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Lattice Boltzmann simulation of cavitating flow in a moving geometry

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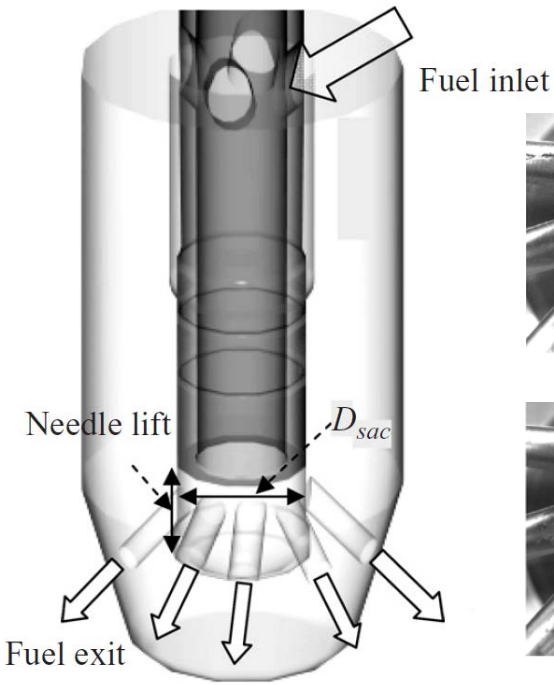
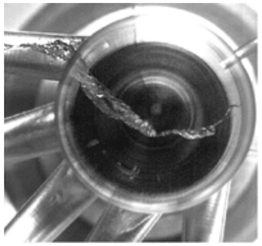
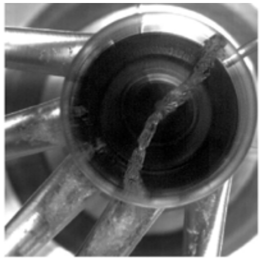
Background and Motivation

● Engineering need and Convention methods' difficulty







•Diesel Injector
(A. Andriotis, M. Gavaises and C. Arcoumanis, 2008)

● Engineering Need

- Key component of diesel engine
- Great affect fuel spray development and spray combustion performance

● A puzzle for traditional method

- Experiment
- Harsh test condition: small scale (0.1-0.2mm), high pressure (up to 1800 bar), short switch intervals (within a few milliseconds)
- Numerical simulation
- Challenge and limited due to cavitating flow and moving needle

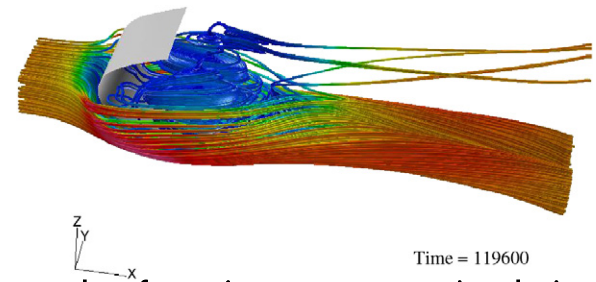
Background and Motivation

● Lattice Boltzmann method (LBM)

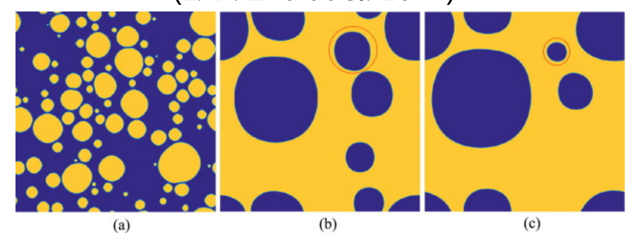
$$f_i(\mathbf{x}+\mathbf{e}_i\delta t, t+\delta t) - f_i(\mathbf{x},t) = -\frac{\delta t}{\tau}\left[f_i(\mathbf{x},t) - f_i^{eq}(\mathbf{x},t)\right] + \left(1-\frac{1}{2\tau}\right)F_i(\mathbf{x},t)\delta t$$

$$f_i^{eq} = \omega_i \rho\left(1+\frac{\mathbf{u}\cdot\mathbf{e}_i}{c_s^2}+\frac{(\mathbf{u}\cdot\mathbf{e}_i)^2}{2c_s^4}-\frac{\mathbf{u}\cdot\mathbf{u}}{2c_s^2}\right)$$

$$\rho = \sum_i f_i \quad \rho\mathbf{u} = \sum_i f_i\mathbf{e}_i + \frac{\mathbf{F}\delta t}{2} \quad \nu = (\tau-0.5)c_s^2\delta t$$



•Example of moving geometry simulation
(L. D. Zhu at el. 2011)



•Example of multiphase flow simulation
(W. Gong at el. 2018)

- An alternative numerical scheme based on mesoscopic fluid dynamics
- Simple scheme, easement of dealing with complex geometry and convenience of parallel computing
- A promising method to deal with multiphase flow and moving geometry

How to deal with moving geometry

No-slip treatment at boundary

- Bounce-back scheme and Immersed boundary method

- Step1: velocity u on the Eulerian grid interpolated to Lagrangian grid

$$\mathbf{U}(\mathbf{X}) = \sum_{\mathbf{x}} \mathbf{u}(\mathbf{x})\delta_h(\mathbf{x}-\mathbf{X})h^3 \qquad \delta_h = \frac{1}{h^2}\phi\left(\frac{x}{h}\right)\phi\left(\frac{y}{h}\right)$$

- Step2: Calculate boundary force in Lagrangian grid

$$\mathbf{F_b}(\mathbf{X}) = \frac{\mathbf{U_b}(\mathbf{X}) - \mathbf{U}(\mathbf{X})}{\delta t}$$

- Step3: Distribute back the force on to Eulerian grid

$$\mathbf{f_b}(\mathbf{x}) = \sum_{X} \mathbf{F_b}(\mathbf{X})\delta_h(\mathbf{x}-\mathbf{X})\Delta V$$

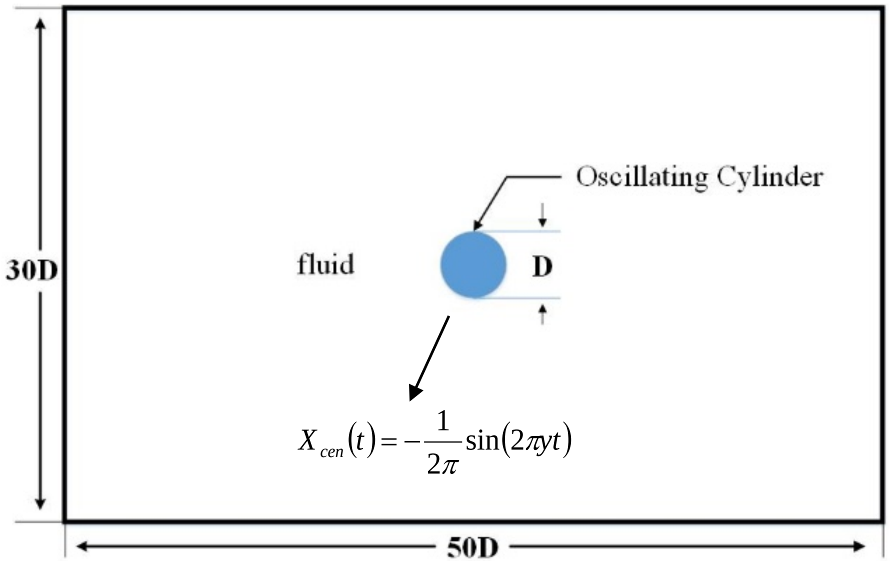
- Step4: Compute the uncorrected velocity, perform LBM, obtain the updated velocity

$$\mathbf{u_n} = \frac{\sum_i f_i \mathbf{e_i}}{\rho} \qquad \mathbf{u_{n+1}}(\mathbf{x}) = \mathbf{u_n}(\mathbf{x}) + \frac{\mathbf{f_b}(\mathbf{x})\delta t}{2\rho}$$

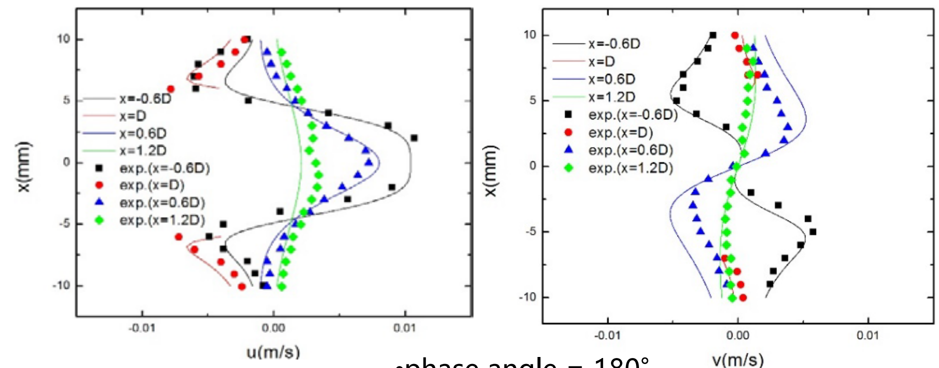
- Step5: update the position of object and perform the next cycle

How to deal with moving geometry

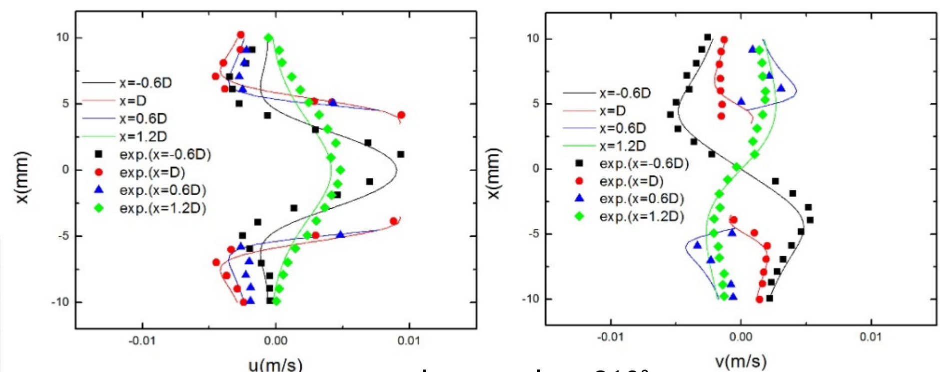
- **Oscillating Cylinder Simulation using immersed boundary method**



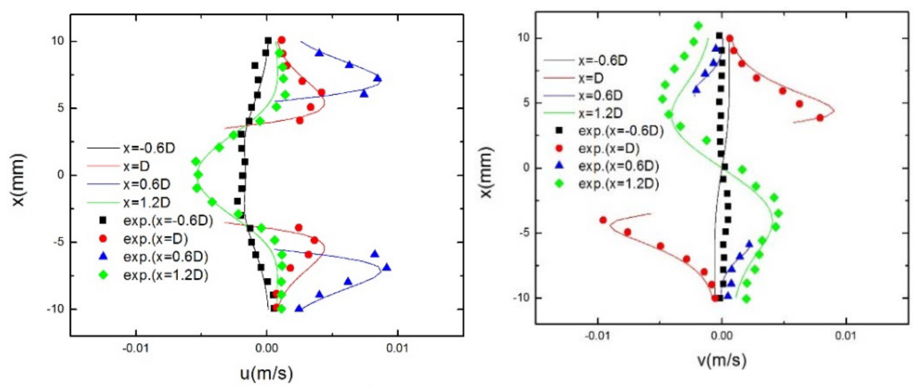
•Experiment by DüTSCH at al, 1998



•phase angle = 180°



•phase angle = 210°



•phase angle = 330°

- Similar moving algorithm with real needle
- 2D simulation, D=25Δx, Grid independent test completed, Neumann boundary Condition (i.e. zero velocity gradient) at all boundary

How to deal with Cavitating flow

● Shan-Chen multiphase model for single-component fluid

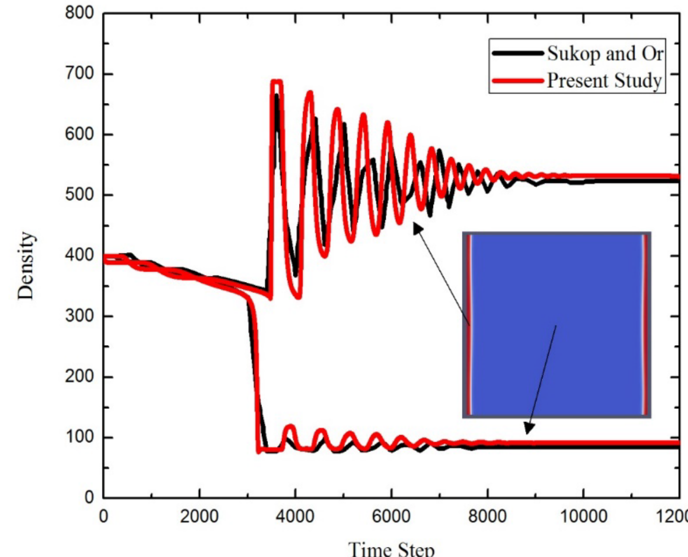
$$\mathbf{F}^{SC}(\mathbf{x},t) = -\psi(\rho) G \sum_i \omega_i \psi(\mathbf{x}+\mathbf{e}_i \delta t)\mathbf{e}_i \delta t$$

$$\psi(\rho) = \rho_0 (1-\exp(-\rho/\rho_0)) \qquad \psi(\rho) = \psi_0 \exp(-\rho/\rho_0)$$

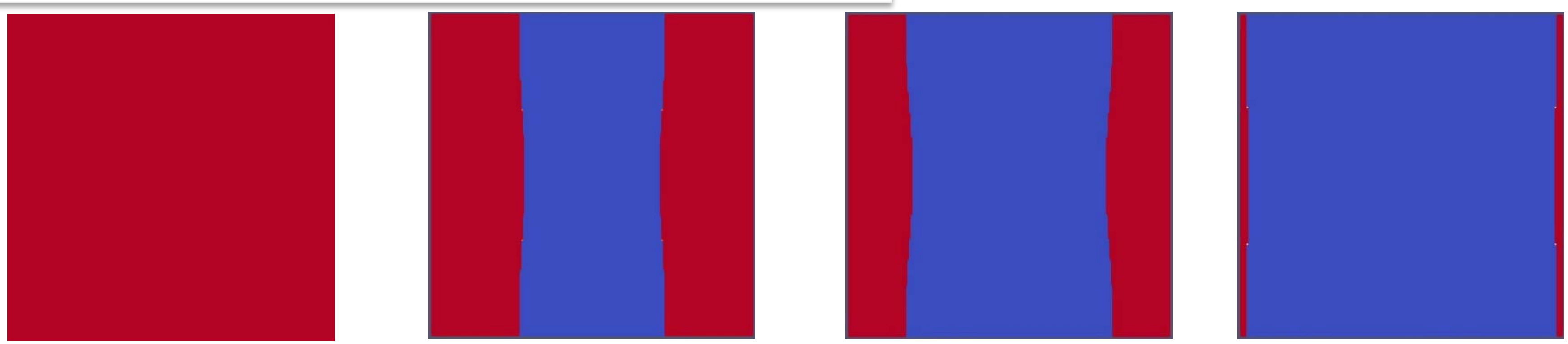
$$\mathbf{F}^{SC}(\mathbf{x},t) = -G\psi(\rho)\left(c_s^2 \delta t^2 \nabla \psi(\rho) + \frac{c_s^4 \delta t^4}{2} \nabla \Delta \psi(\rho)\right)$$

$$p = \rho c_s^2 + \frac{G c_s^2 \delta t^2}{2} \psi^2(\rho)$$

- 200Δx×200Δx domain
- Periodic boundaries at the top and bottom
- Constant normal outflow velocity (0.005) boundary at left and right
- Initial density of 400 and viscosity set to be 0.25



•Density variations at two monitored locations (100,100 and 1,100)

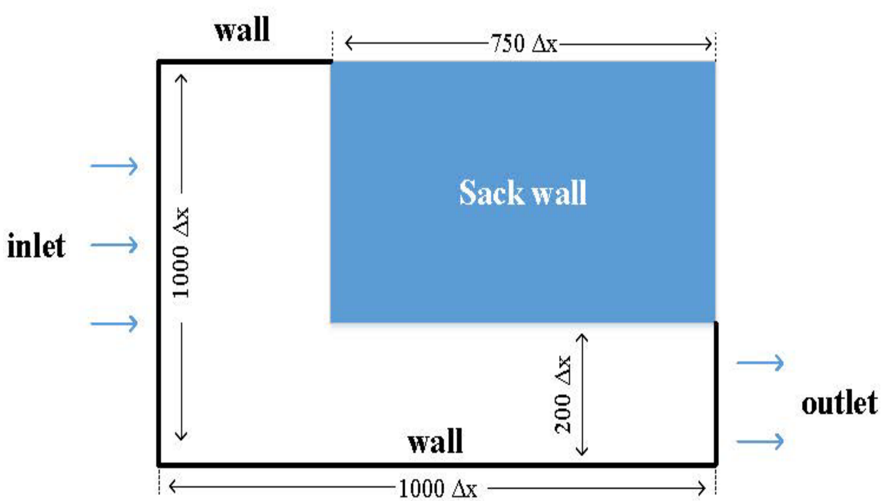


•t=0 •t=3500 •t=6500 •t=12000

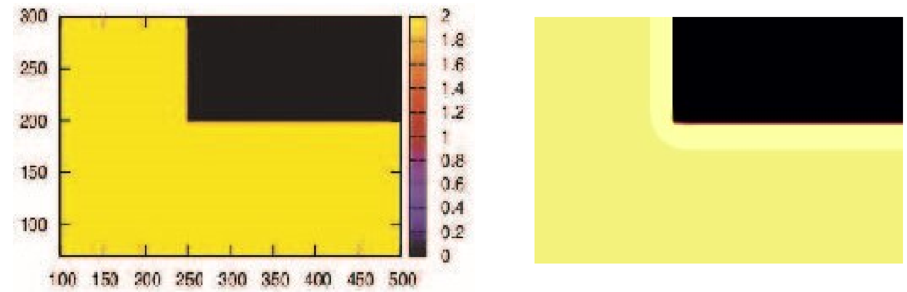
•Two-phase condition at different time

How to deal with Cavitating flow

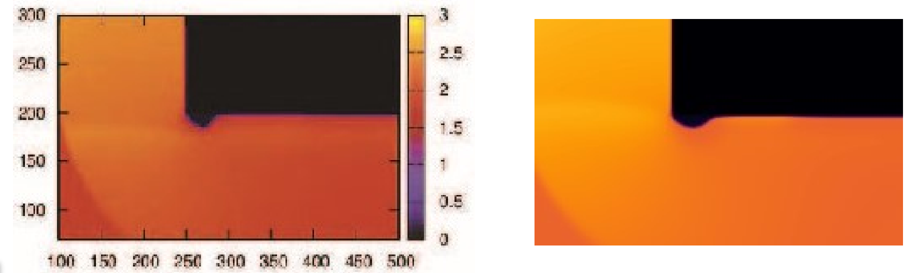
● Shan-Chen multiphase model for single-component fluid



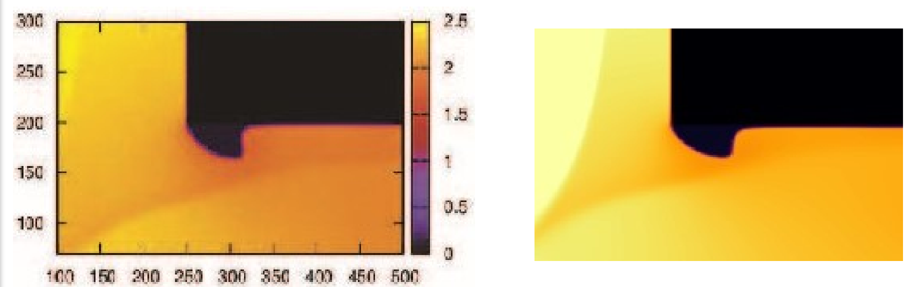
- Numerical results by G. Falcucci at al. 2013. First known flow-induced cavitation in model injector using LBM.
- Velocity inlet boundary condition 0.13, Neumann boundary condition at outlet, bounce-back Scheme at all wall.
- Initial value: 0.13 for velocity (same value of inlet), 1.92 for density (density value of liquid)



•t=50



•t=500



•t=1000

•Density-contour comparisons at t = 50, 500 and 1000 between G. Falcucci at al the present study (right)

Ongoing and future work

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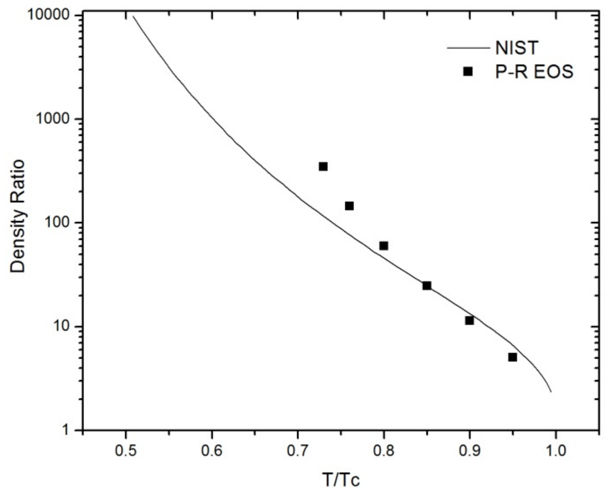
● Shan-Chen model's improvement

- Incorporate the real gas Equation of state (Peng-Robinson or Carnahan-Starling) to Original Shan-Chen model
- Adopt the Exact Different Method for the Force term (Kupershtokh at al. 2009)

→ **Promote density ratio limitation from $O(10)$ to $O(10^3)$**

- Multiple-relaxation-time (MRT) principle for high Reynolds number flow
- Combine immersed boundary method, modified Shan-Chen model and MRT into LBM code



•Density ratio promoted from $O(10)$ to $O(10^2)$ after incorporated P-R Equation of State

Summary

1 Overall aim: to develop LBM for investigating internal-flow dynamics in fuel spray injectors and spraying devices.

2 First-stage study:

(1) Immersed boundary method + LBM: validation on an oscillating-cylinder case;

(2) Shan-Chen model in LBM: validation on

(i) Spinodal decomposition;

(ii) Cavitating flow in a model nozzle.

3 Planned future work:

(1) Further development of Shan-Chen model for more realistic engineering flow conditions;

(2) Immersed boundary method + Shen-Chen model in LBM.

4 More details in

T.P. Luo, J.X. Zhang, J. Xia*,
Y.W. Liu, R.M. Liu, S.F. Yang, H. Zhao:
Towards lattice Boltzmann simulation of flow dynamics inside a model fuel injector: a first-stage study,
ILASS–Europe 2019, 29th Conference on Liquid Atomization and Spray Systems, 2-4 September 2019, Paris, France.