Experimental data



Size of fluid streaks too small for detection with multiphase CFD only

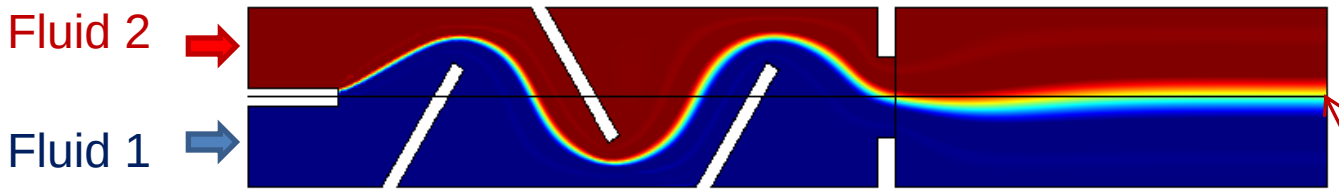
Is there a more suitable approach?

Yes!



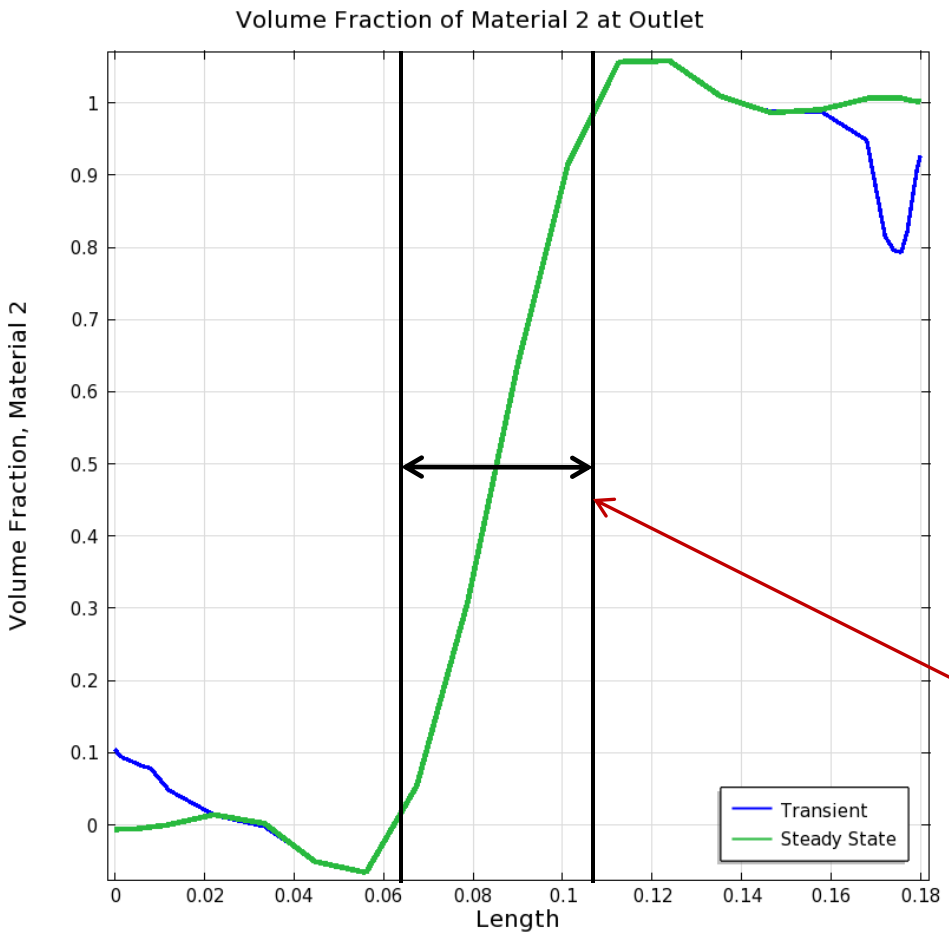
Multiphase CFD Example

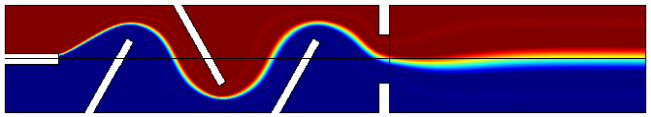
- A 2D example demonstrating dispersion in multiphase flow



Too much phase dispersion even with fine mesh and low numerical diffusion

Multiphase CFD Example





Phase dispersion region too wide

If there is no diffusion between fluids this width should be zero

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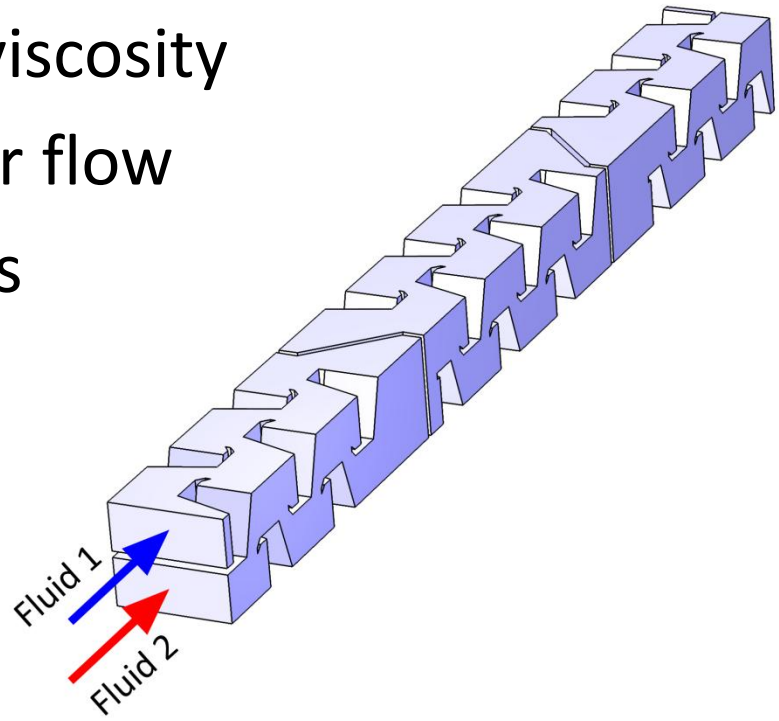
Modeling Approach

1. CFD analysis to predict overall mixer performance, flow pattern and pressure drop
2. Use streamlines or mass-less particle tracing to track motion of the fluid particles
3. Export streamline or particle tracing data for evaluation of mixing efficiency

Step 1: CFD Analysis

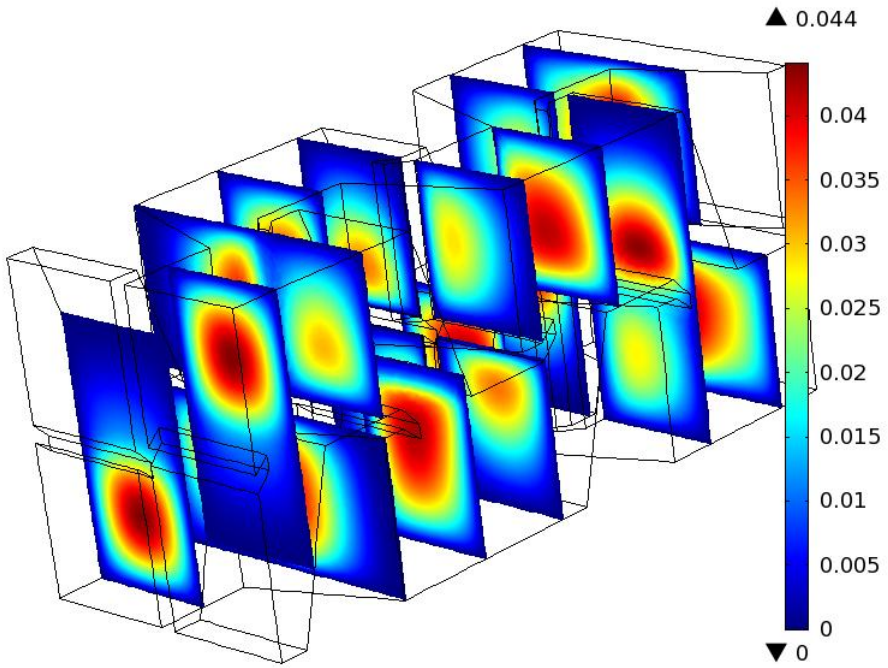
- CFD analysis to predict overall mixer performance, flow pattern and pressure drop
  - May be a two-phase analysis if two fluids have different density or viscosity
  - Very low Reynolds number flow
  - Assumed Newtonian fluids



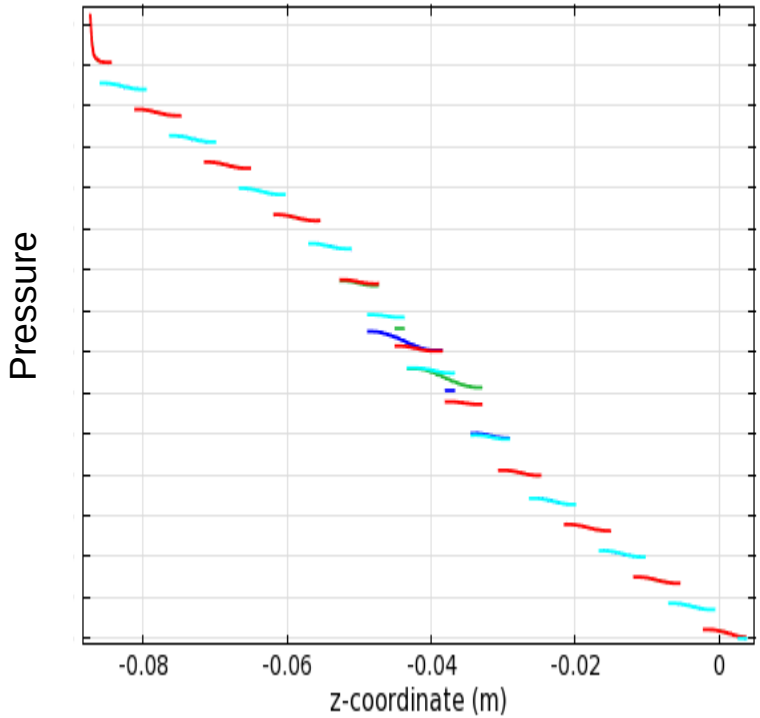
CFD Analysis

- Velocity and pressure drop for a specific mixer

Velocity profile



Pressure drop



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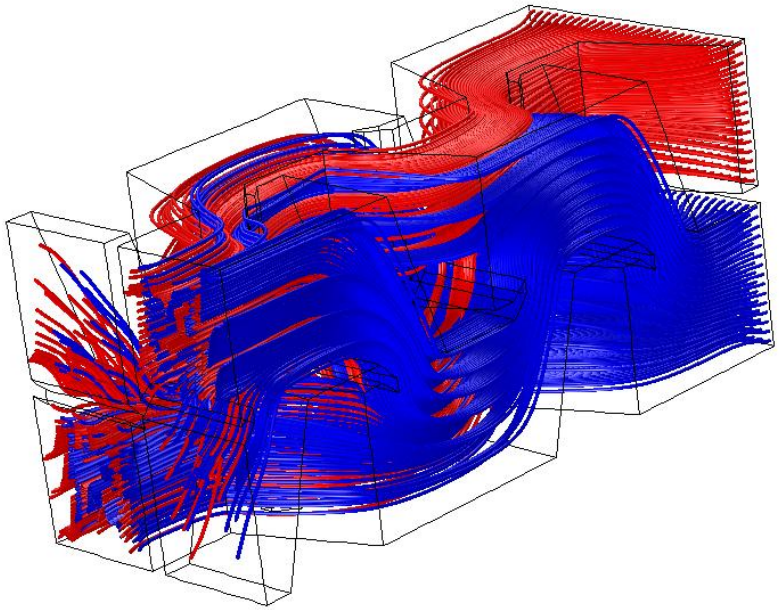
Step 2: Streamlines/Particle Tracing

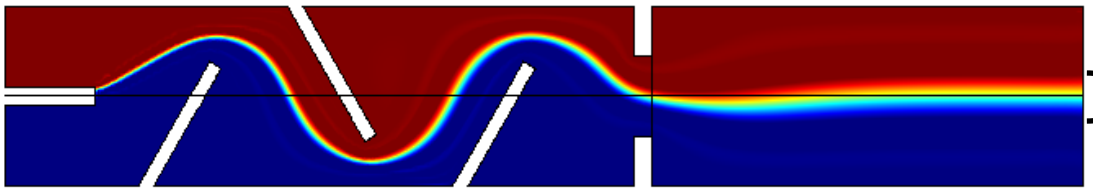
- Use streamlines or mass-less particle tracing to track the motion of fluid particles
  - Limited numerical diffusion
  - Large number of particles required
  - Accuracy of time integration essential
  - Insert streamlines in a uniform grid at any section



Streamlines Calculation

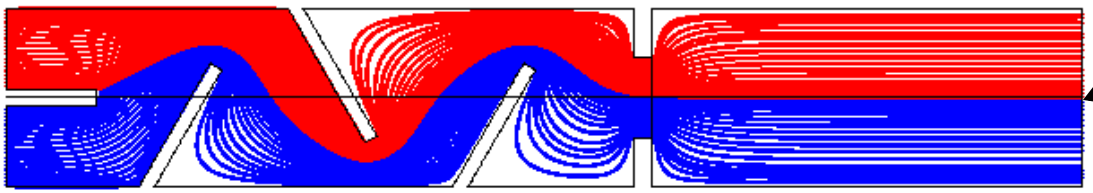
- The same 2D example

Two-phase flow



Unrealistic mixed region due to numerical diffusion

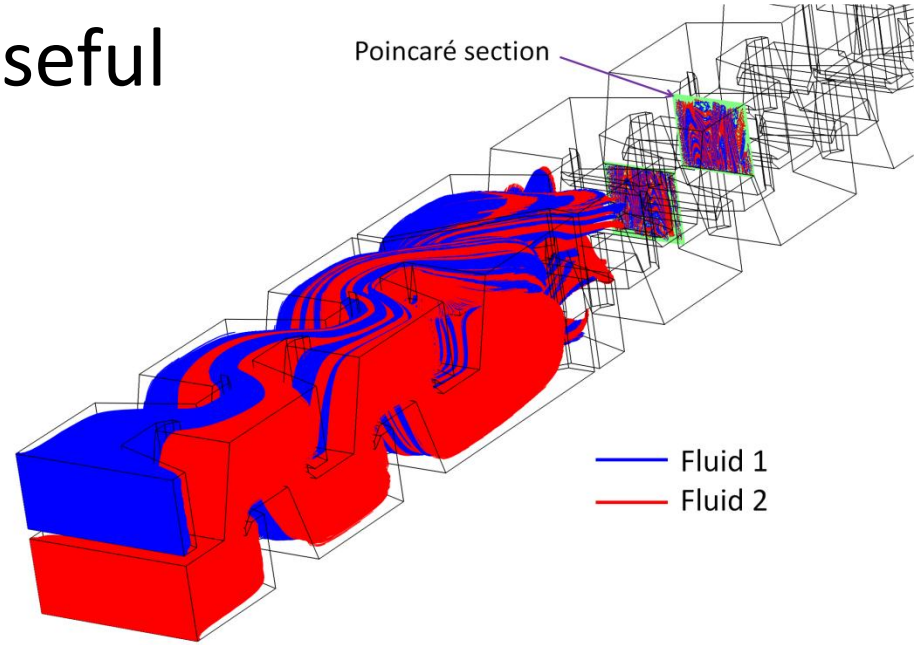
Single-phase flow with streamlines



Distinct fluid boundary

Particle Tracing

- Generate grid of mass-less particles instead of streamlines
- Poincare sections generated by COMSOL provide useful visualization tool



Step 3: Mixing Algorithm

- Export streamlines or mass-less particle tracing data using COMSOL's Java script feature
- Calculate coordinates where each streamline intersects different sections along static mixer
  - Similar to Poincare maps
- Divide each mixer section into a suitable sized grid and calculate number of streamlines intersecting each grid

Mixing Algorithm

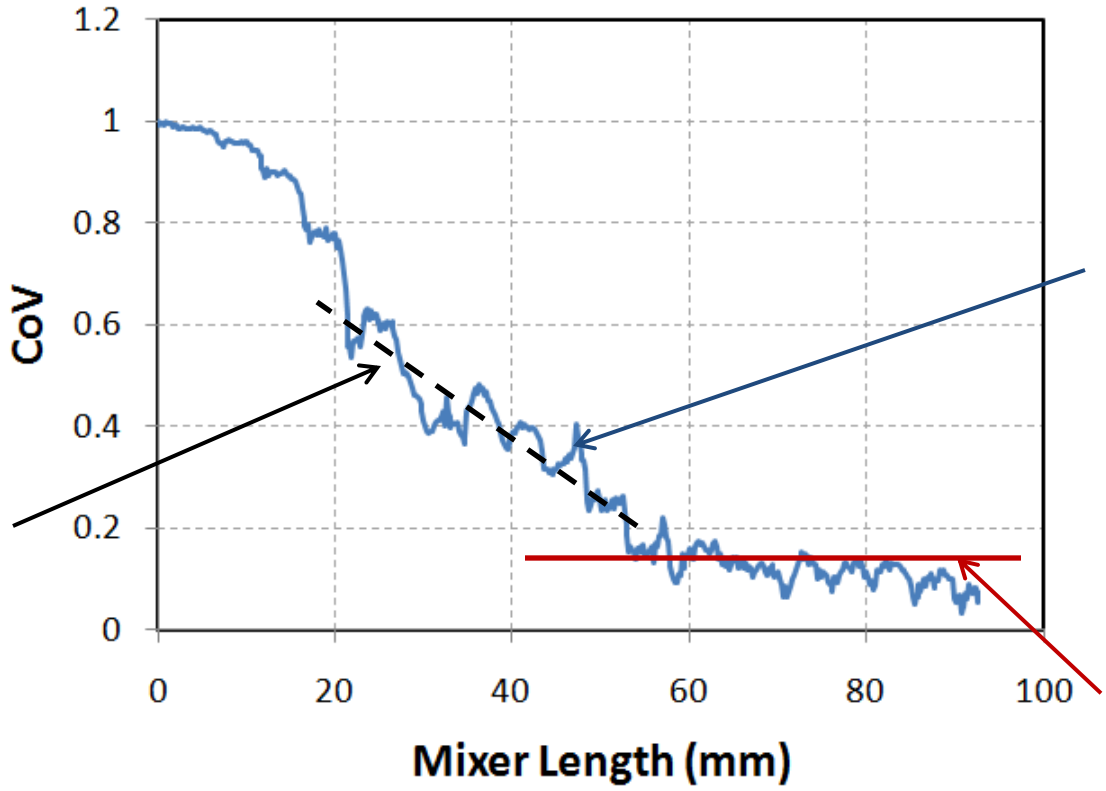
- Evaluate mixing using 2 metrics:
  - Coefficient of variation
  - Sectional images for detecting unmixed streaks
- Insert streamlines at multiple locations along mixer to increase accuracy and check level of numerical diffusion
  - Find optimal settings for streamline calculation

Coefficient of Variation

- One number that measures the mixing quality at a mixer cross-section
- Has positive value (~1.0) for no mixing, and 0.0 for “complete mixing”
- Complete mixing means good mixing at a specific cell size

Coefficient of Variation

- Typical Coefficient of Variation result



Rate of CoV drop indicative of mixer efficiency

Local oscillations function of cross-sectional area of mixer

Minimum detectable value for current settings

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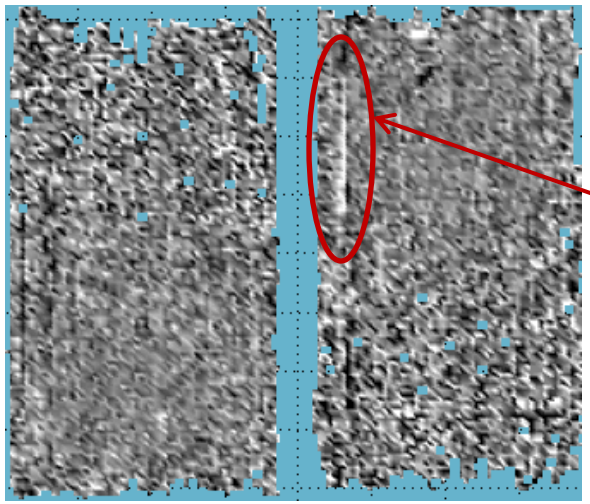
Coefficient of Variation

- Coefficient of variation predicts overall mixing quality. It is not ideal for detecting streaks.
- Streaks best detected by examining images of mixing at different cross-sections



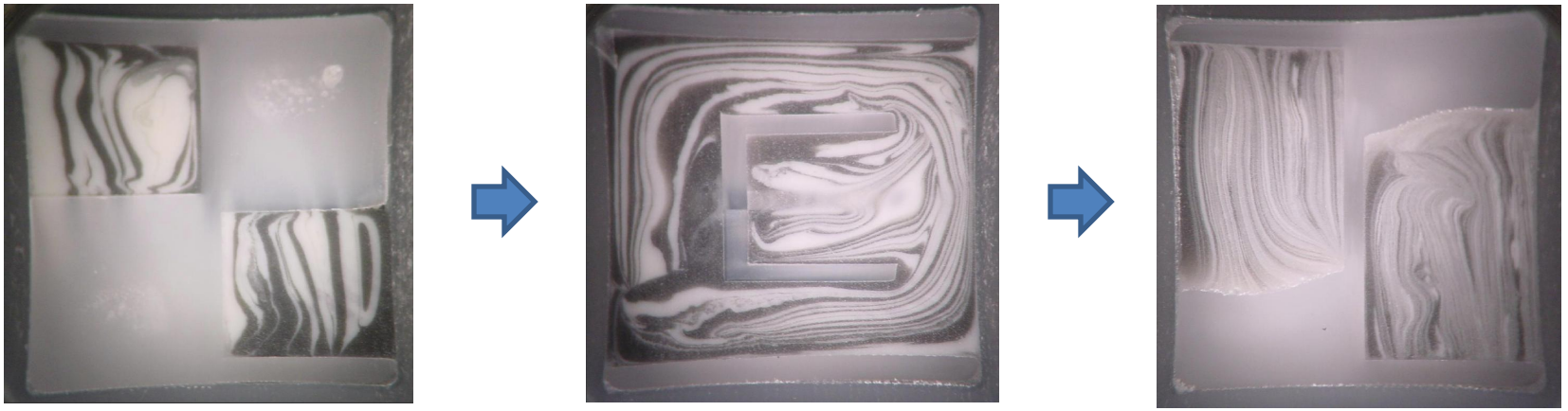
A fluid streak. Easy to detect visually, not through CoV

Algorithm Validation

- Performed mixing experiments using two epoxy materials that solidify when mixed – a black and a white compound
- After solidification mixer sliced into about 40 sections to visually assess mixing progression
- Simulate same experiment with developed mixing algorithm and compare predictions

Algorithm Validation

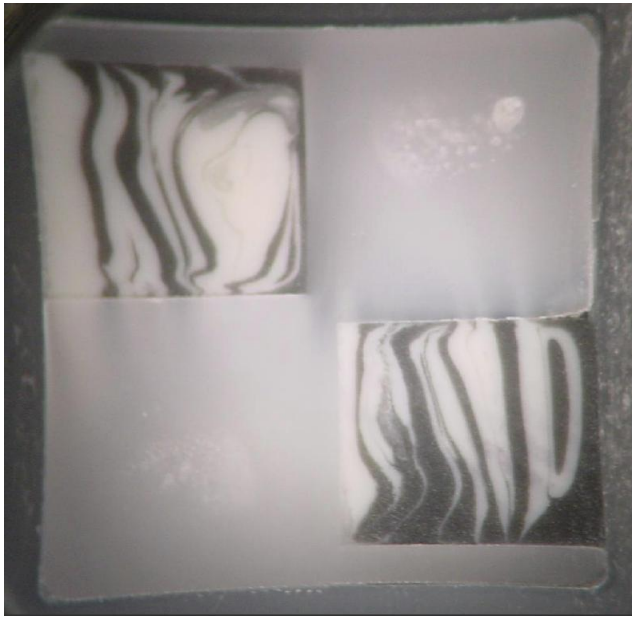
- Experimental sectional images
  - Images only shown for first half of mixer
  - Exact entry angle of fluid into mixer not captured



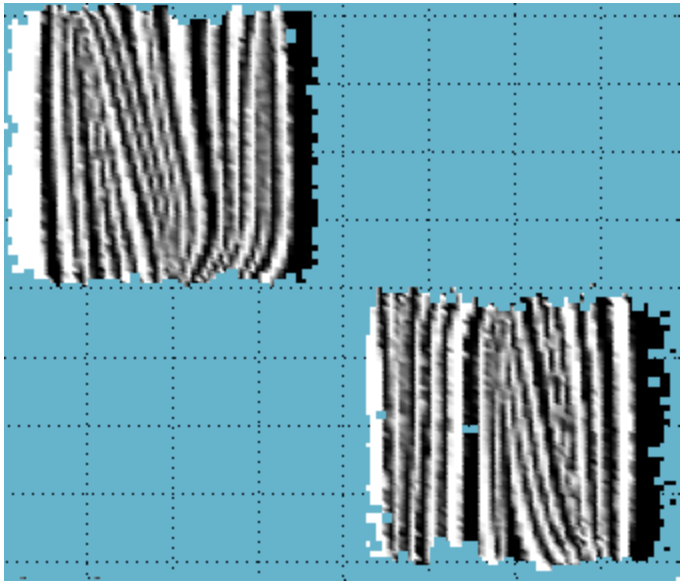
Mixing Results

- Before first inverter

Experiment



Simulation

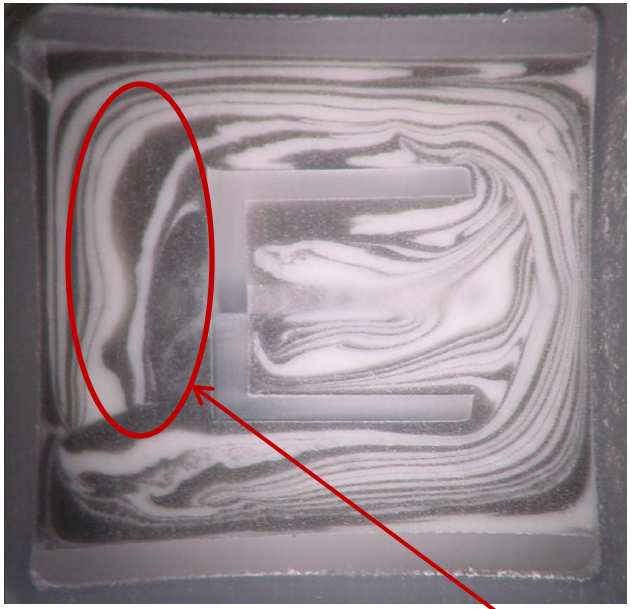


Good agreement between experimental and numerical predictions

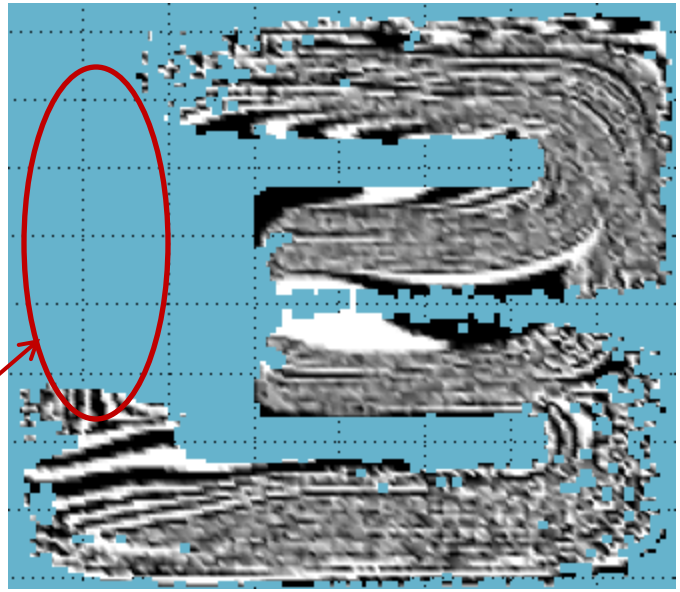
Mixing Results

- At end of first inverter

Experiment



Simulation



Area of very slow flow/recirculation

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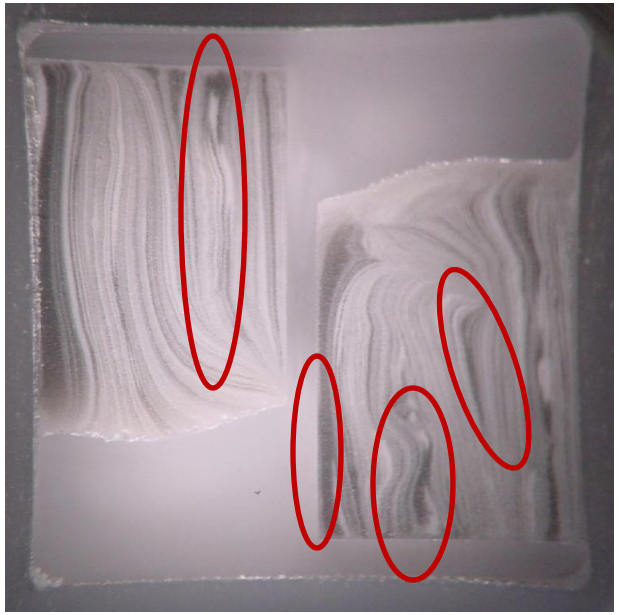
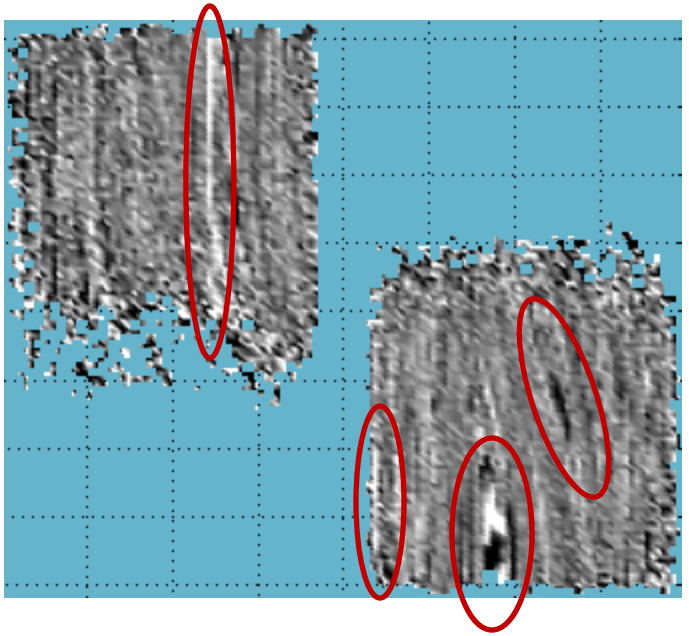
Mixing Results

- Before second inverter

Experiment



Simulation

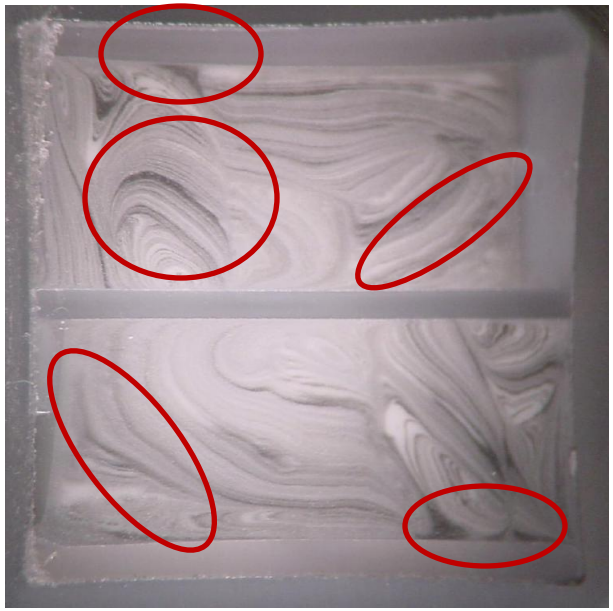


Ellipses show captured streaks

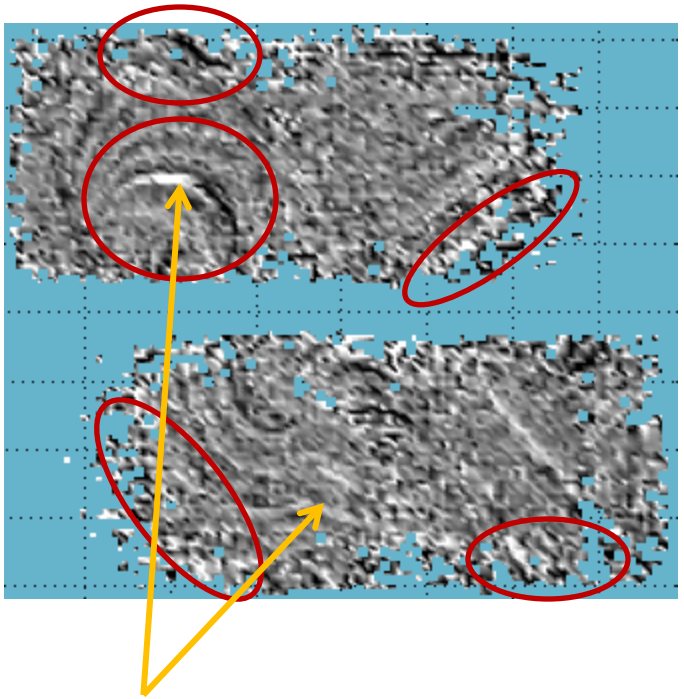
Mixing Results

- After second inverter

Experiment



Simulation



Simulation also captures flow patterns

Summary

- Developed algorithm for evaluating mixing quality in static mixers
  - CFD simulation to predict overall fluid flow and pressure drop in mixer
  - Streamline or particle tracing calculation to track fluid particles
  - Sectional images at multiple sections along mixers
  - Coefficient of variation that gives quantitative assessment of mixing quality

Summary

- Very good agreement obtained between experimental and simulation results
- Advantages of using COMSOL Multiphysics
  - Accurate CFD simulation
    - Single-phase and multi-phase flows
  - Accurate streamline and particle tracing calculations with over 200,000 particles
  - Ease of scripting with interfaces to Java and MATLAB

Current and Future Work

- Evaluating mixing quality for different fluid flow rates, viscosities and mixing proportions
  - Mixed fluids are frequently non-Newtonian (shear thinning, shear thickening or thixotropic)
- Using developed tool to optimize static mixer designs for Nordson EFD and investigate radically different mixer designs