Optimization Module Enables Hybrid Experimental-Numerical Algorithm for 3D Particle Image Velocimetry (PIV)

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Introduction: A 3D 3-component PIV measurement is required for evaluation of a micro mixer using a mix-prediction algorithm [1]. While 2D PIV is well developed, 3D methods are experimentally cumbersome or error prone. This hybrid approach combines 2D measurements, an imperfect numerical model, and fitting parameters. Because our purpose is a measurement, rather than development of a physically accurate and predictive model, it not necessary that parameters match actual conditions, only that the flow is represented.

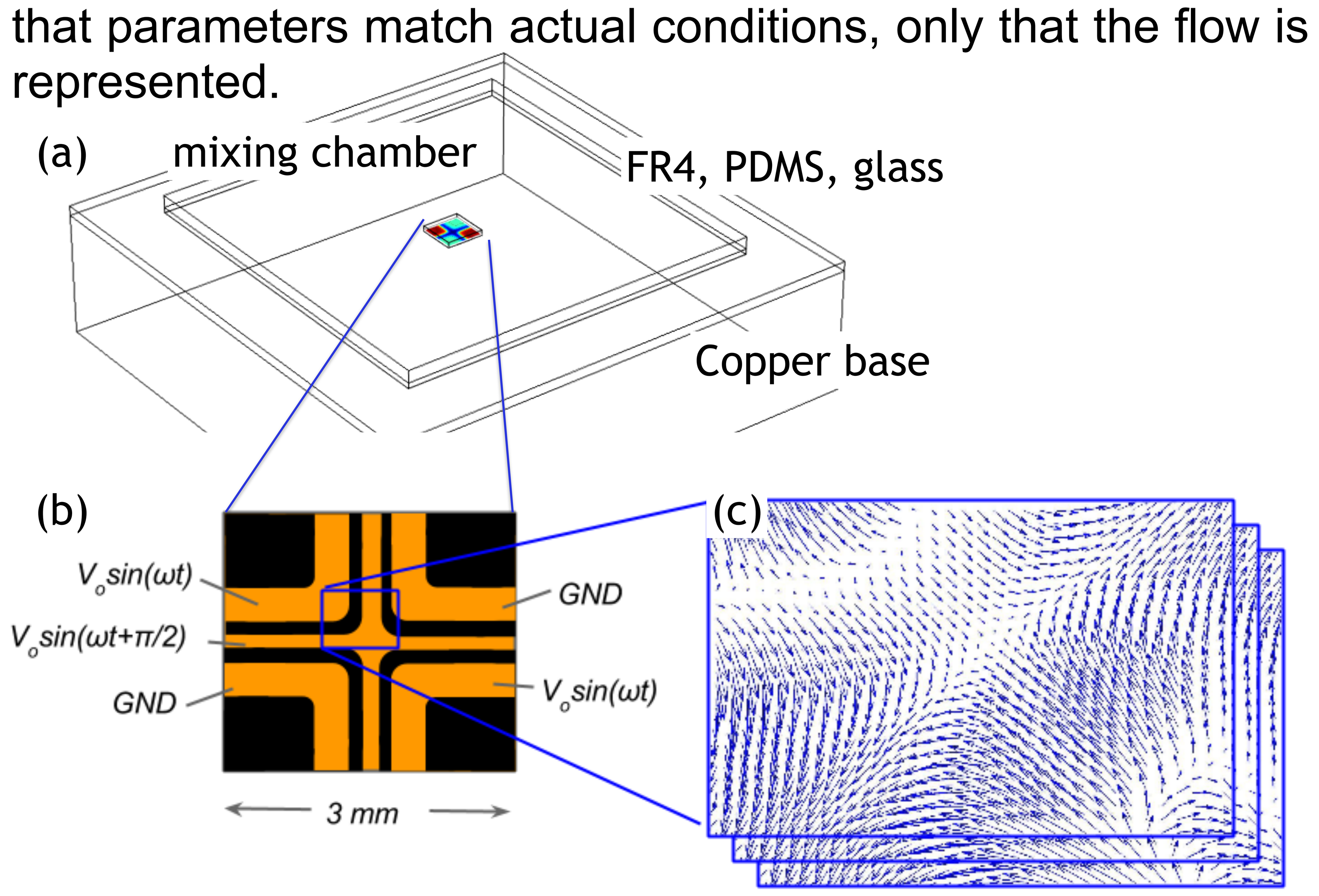

Figure 1. (a) Experimental Mixing testbed: programmable, blinking AC electrothermal flow. (b) Voltage is applied to electrodes (orange), which produces fluid circulation in mixing chamber. (c) PIV: sequential images are taken of fluorescent tracer particles in the flow; cross correlation yields 2D, 2 component velocity field [2]. Several z-levels are measured. Still need 3rd velocity component.

Computational Methods:

1. Physical model to get us close

Steady state solution for:

- Electrostatics
- Heat transfer subject to Joule Heating $\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + \sigma E^2$
- Laminar Flow with AC Electrothermal & buoyancy body forces [3]

$$\vec{F}_{ET} = -0.5\left[\left(\frac{\nabla\sigma}{\sigma}-\frac{\nabla\varepsilon}{\varepsilon}\right)\cdot\vec{E}\,\frac{\varepsilon\vec{E}}{1+(\omega\tau)^2}+0.5\left|\vec{E}\right|^2\nabla\varepsilon\right] \qquad \nabla\varepsilon = \left(\frac{\partial\varepsilon}{\partial T}\right)\nabla T, \nabla\sigma = \left(\frac{\partial\sigma}{\partial T}\right)\nabla T$$

2. ID potential shaping & scaling parameters

- Force scaling constants: a_B, a_E
- Temperature field shaping: *k, h*
- Electrode scaling: gap, width
  Use parametric sweep to test

3. Optimization module - find best combination

- Optimization Physics Mode: import experimental data file
- Optimization Solution Mode: choose parameters; iterate to minimize RSS difference between model & experimental data

4. Time dependent model

- "blinked" voltage Bounday Conditions
- Particle Tracking
- Export trajectories for use in mix-prediction algorithm

Results:

1. Physical model before optimization

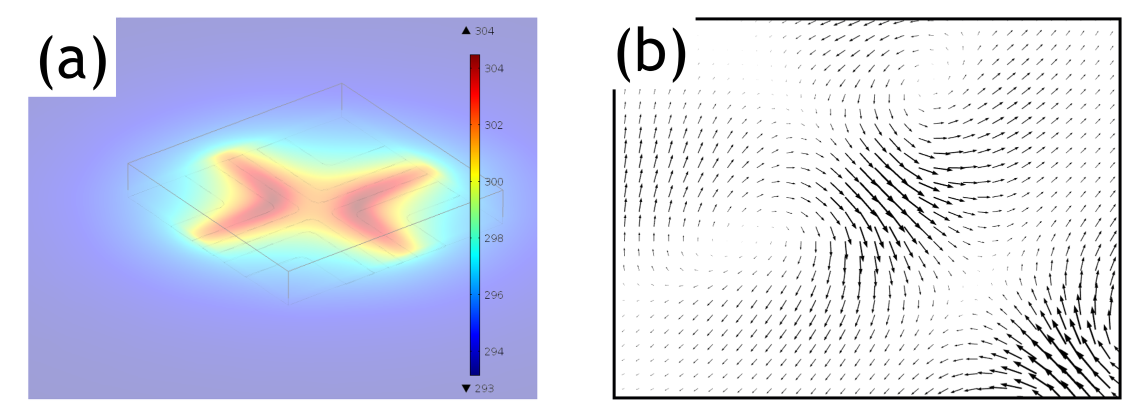

Figure 2. (a) Temperature solution showing heated areas where current through buffer is highest. (b) Resulting u,v velocity vectors. This first attempt does not match well measured velocity in Fig. 1.

2. After Optimization

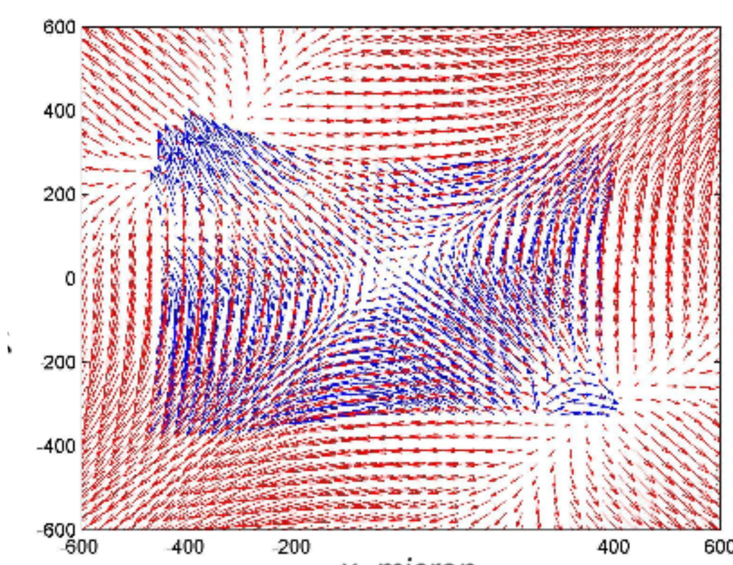

Figure 3. Optimized velocity field (red) overlaid with experimental data (blue) at z=130 um. Optimization parameters: a_B=2.5 a_E=0.

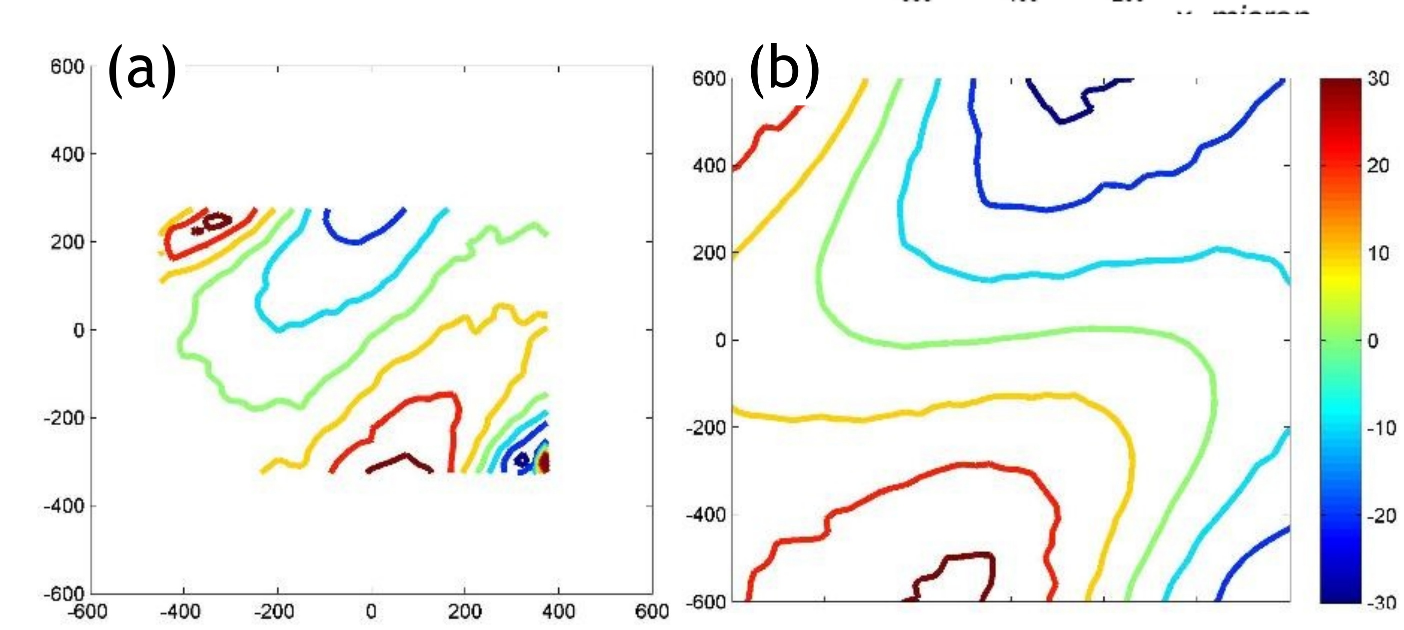

Figure 3. Optimized velocity field: velocity magnitude contours, at z=335 um for (a) experimental data and (b) Optimized solution.

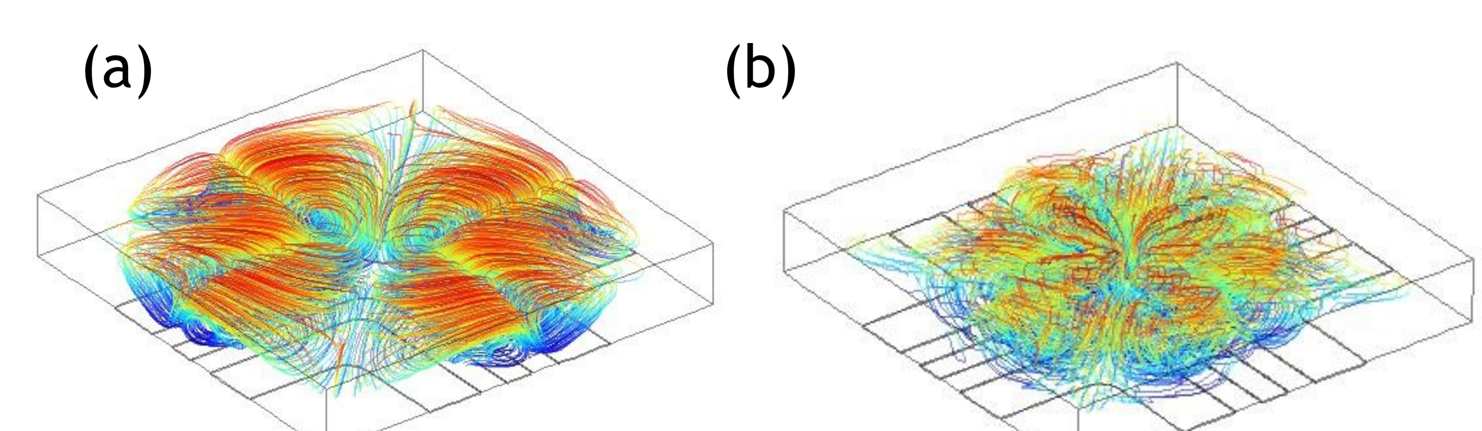

Figure 4. Particle trajectories (a) unblinked and (b) blinked. Trajectories are input to an algorithm [1] which identifies multi scale flow structures which impede mixing (not shown). By blinking the E-field, flow vortices are disrupted, and we expect better mixing, although (b) seems to show some flow structures remain in this design iteration. We are developing a new design, and will use the same hybrid 3D PIV technique to evaluate.

Conclusions: This technique can be used together with 2D PIV to generate a 3D velocity approximation for further analysis. Optimization with additional parameters is planned.

References:

1.Budišić, Marko, and Igor Mezić. "Geometry of the ergodic quotient reveals coherent structures in flows." Physica D: Nonlinear Phenomena 241.15 (2012): 1255-1269.
2.Meinhart, Carl D., Steve T. Wereley, and Juan G. Santiago. "PIV measurements of a microchannel flow." Experiments in fluids 27.5 (1999): 414-419.
3.Morgan, Hywel, and Nicolas G. Green. AC electrokinetics: colloids and nanoparticles. No. 2.Research Studies Press, 2003.