SAND2008-5320C

Multiphase Flow Through Microchannels

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Abstract

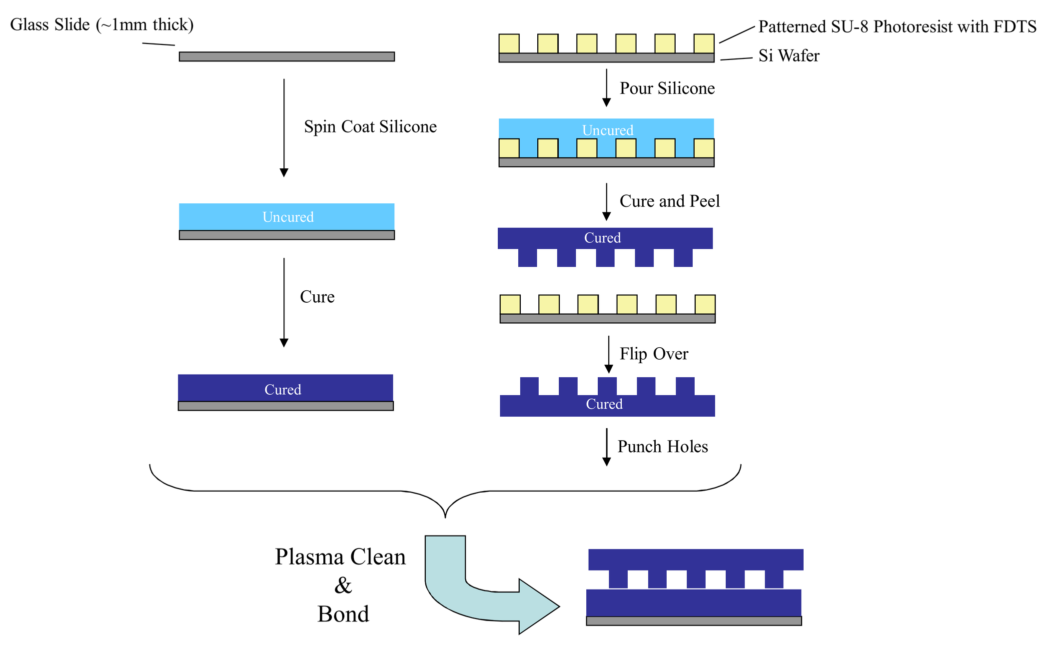
We compare experiments and simulations of multiphase flow behavior as one liquid displaces another in micro-scale geometries. Microfluidic channels with posts partially obstructing the flow path were made with different surface energies to examine how the dynamic contact angle affects multiphase transport in a hydrocarbon-water system. Laser-scanning fluorescence confocal microscopy was used to monitor the interface dynamics while simultaneous pressure measurements were used to measure fluctuations in capillary forces. These results are compared to computational work modeling the wetting line motion using level set-based finite element methods (FEM) for multiphase transport in microchannels. To accurately model the multiphase motion, we use the interfacial tension, equilibrium contact angle, and a Blake model to describe how the contact angle changes with the velocity of the three-phase contact line.

Experiments

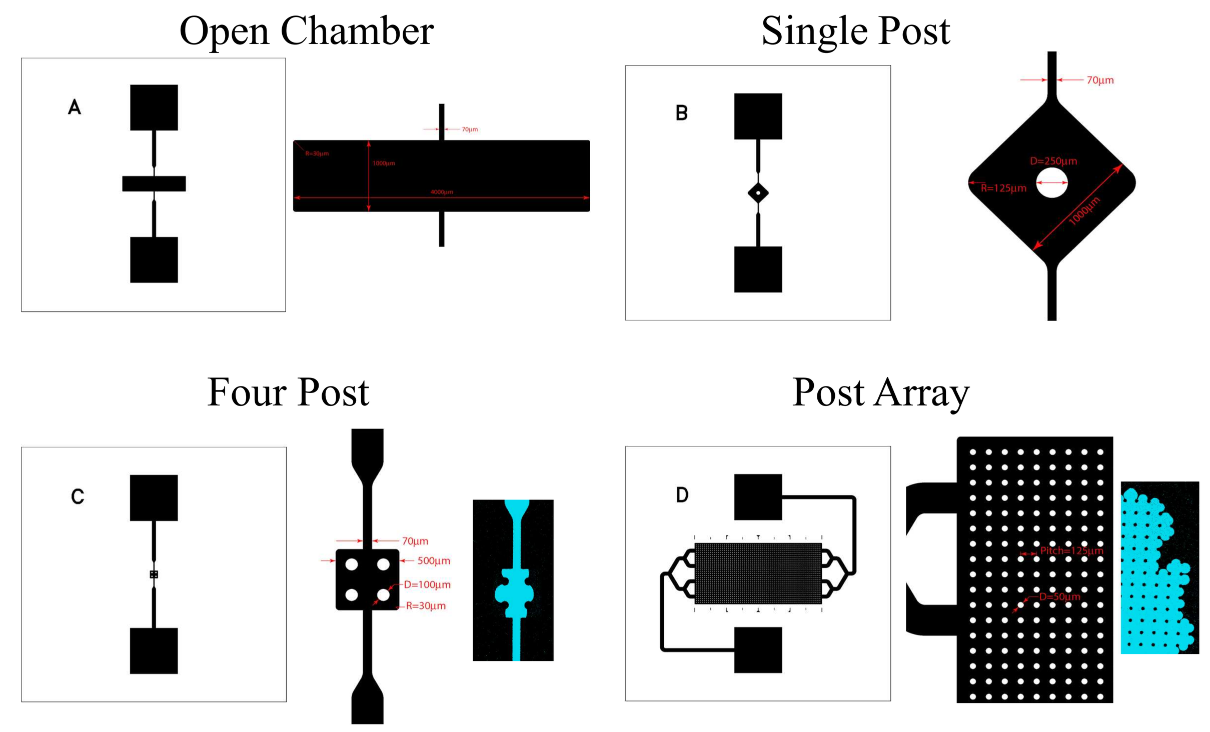
•Interfaces Investigated
- •Water/Air in a silicone elastomer microfluidic device

•Flow Visualization
- •Use a Zeiss LSM510 Meta confocal microscope scanning only in a single plane for image uniformity and maximum frame rate (2 fps, 256x256 resolution)
- •Fluorescent dyes are mixed into the liquids to allow visualization of the interface
- •Water soluble dyes used
  - •Alexa Fluor® 488 (λ_{ex}=495nm/λ_{em}=519nm)
  - •Alexa Fluor® 633 (λ_{ex}=632nm/λ_{em}=647nm)

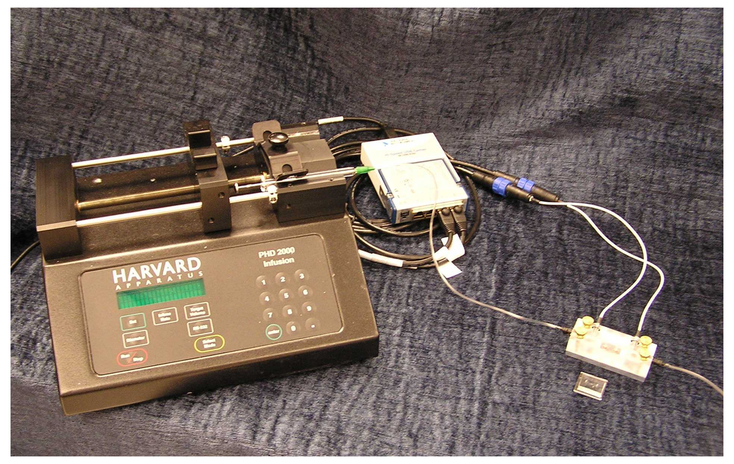
• Fabrication of Microfluidic Devices
- •Sylgard 184 (Silicone Elastomer)
  - •Pattern a Si wafer with SU-8 photoresist using photolithography (30μm thick)
  - •Vapor deposit (heptadecafluoro-1,1,2,2-tetrahydrooctyl)-trichlorosilane (FDTS) onto wafer
  - •Mix Sylgard 184 Elastomer Base + Curing Agent (10:1 parts by weight) and degas in vacuum chamber
  - •Pour Sylgard over mold, degas, and cure
  - •Spin coat Sylgard 184 onto an glass slide to make a cover plate and cure
  - •Punch holes in patterned Sylgard using syringe tip
  - •Plasma clean flat and patterned surfaces using an air plasma (20% O_2)
  - •Press the layers together to bond

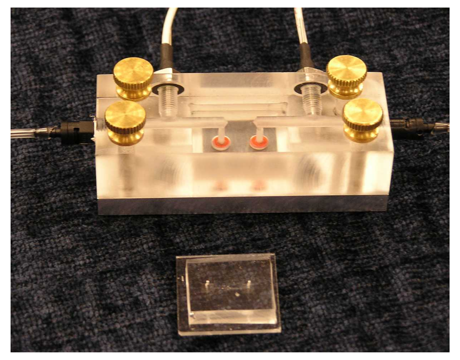


•Microfluidic Channel Designs

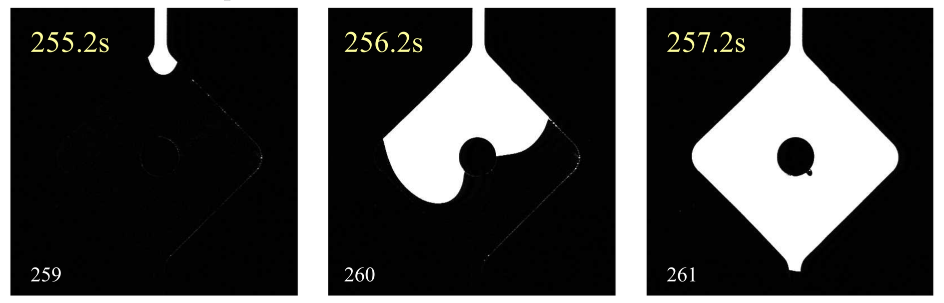


• Test Setup



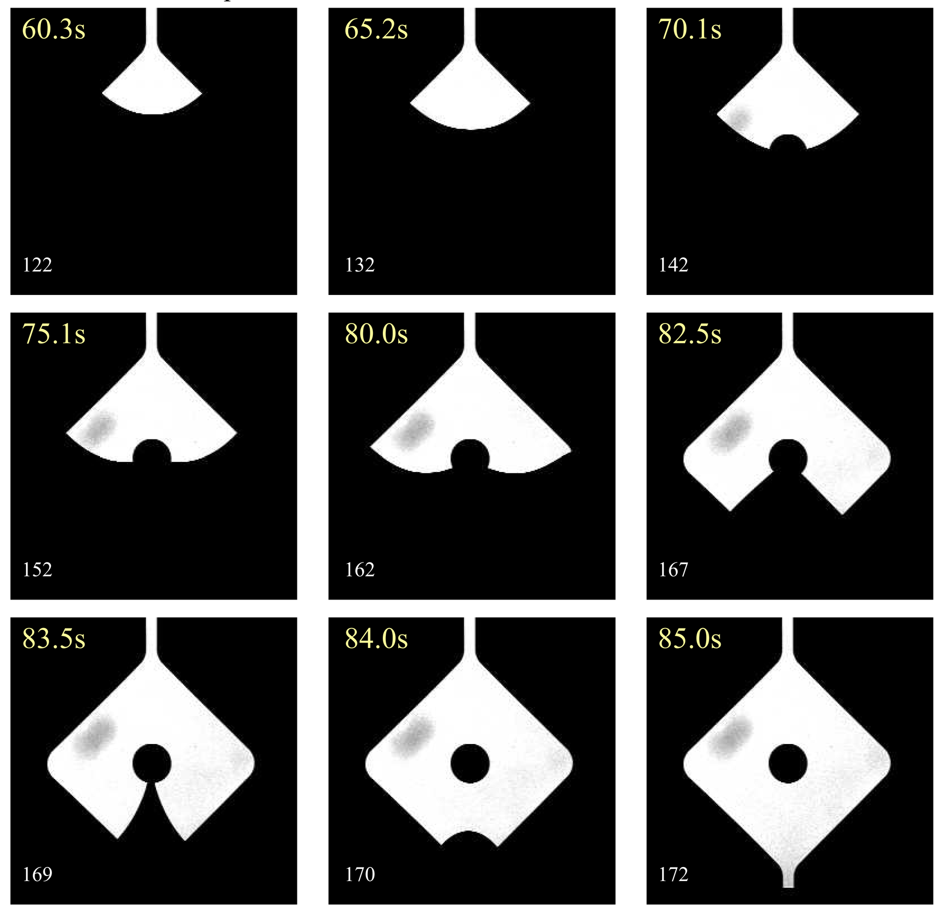


•Results
- • Water (0.1 mg/mL Alexa Fluor® 488) displacing Air [σ_{lv} = 73mN/m ; θ_{equil} = 102º]



Haines jump phenomena – rapid advance of contact line as pressure builds up and and cannot be balanced by interface curvature (Laplace/capillary pressure)

- • Water + 10mM SDS (0.1 mg/mL Alexa Fluor® 488) displacing Air [σ_{lv} = 40mN/m ; θ_{equil} = 69º]



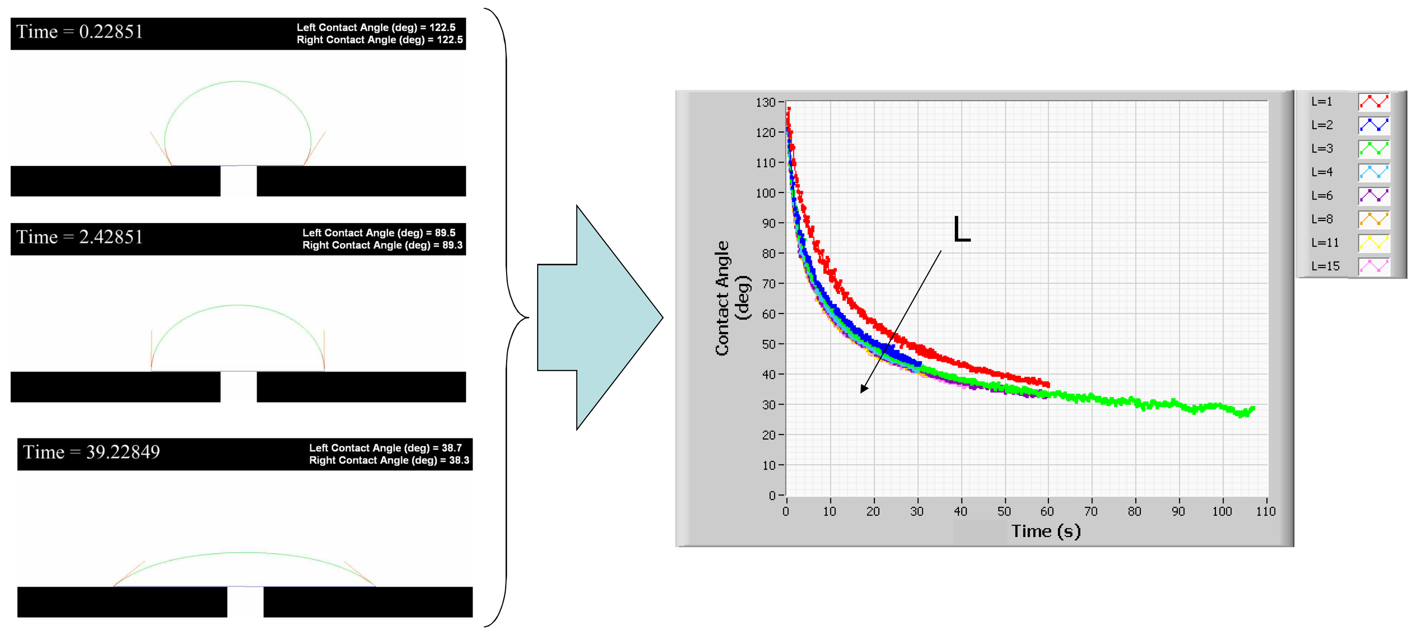
Dynamic Wetting Modeling

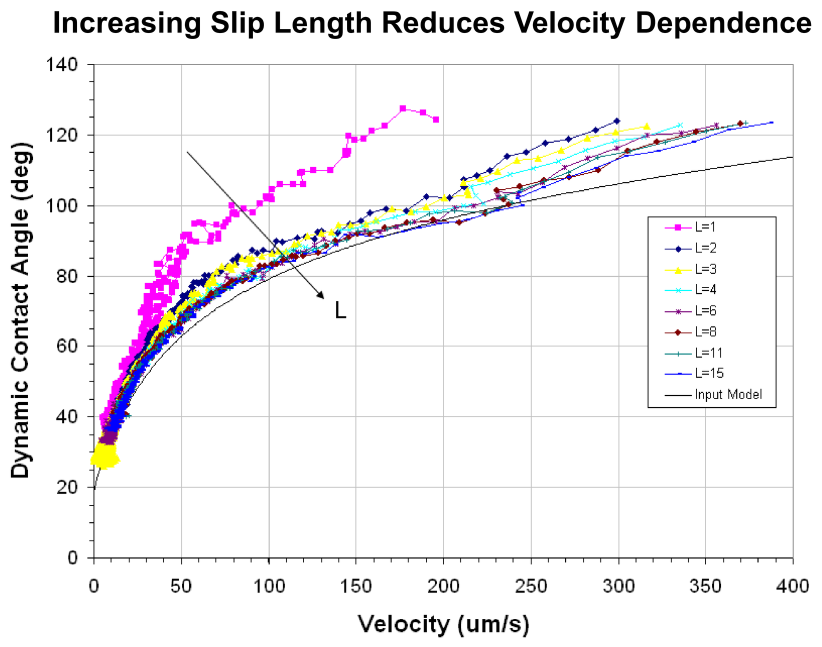
- •Simulated the spreading dynamics of an axi-symmetric drop
- •Used level-set methods to simulate the moving interface
- •Employed a modified Blake wetting model to permit wall slip ($U\neq0$) near the moving contact line

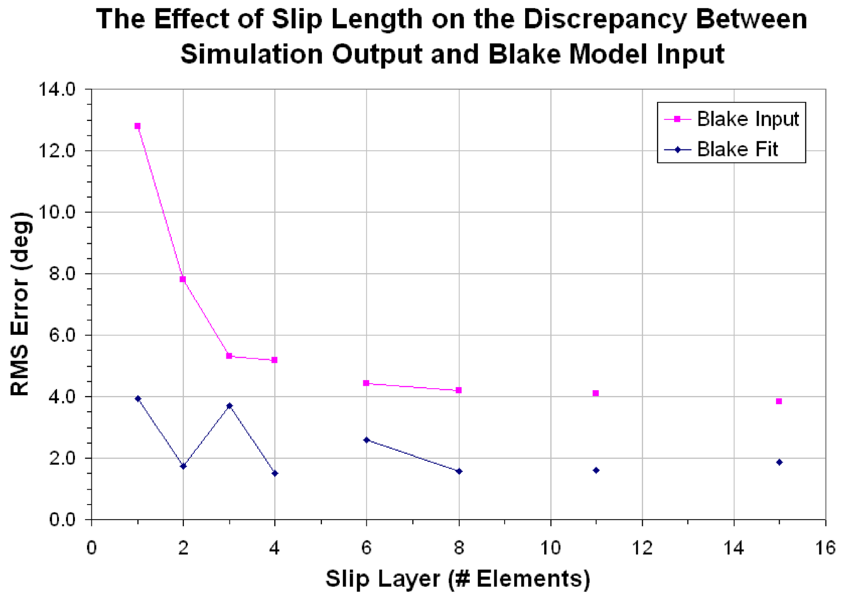
$$U = f(\phi;L)V_W \sinh\left[g\left(\cos\theta_{equil} - \cos\theta\right)\right]$$

$$f(\phi) = \begin{cases} 0 & \text{when } |\phi| > L/2 \\ 1-\dfrac{|\phi|}{L/2} & \text{when } |\phi| \le L/2 \end{cases}$$

- •V_w=36.5μm/s ; g=2.29 ; θ_{equil} = 18.8º
- •μ= 3100 mPa-s; ρ= 1.03 g/mL; σ_{lv}= 21.7 mN/m
- •Number of Elements 3000-5000 (1element = ~66um); 60s of simulation takes ~1 week on a single processor
- •Simulation results of drop spreading are analyzed to measure the contact angle and the contact line velocity



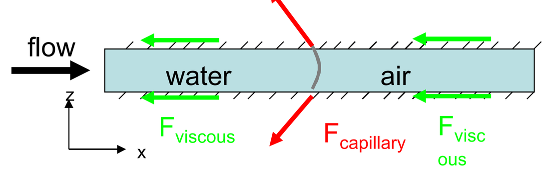




- •Deviation from the input model plateaus at a slip layer length of 6-8 elements
- •Residual error remains that could be due to finite level set width, mesh size, and time step.

Reduced Order Model

- • Microfluidic models are thin and uniform in vertical dimension -> reduce modeling to 2D
- • Include viscous (Poiseuille) and capillary (Blake wetting) effects from vertical dimension



$$F_{viscous} = 12\,\mu\,\bar{u}/\,h\,\Delta A$$

$$F_{capillary} = 2\,\sigma\left(\frac{1}{g}\operatorname{arcsinh}(\bar{u}/v_w) + \cos(\theta_{static})\right)\delta(LS)\Delta A$$

where

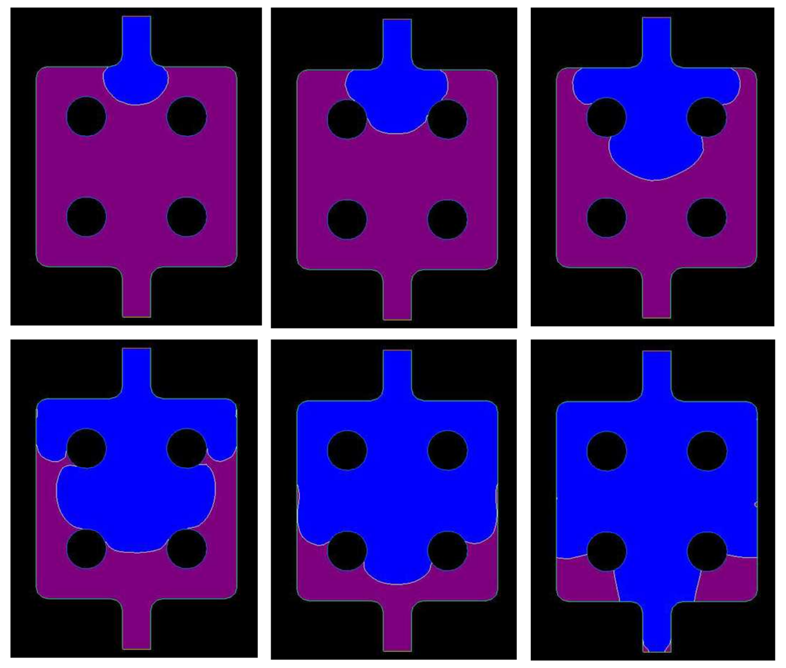
σ is surface tension, μ is viscosity, ΔA is in-plane area element, θ_{static} is static contact angle, $\bar{u}$ is the in-plane velocity, h is the micromodel depth, v_w and g are Blake model parameters, and δ(LS) is a delta function of the level set function.

- • Finite Element Simulation with Level Set Formulation

Water (blue) is injected with constant pressure through upper inlet and displaces air (purple)

Static contact angle is 102º

Breakthrough time is 0.55 seconds



Summary

- Developed an experimental platform to test simulation methods to predict multiphase flows in microchannels
- Microfabricated simple geometries with posts for "trapping" the receeding phase
- Determined the diffuse length scale for slip to obtain self-consistency in level-set predictions of axi-symmetric drop spreading
- Developed a reduced order model for that is excellent at predicting multiphase flows through 2D geometries

Future Work

- Investigate water/decane flows and devices made of different materials (e.g. SU-8, glass)
- Acquire simultaneous pressure data
- Sharpen interface prediction using level-set methods
- Attempt simulation of more complex geometries/channel networks (e.g. post array)

Acknowledgements

We would like to thank Andy Kraynik for assistance with the dynamic wetting modeling, Mike Hickner for discussions on experiments, and Anubhav Tripathi for suggestions on the SU-8 replication process.

This work was funded as part of Sandia's Laboratory Directed Research and Development (LDRD) program

NNSA National Nuclear Security Administration

Sandia is a multiprogram laboratory operated by Sandia Corporation, a LockheedMartin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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