SCEJ 89th Annual Meeting
Mar. 19, 2024

Rheological properties of slurry in microfluidic channels
-A direct numerical simulation analysis-

マイクロ流路におけるスラリーのレオロジー特性
–直接数値シミュレーションによる解析–

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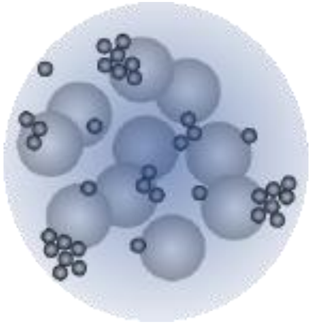
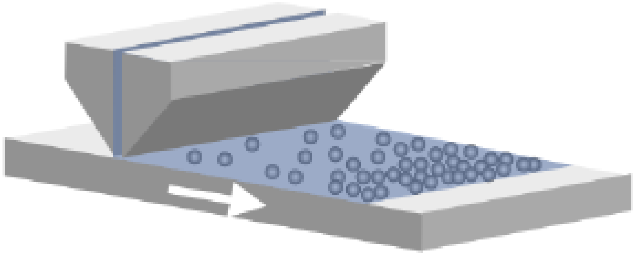
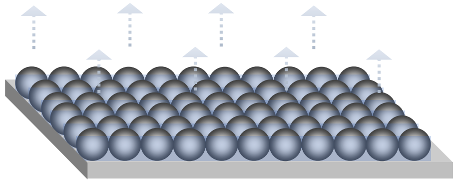
Material fabrication from suspensions



Dispersing



Coating



Drying

Slurry

Functional materials

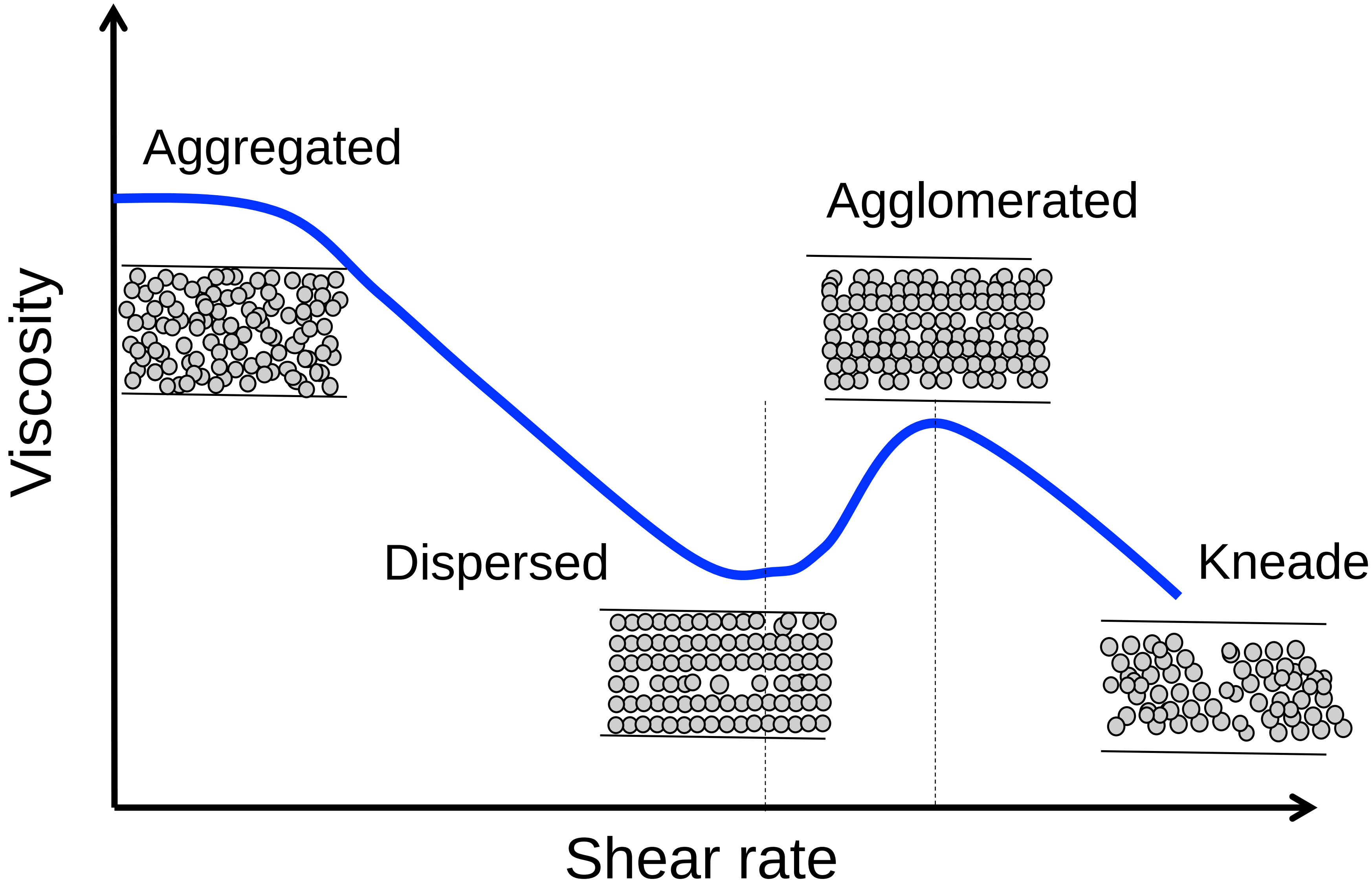
Electrode

Ceramics

Rheological properties

Viscosity vs. **shear rate**

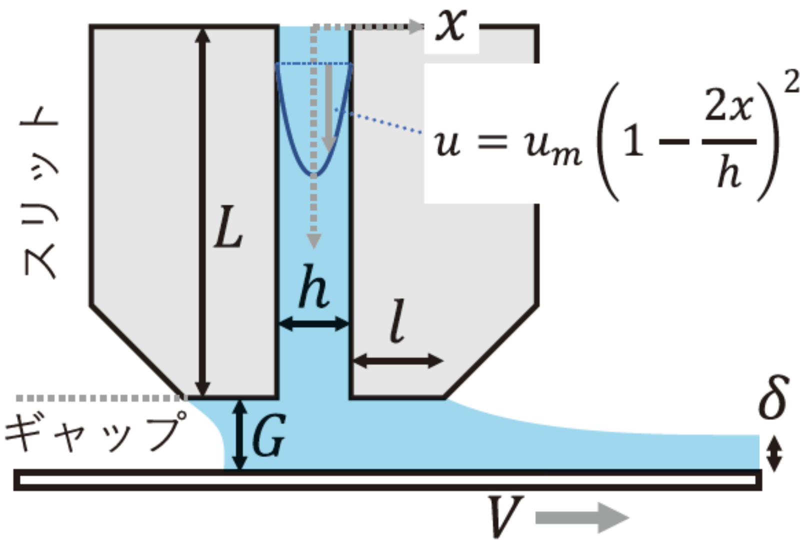
Shear thinning/thickening



山口 由岐夫 「ものづくりの化学工学」, 丸善 (2015).

Microfluidic flow of slurry

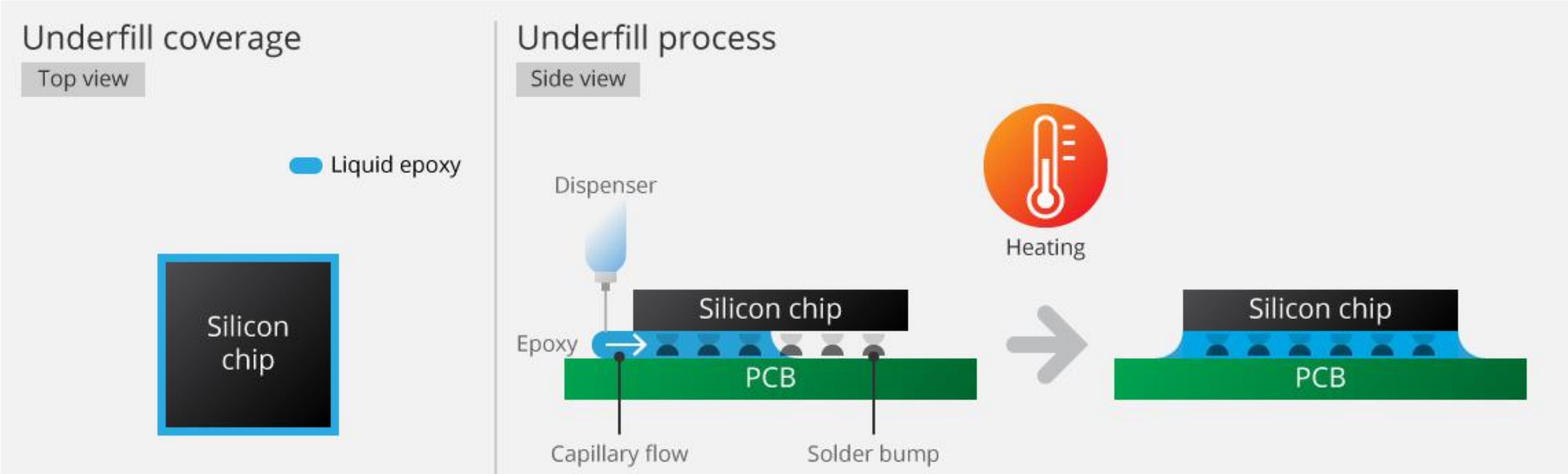
Coating



Slot die coater

菰田 悦之, 化学工学 86(1), (2024).

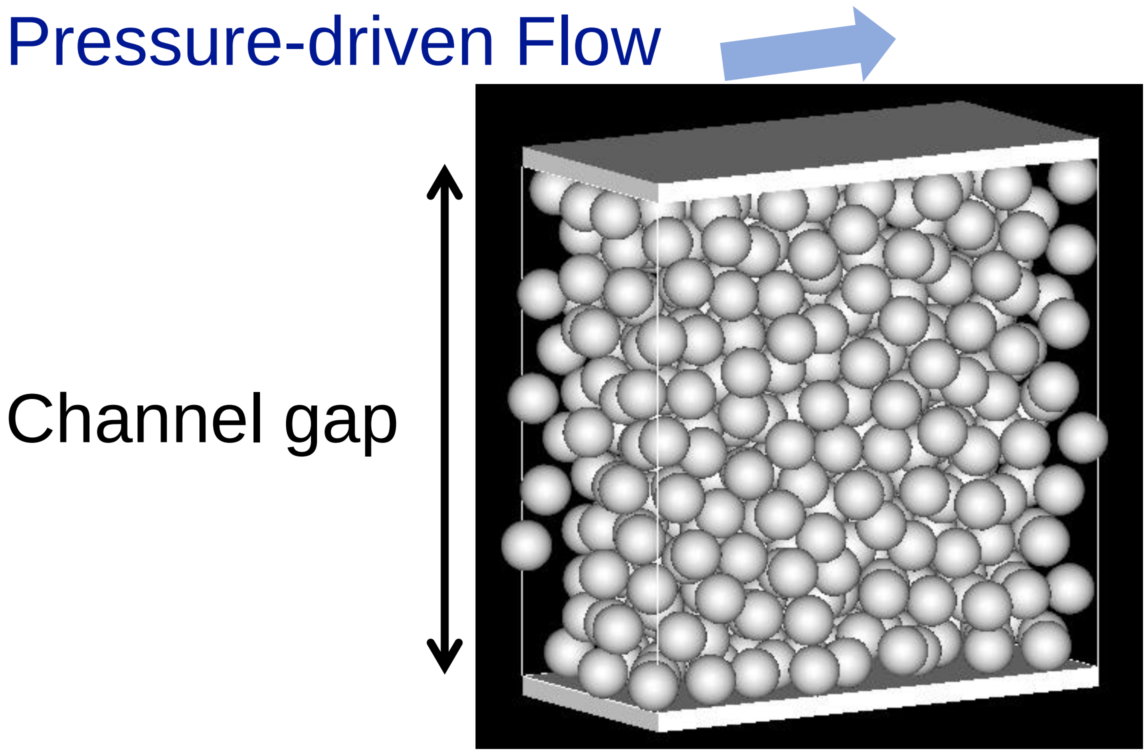
Underfilling

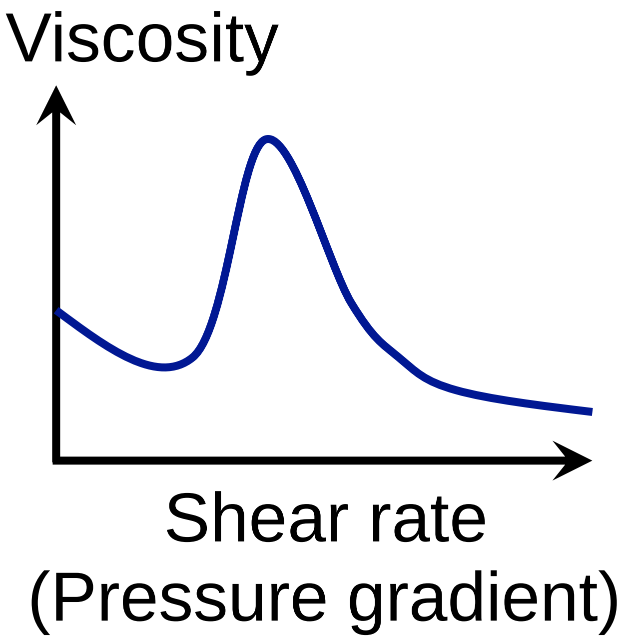


https://www.transcend-info.com/embedded/technology/underfill

Objective & Method

- Investigating the effects of channel gap on the rheological properties of slurry
- Direct numerical simulation analyzing coupled motions of particles and fluid





Equations

Particles

Inter-particle force

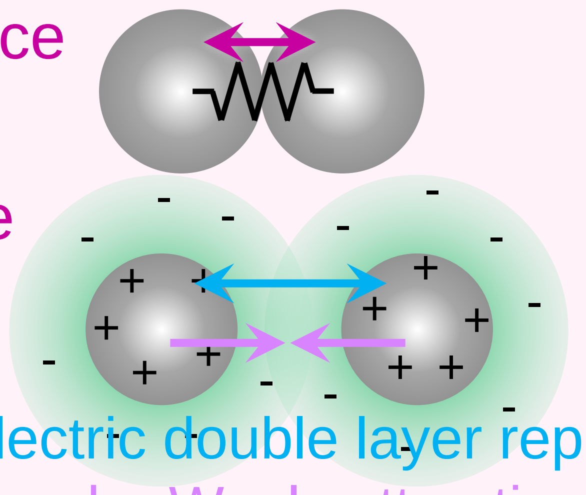
$$M\dot{\boldsymbol{V}} = \boldsymbol{F}^{\mathrm{H}} + \boldsymbol{F}^{\mathrm{P}}$$

$$I\dot{\boldsymbol{\Omega}} = \boldsymbol{N}^{\mathrm{H}}$$

Hydrodynamic force/torque

Contact force

DLVO force



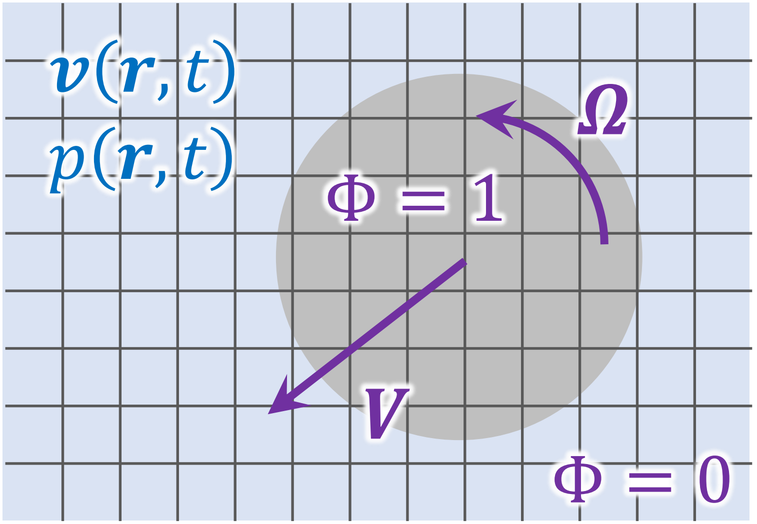
Fluid flow: Navier–Stokes equations

$$\nabla \cdot \boldsymbol{v} = 0$$

$$\rho(\partial_t \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \boldsymbol{v}) = \nabla \cdot \boldsymbol{\sigma} + \Phi \boldsymbol{f}_{\mathrm{P}}$$

$$\boldsymbol{\sigma} = -p\boldsymbol{I} + \eta[\nabla \boldsymbol{v} + (\nabla \boldsymbol{v})^{\top}]$$

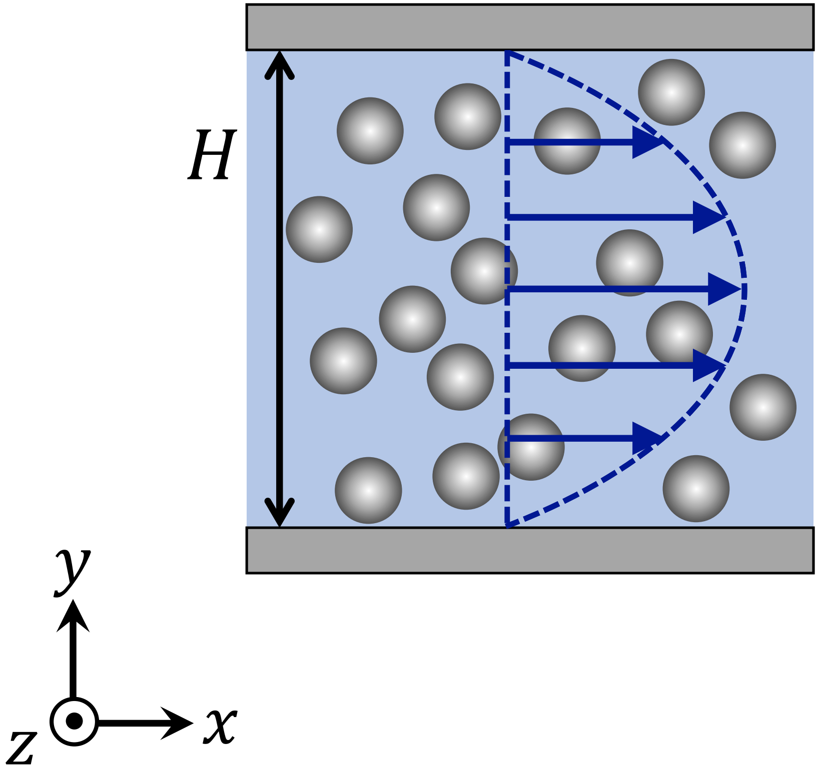
Imposition of velocity in particle domains



Indicator function : $\Phi(\boldsymbol{r}, t)$

Evaluation of viscosity

Pressure-driven channel flow



Relative viscosity $\frac{\eta}{\eta_0} = \frac{\bar{u}_0}{\bar{u}}$

Plane Poiseuille flow
(without particles)

$$\bar{u}_0 = \frac{H^2 P_{\mathrm{g}}}{12\eta_0}$$

Mean flow rate: $\bar{u}$

Pressure gradient: P_{g}

Viscosity of host fluid: η_0

Simulation conditions

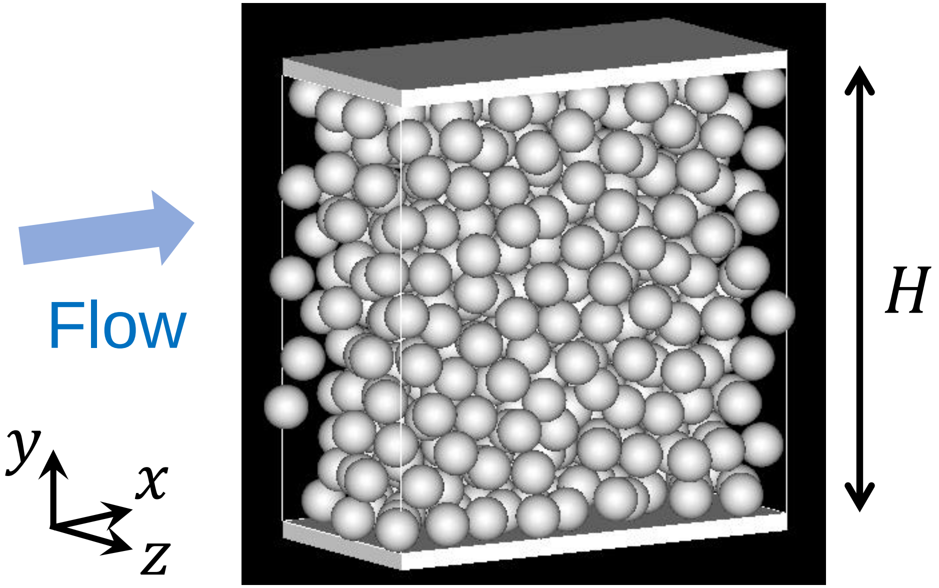
Particles

- Diameter: $d = 1\ \mu\mathrm{m}$
- Concentration: $45\ \mathrm{vol\%}$
- Zeta potential: $-12\ \mathrm{mV}$
- Hamaker constant: $2 \times 10^{-20}\ \mathrm{J}$

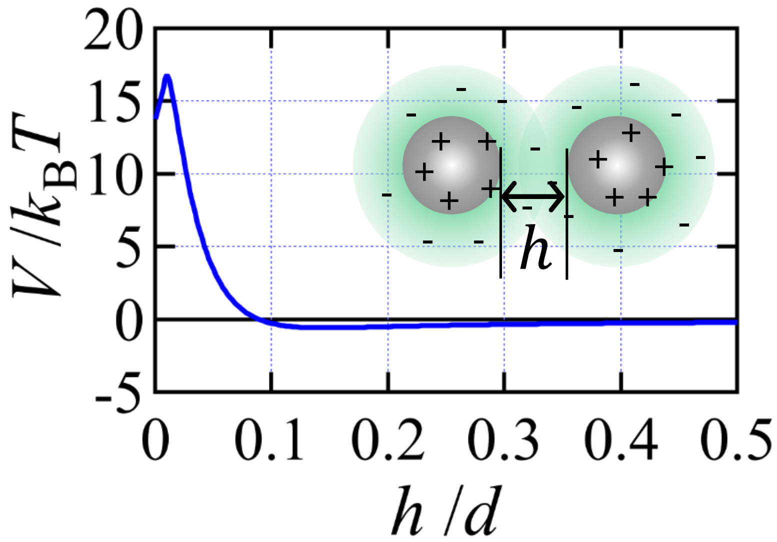
Fluid: Water

- Ion concentration: $0.31\ \mathrm{mM}$

System size: $10d \times H \times 5d$



DLVO potential



Varied parameters

- Channel gap: $H = 5d, 10d, 20d$
- Shear rate: $\dot{\gamma}\tau = 10^{-2} - 10^{1}$

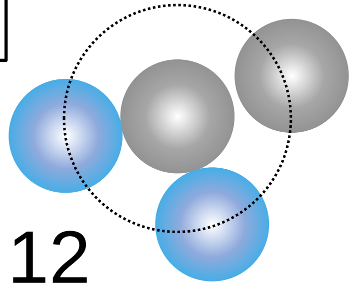
$$\dot{\gamma} = \frac{\bar{u}_0}{H} = \frac{HP_g}{12\eta_0}$$

Pressure gradient: P_g

Viscosity of host fluid: η_0

Effects of shear rate

$H = 10d$

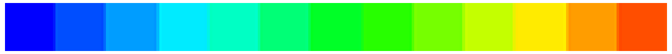


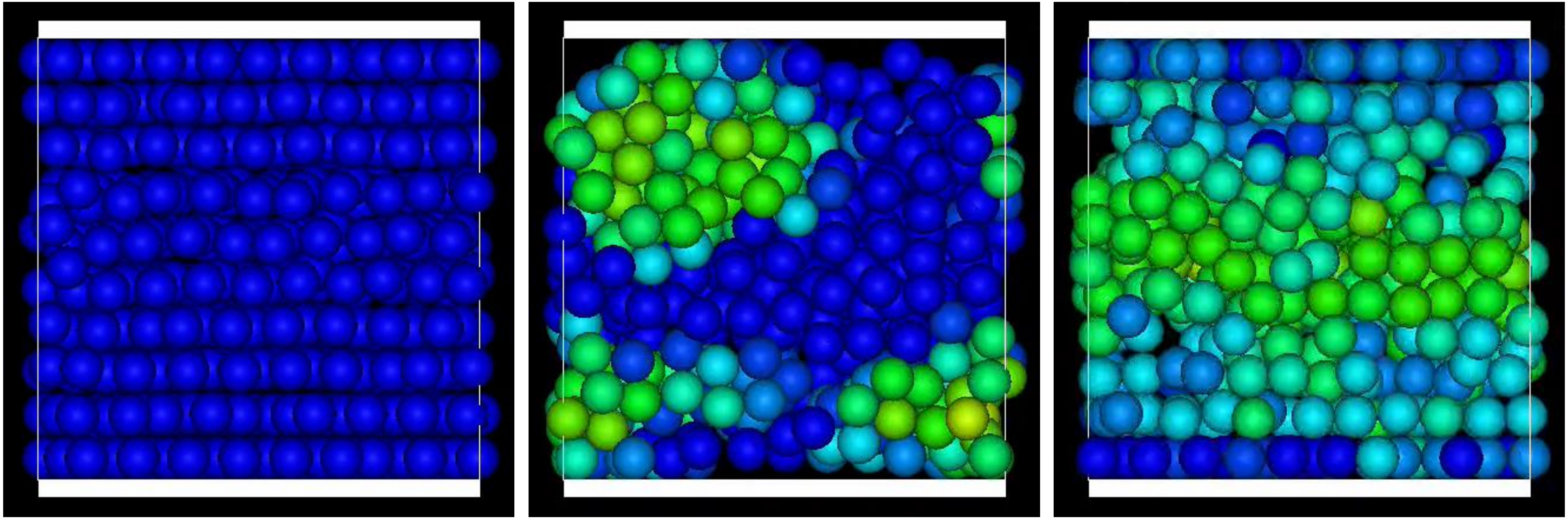
Characteristic time

$$\tau = \frac{d}{U} = \frac{3\pi\eta d^2}{F} \quad \leftarrow 3\pi\eta dU = F$$

Drag = Adhesion force

Contact number

0  12

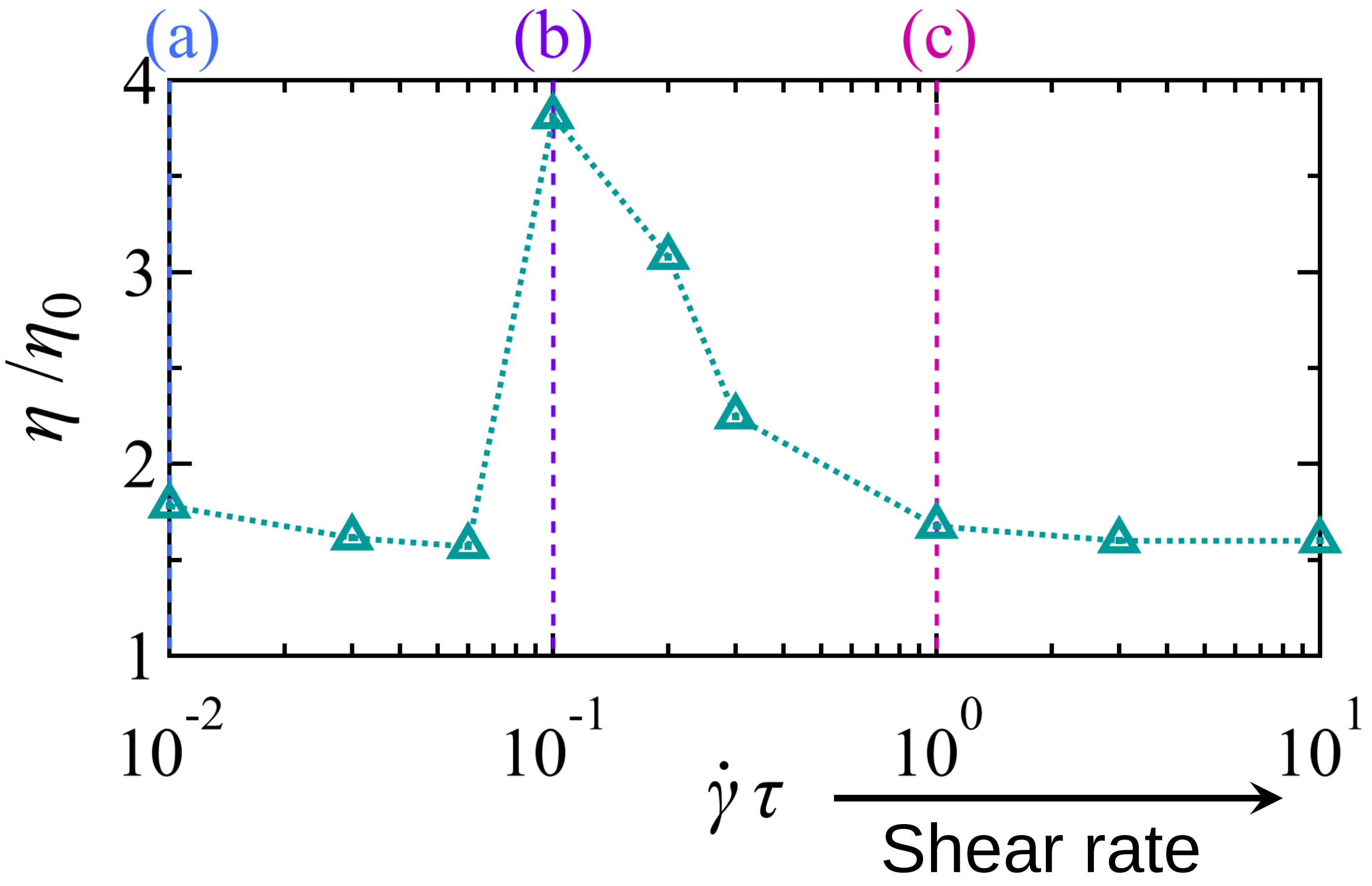


(a) $\dot{\gamma}\tau = 0.01$ (b) $\dot{\gamma}\tau = 0.1$ (c) $\dot{\gamma}\tau = 1$

Up to $\dot{\gamma}t = 50$

→ Shear rate

Viscosity

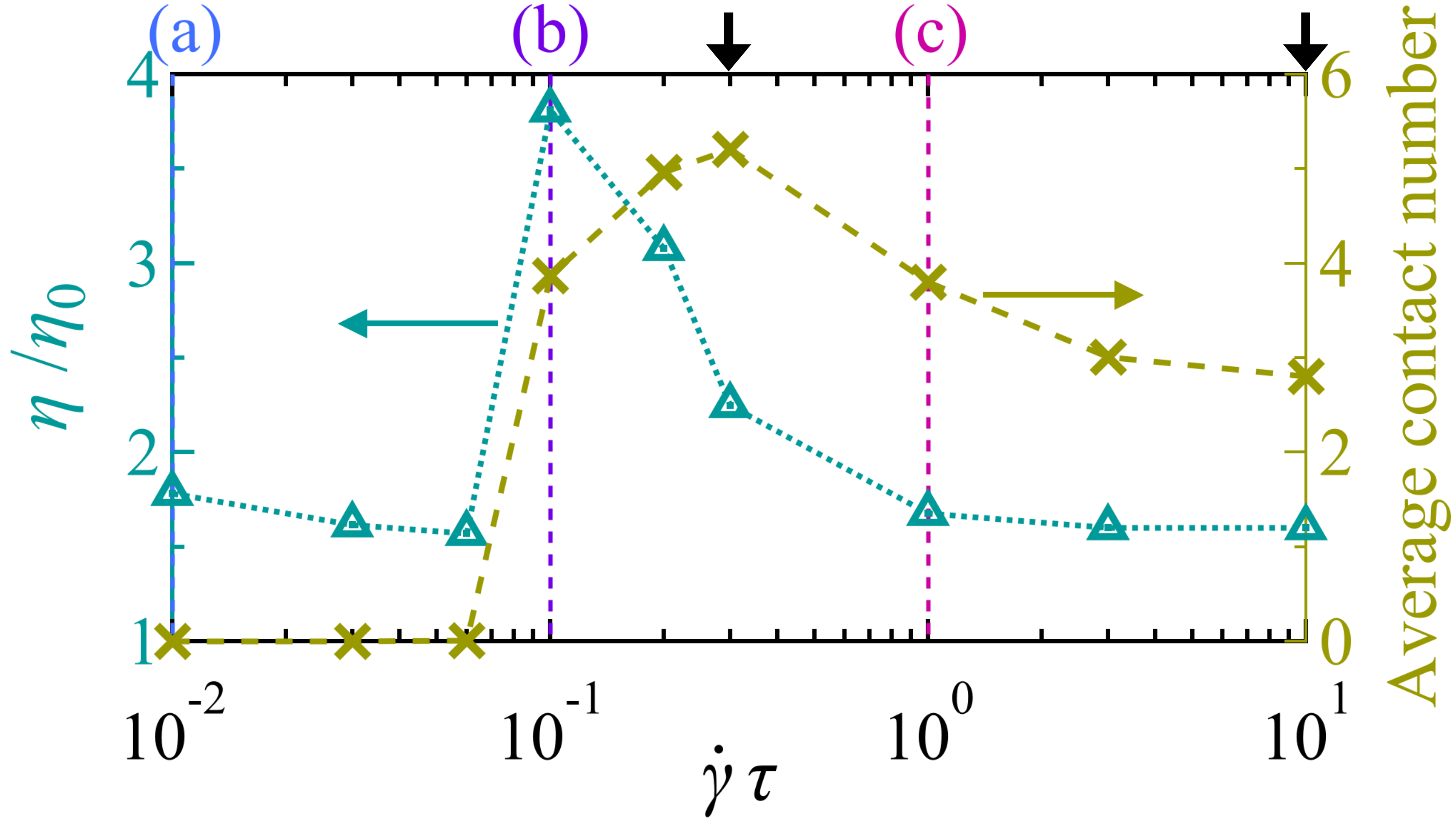


Dimensionless shear rate

$$\dot{\gamma}\tau = \frac{3\pi\eta\dot{\gamma}d^2}{F}$$

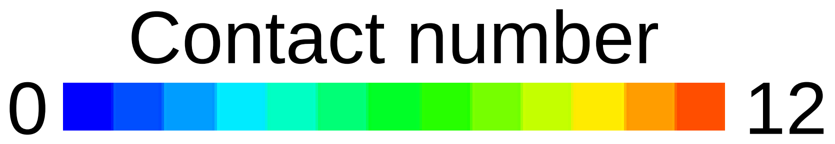
$$= \frac{\text{(Shear force)}}{\text{(Adhision force)}}$$

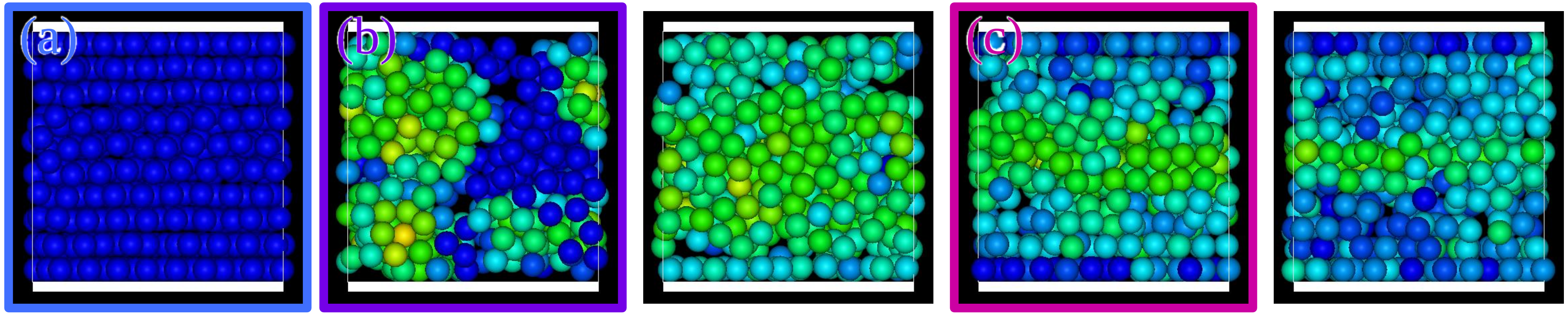
Structure

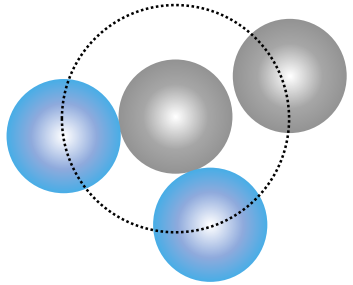


Dimensionless shear rate

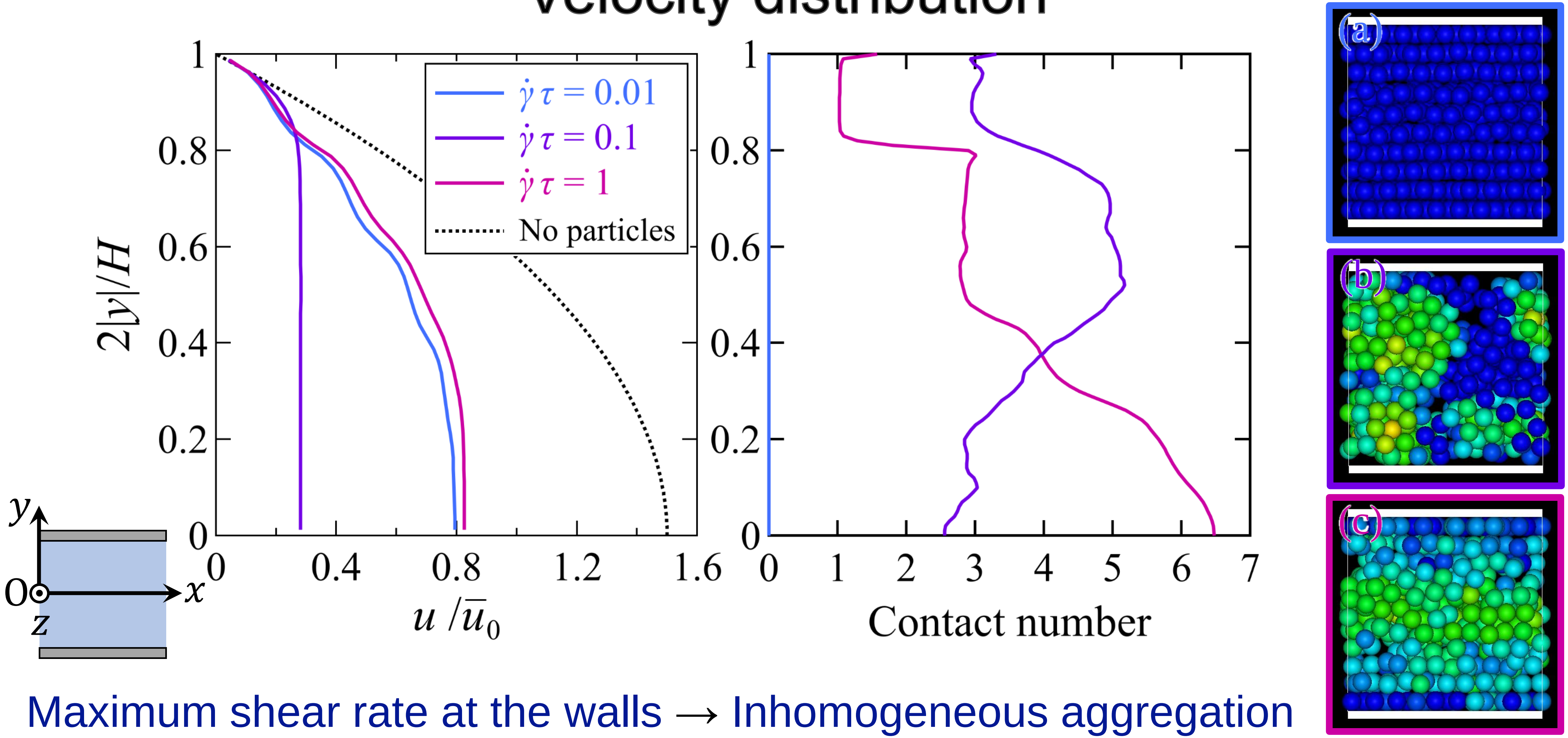
$$\dot{\gamma}\tau = \frac{3\pi\eta\dot{\gamma}d^2}{F} = \frac{(\text{Shear force})}{(\text{Adhision force})}$$







Velocity distribution



Maximum shear rate at the walls → Inhomogeneous aggregation

(b) Aggregate grows from the walls

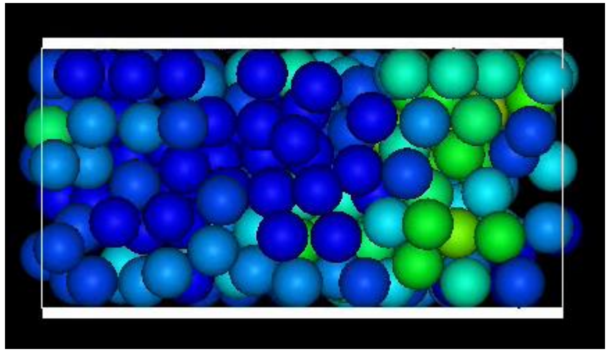
(c) Aggregate breaks near the walls

Effects of channel gap

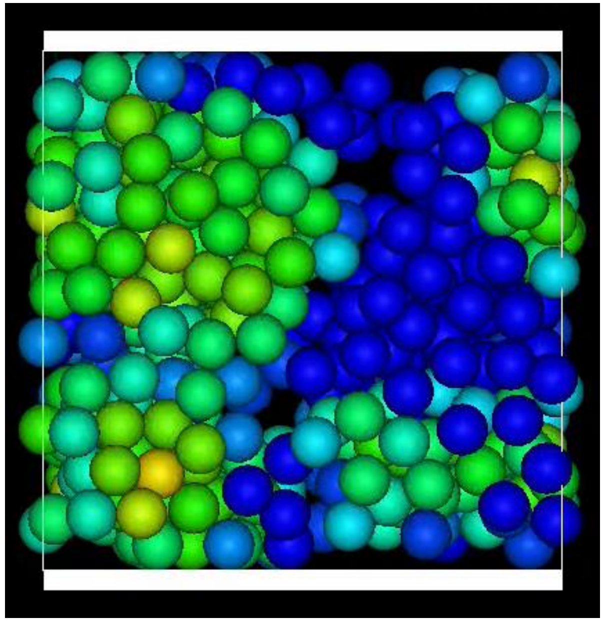
$\dot{\gamma}\tau = 0.1$

Contact number

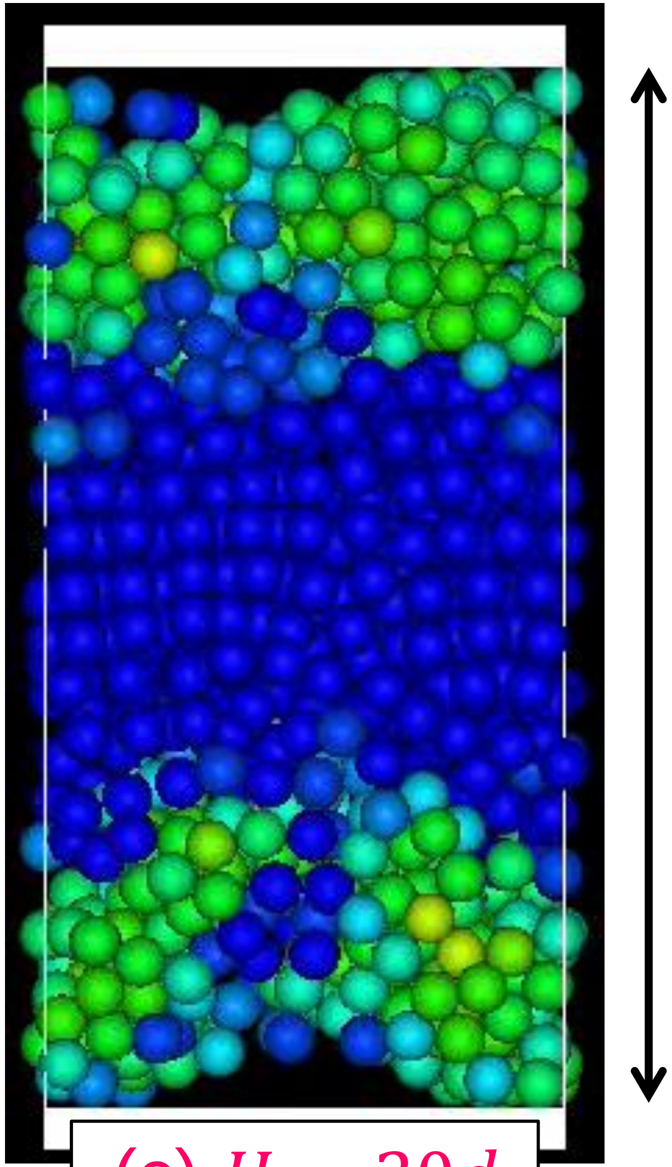
0 12



(a) $H = 5d$



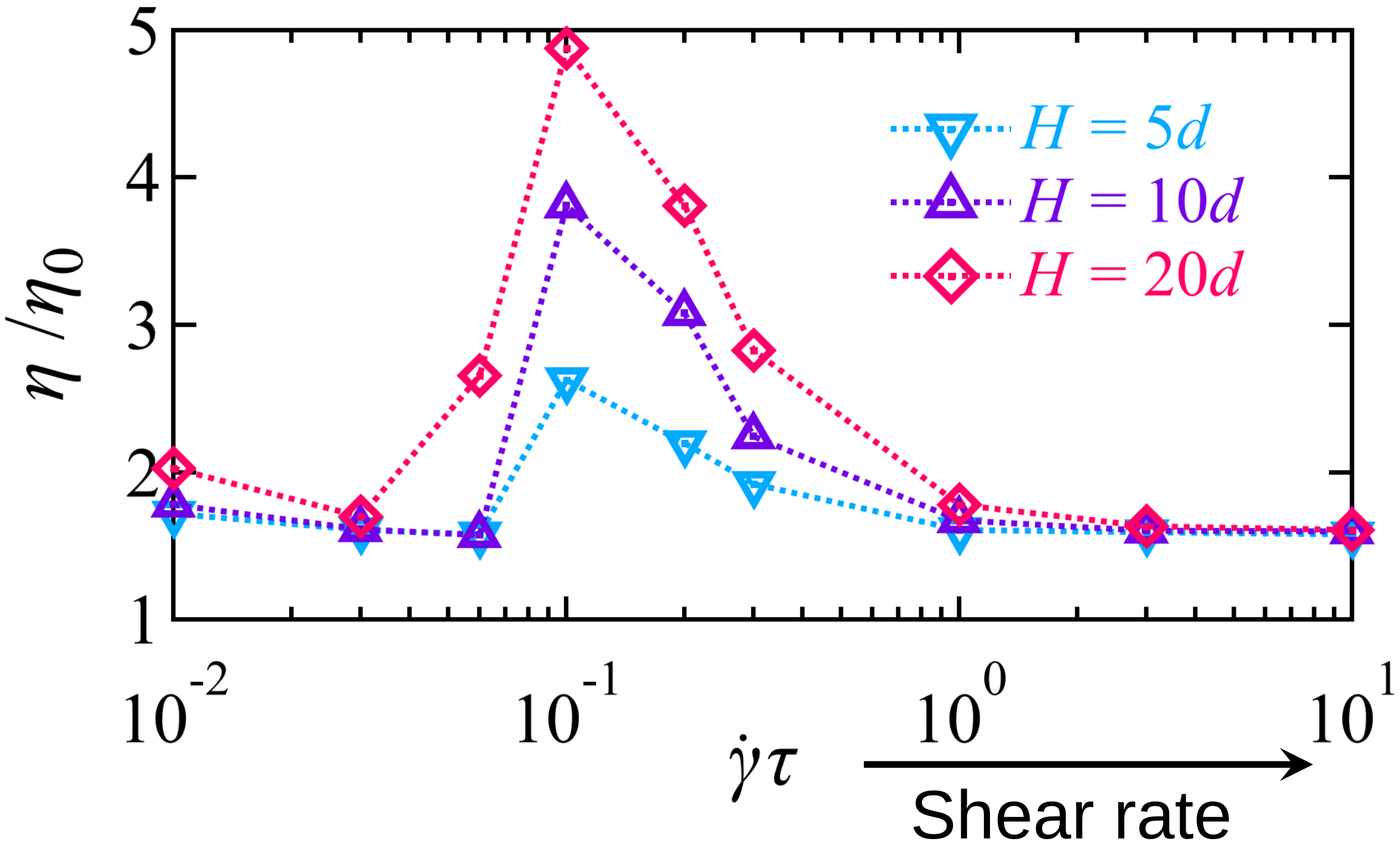
(b) $H = 10d$

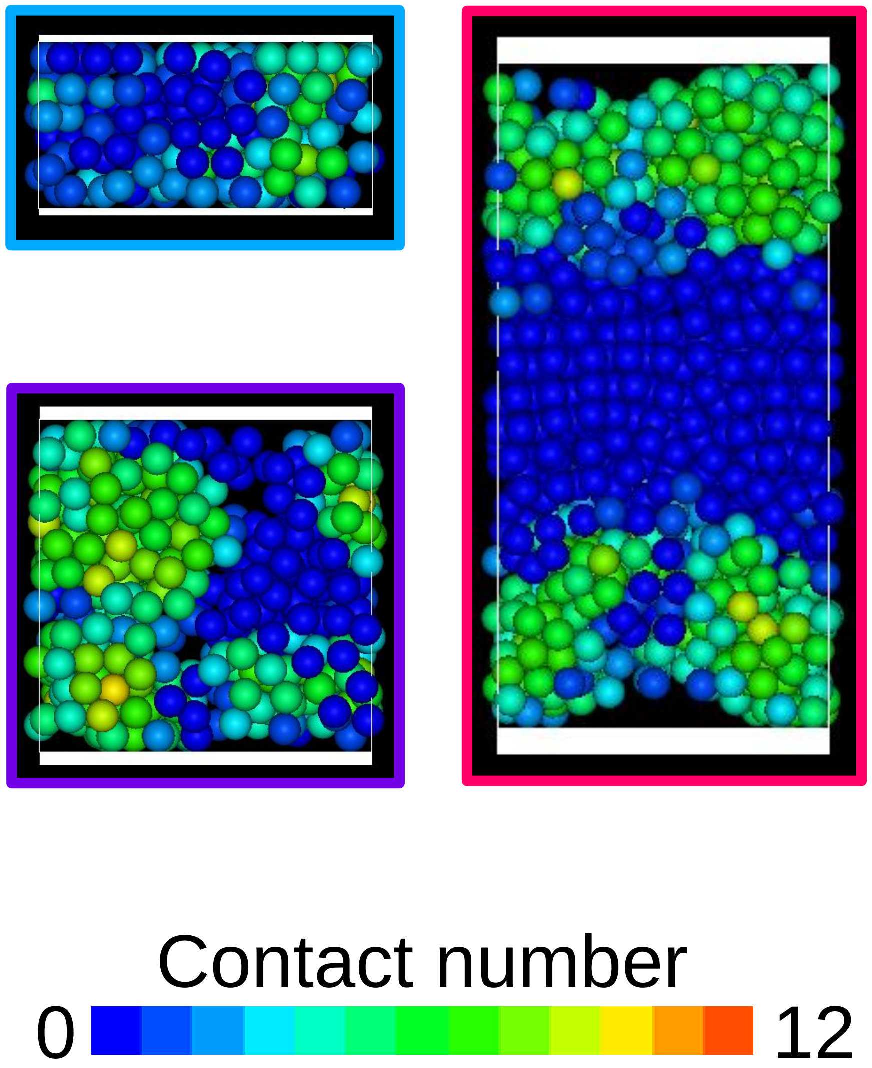


(c) $H = 20d$

Up to $\dot{\gamma}t = 100$

Viscosity

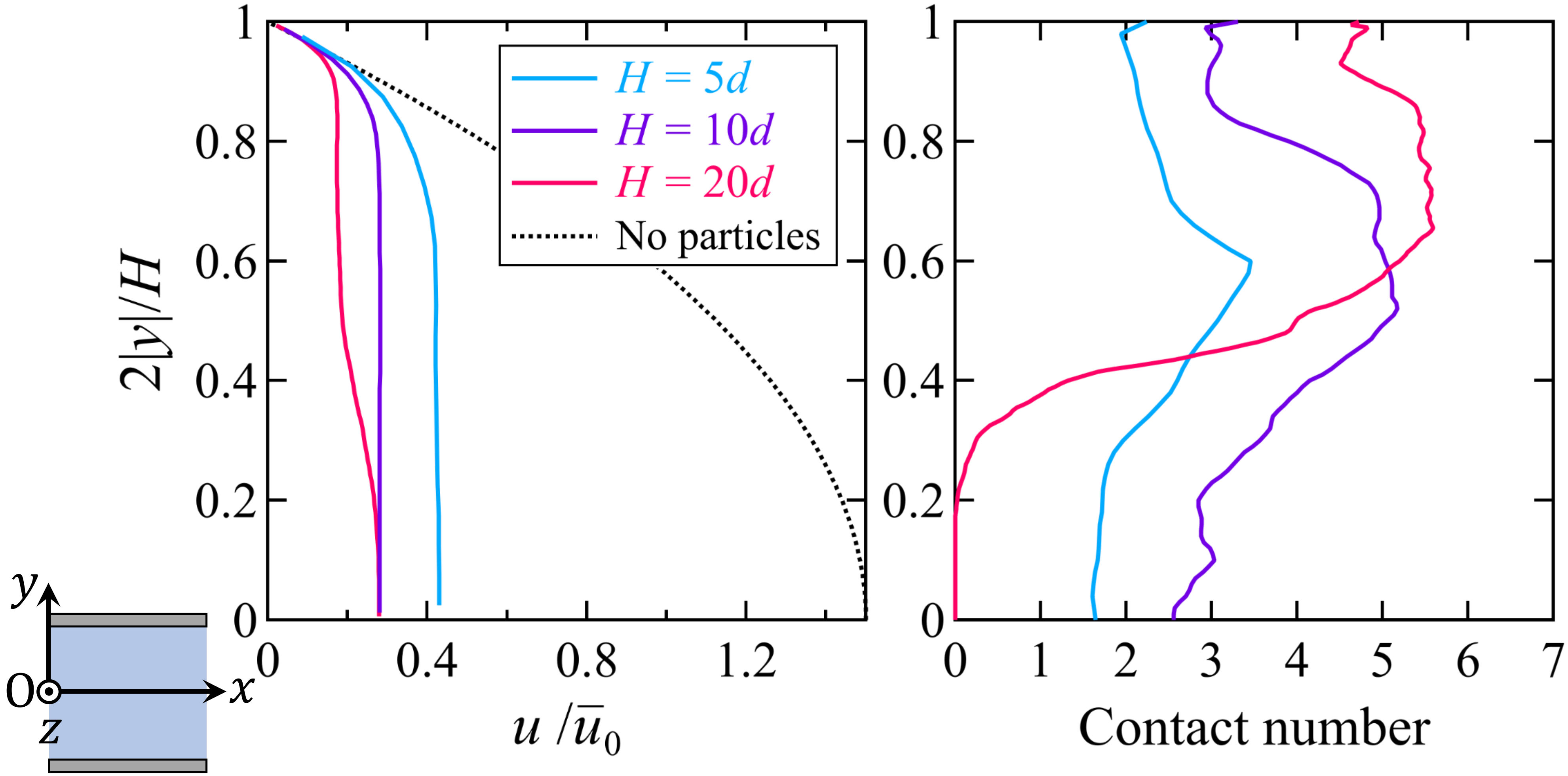


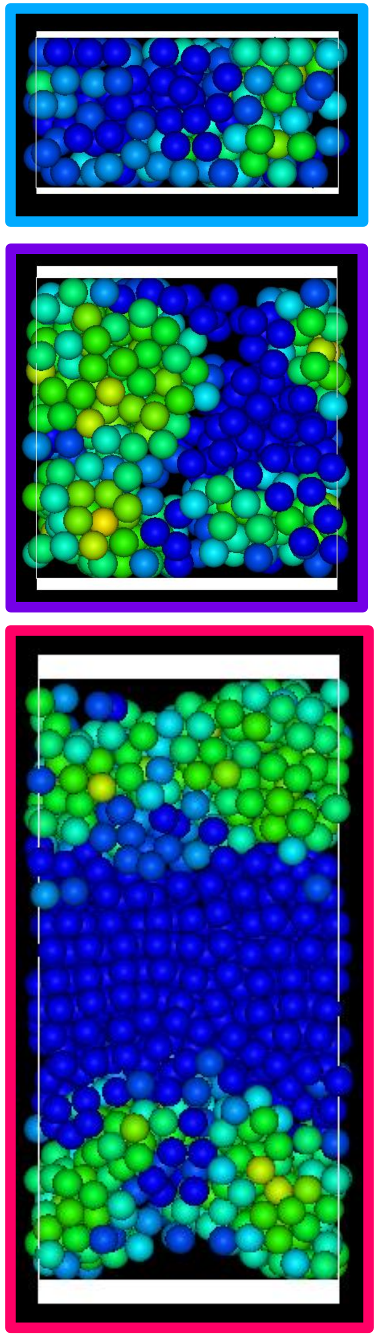


Decrease in channel gap H

→ Reduction of shear thickening

Velocity distribution





Decrease in channel gap H → Inhibition of aggregation

Summary

- Shear thickening causes with aggregation
- Maximum shear rate at the walls (Inhomogeneous shear rate)
  → Inhomogeneous aggregation
- Effects of channel gap on the rheological properties:
  Inhibition of aggregation → Reduction of shear thickening