Research Summary

COLOR-GRADIENT LATTICE BOLTZMANN MODEL FOR 3D MULTIPHASE FLOWS WITH DENSITY RATIOS

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Introduction: Reservoir vs. Pore Level Simulation

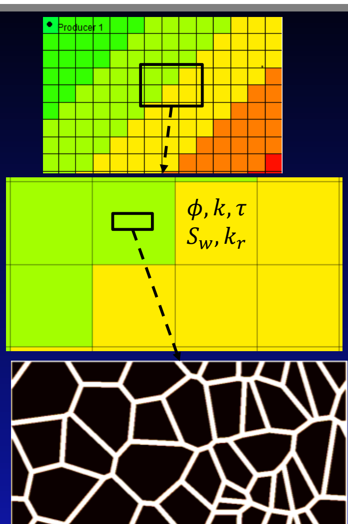


Figure 1—Illustration of the reservoir vs. pore level simulations

Reservoir Simulation

- Based on Darcy's Law
- Multiphase flows are simulated using relative permeability function
- Does not provide details on the dynamic of fluid inside pores

Pore Scale Simulation

- Can capture the complexity of pores
- More flexible in controlling the properties than experiments
- Can provide better information on physics of flow

Pore Level Direct Numerical Simulation

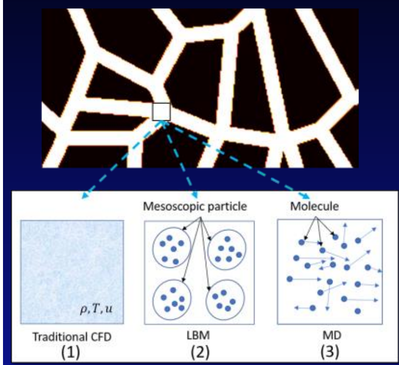


Figure 2—Schematic of different direct numerical simulation methods

No	Methods	Description
1	Traditional Computational Fluid Dynamic (CFD)	• Assume the fluid as continuum • Solve discretized classical fluid flow equations • Often need to handle implicit matrix operations
2	**Lattice Boltzmann (LB)**	• Assume the fluid as a group of molecules with different velocities • Simulate the evolution of the molecular velocity distribution through time • Explicit in time and easier to parallelize
3	Molecular Dynamic (MD)	• Focuses on motions of many molecules • Most realistic but incurs very high computational cost

Objectives and Methods

Objective

- To derive a **3D color-gradient lattice Boltzmann** method that can handle fluid flows with **density ratios**

Method

- Take moments of designed LB evolution equations and show that they recover 1) continuity equation, and 2) Navier-Stokes equations

Model Development

- Original Color Gradient Model (Gunstensen et al. 1991; Latva-Kokko & Rothman 2005; Reis & Phillips 2007) contains errors in simulating flows with density ratios
- More recent developments (Ba et al. 2016) modified the evolution equations to accommodate density ratios and better recovered Navier-Stokes equations
- However the work was 2D

Validation Case: Flows between Parallel Plates

- Validate model's ability to simulate flows with two fluids of different densities and viscosities
- The new model demonstrated very good agreement with the analytical solutions

Flow direction

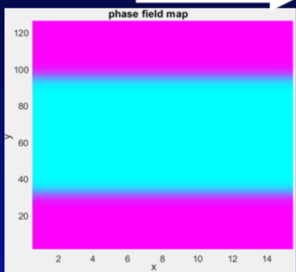


Figure 3—Setup for layered flows between two parallel plates. A body force moves the fluids from left to right. The blue fluid is placed at the center

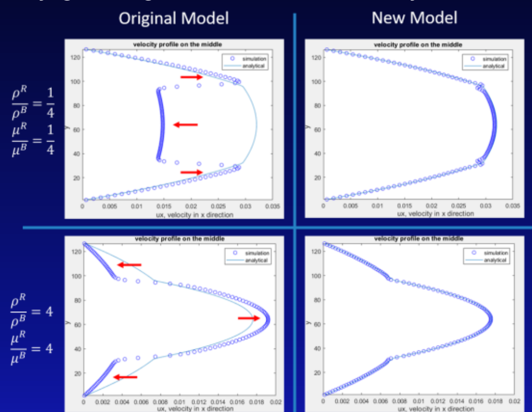
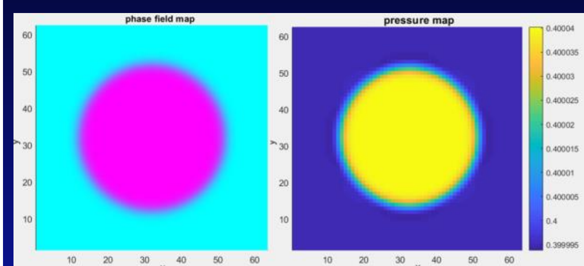


Figure 4—Velocity profiles from the original model and the new model compared with analytical solutions

Validation Case: Static Droplet Test

- Verify that the new model has an interfacial tension that satisfies the Young-Laplace equation
- In 3D, the pressure difference across the surface of a spherical droplet is

$$\Delta p = \frac{2\sigma}{R}$$



(a) (b)

Figure 5—Result of a static single droplet case. The figures show (a) saturation map and (b) pressure map through the center of the droplet.

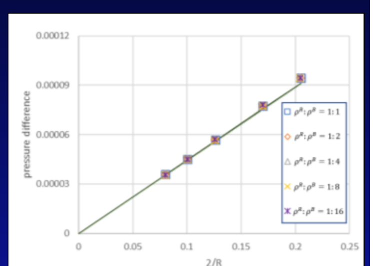


Figure 6—Pressure difference ΔP vs .2/R. The slope is the simulated interfacial tension. Different symbols and colors present different density ratios.

Simulation in a Microfluidic Porous Medium

Fluid 1 (Oil) Fluid 2 (Gas)

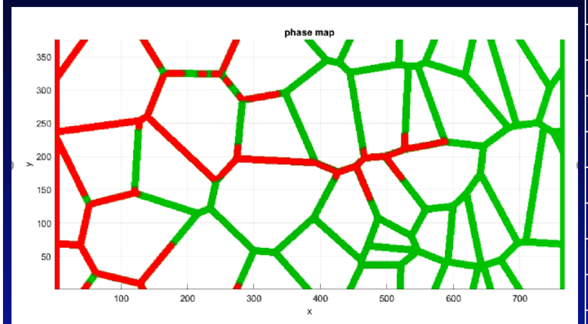
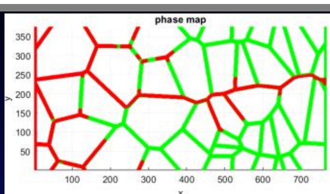


Table 1—Simulation's Parameters

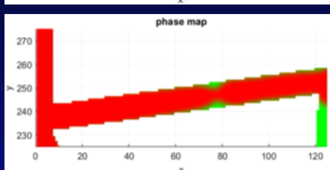
Parameter	Values	
	LBM units	Real units
Length, x	768	640 μm
Width, y	376	313 μm
Thickness, z	12	10 μm
Density ratio	5.2	
Viscosity ratio	23.2	
Porosity, ϕ	23%	
Wetting angle, θ	143° oil wet	
Permeability, k	0.5322	370 mD
Total timesteps	640,000	0.44 s
Simulation Time	8.6 days	

Hydrodynamic Phenomena



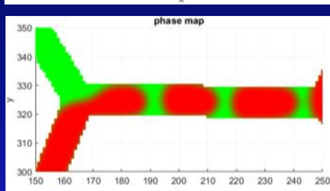
Gas Channeling

- It causes accelerated gas velocities inside the channels
- It occurs because of high viscosity ratio between two phases



Plateau-Rayleigh Instability

- Formation of a neck that cuts the gas phase into two separate fluid body



Flow Segmentation

- Formation of fluid segments at Y-junctions
- The length of segments was controlled by the velocities of channels in the junctions

Conclusions

- The newly developed 3D color-gradient lattice Boltzmann model can correctly simulate fluid flows with density ratios
- It was validated with several cases with known analytical solutions
- We simulated two-phase fluid flows in a simple porous medium and captured several interesting hydrodynamic phenomena
- Improving parallel computing efficiency on the algorithm is suggested to improve the model's capability to simulate larger problems