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Shibaura Institute of Technology

Structure control based on the drying characteristics of colloidal suspensions

微粒子分散液の乾燥特性に基づく構造制御の提案

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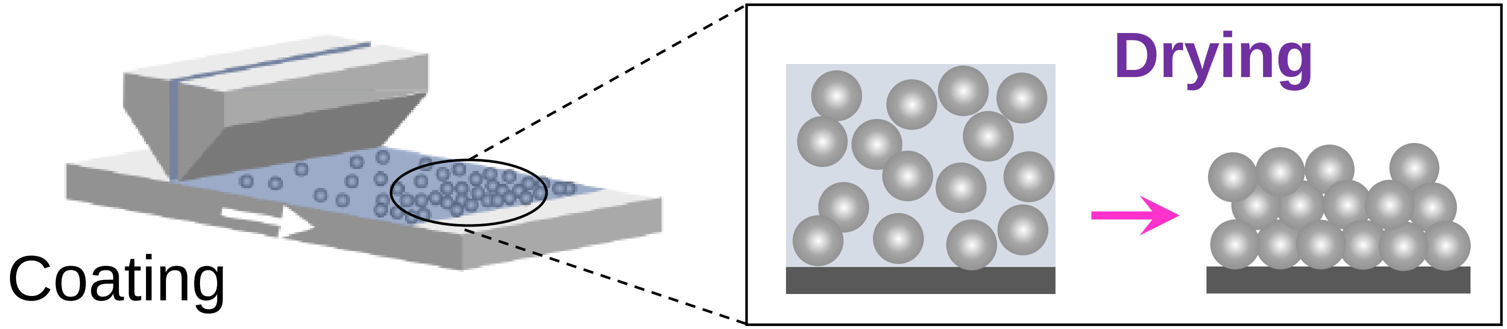
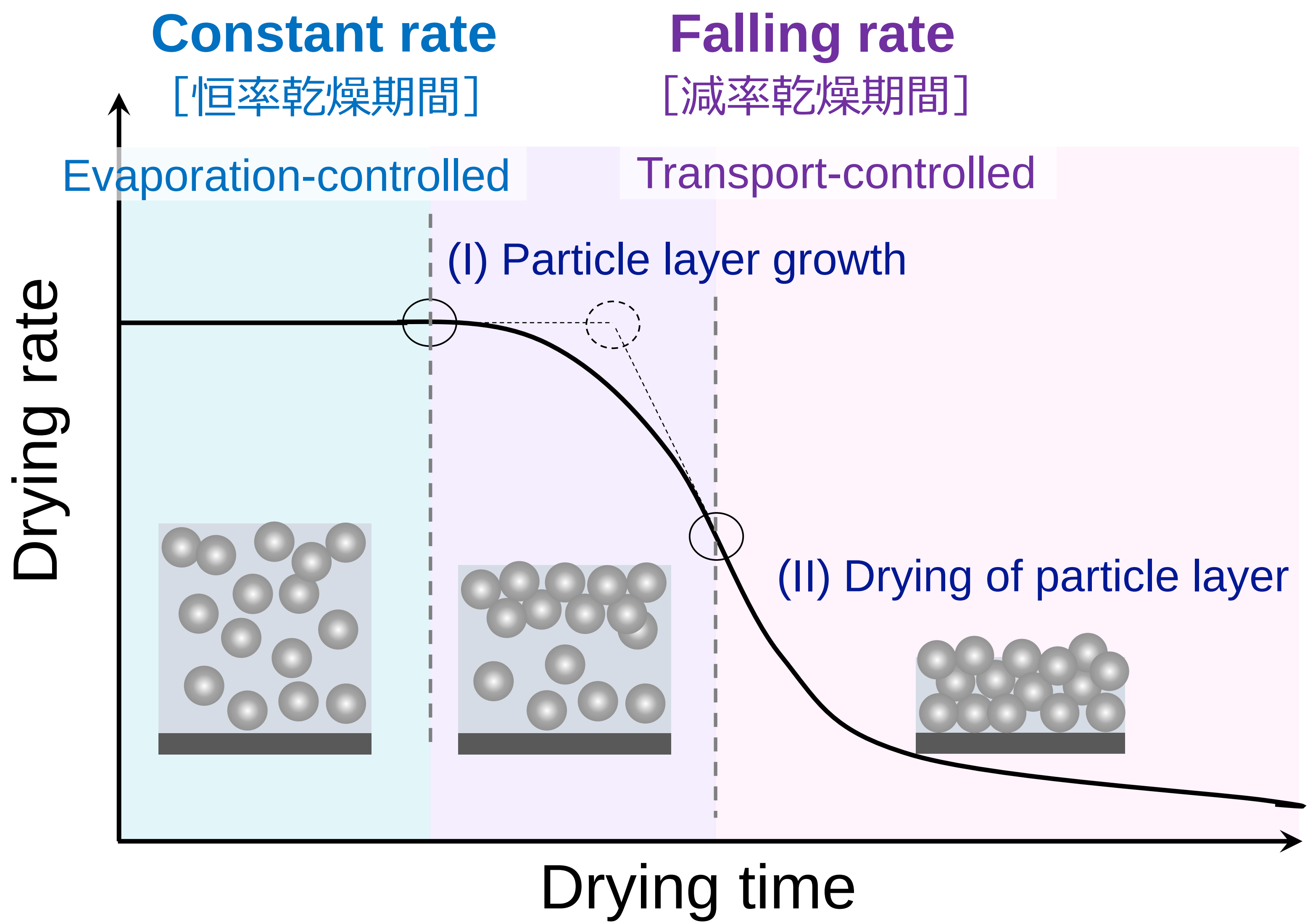


Drying Curve of Colloidal Suspensions

Drying characteristics ↔ Structure

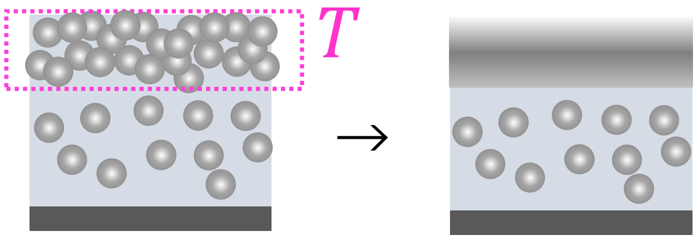


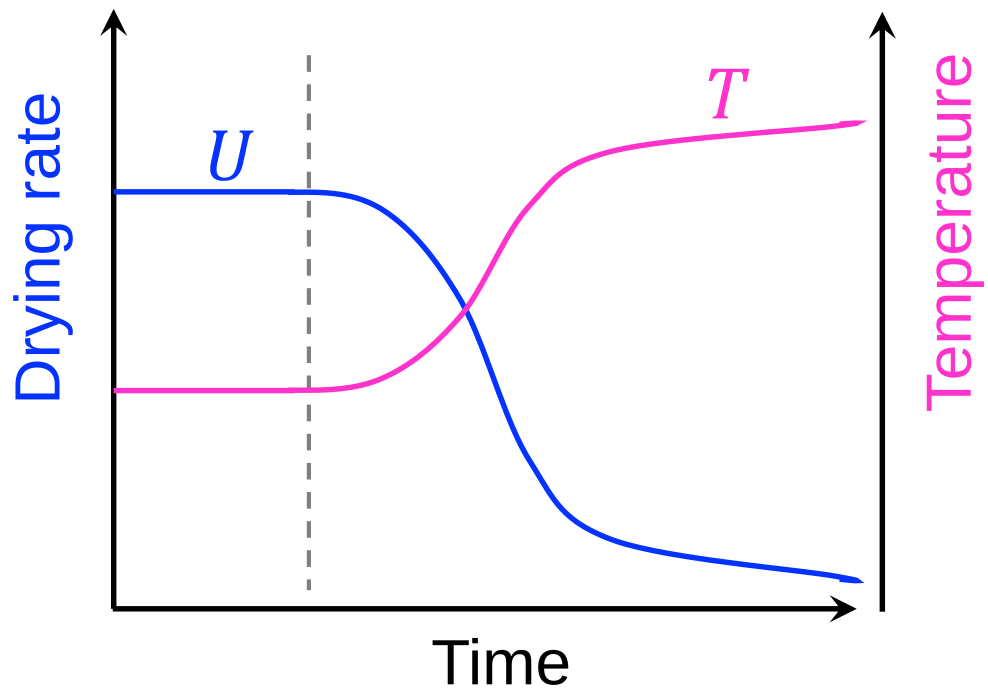
Skinning

Heat balance

$$\rho U \Delta H_{\mathrm{v}} = h(T - T_{\mathrm{ex}})$$

Liquid density: ρ
Latent heat: ΔH_{v}
Heat transfer coefficient: h
Drying temperature: T_{ex}





減率乾燥期間で材料温度上昇

→ 表面での乾燥，析出・熱変性

→ スキン層形成（Skinning）

- 透水抵抗 → 乾燥速度の低下
- 材料密度の不均一化
- 表面荒れの誘起

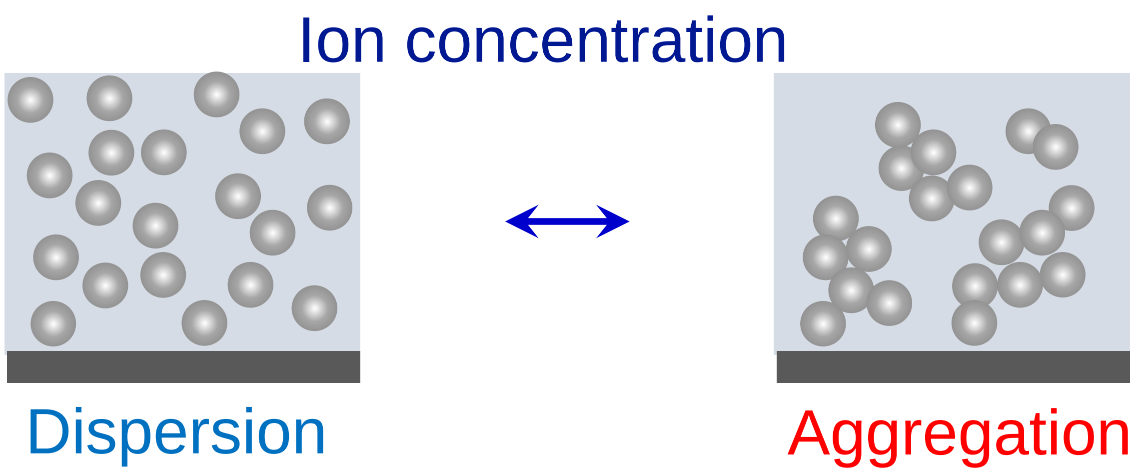
対策

- 乾燥温度の制御（下げる）
- 乾燥速度低下の抑制

Objective

- Estimation of the drying curve of colloidal suspensions by numerical simulations (SNAP-L)

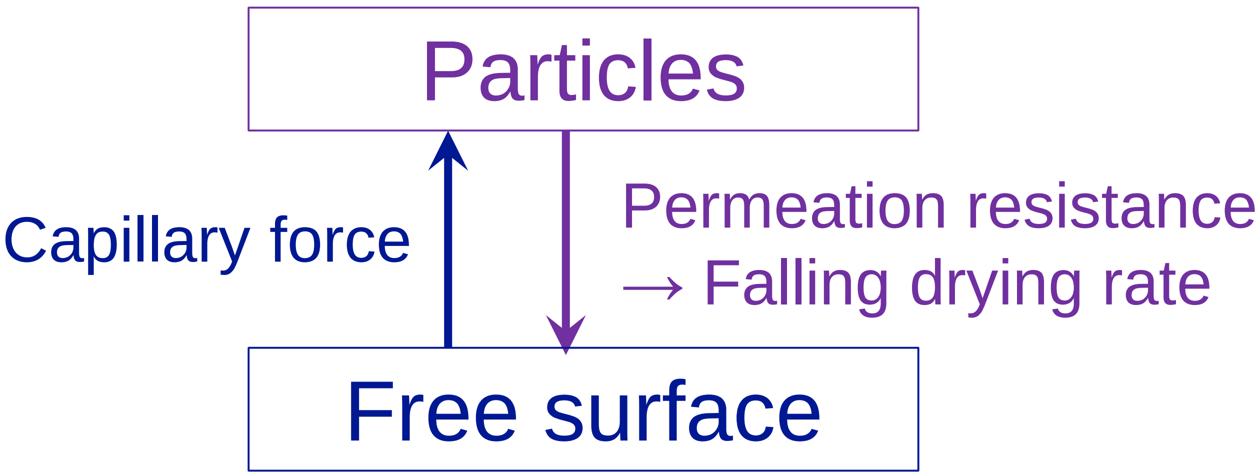
- Control of drying characteristics by dispersion/aggregation

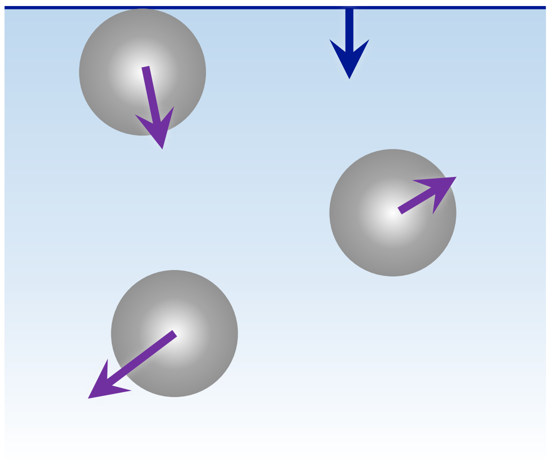


Drying characteristics ↔ Structure

Model

- **Particles**: Equation of motion (Langevin eq.)
- **Free surface**: Recession with a varying rate





Particles' Brownian Motion

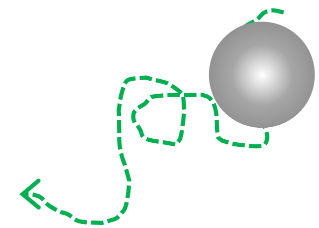
Langevin equation

$$M\dot{\boldsymbol{V}} = -\xi \boldsymbol{V} + \boldsymbol{F}^{\mathrm{R}} + \boldsymbol{F}^{\mathrm{cpl}} + \boldsymbol{F}^{\mathrm{cnt}} + \boldsymbol{F}^{\mathrm{DLVO}}$$

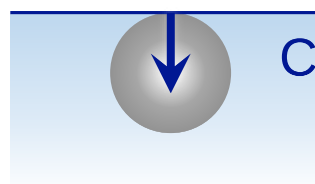
Fluid | Free surface | Interparticle

- **Drag force**: $-\xi \boldsymbol{V}$ (Stokes' law: $\xi = 3\pi\eta d$)
- **Random force**: $F_{\alpha}^{\mathrm{R}}(t) \sim N(0, 2\xi k_{\mathrm{B}} T \Delta t)$ (Gaussian dist.)

→ **Brownian Diffusion** (Diffusion coefficient: $D = \frac{k_{\mathrm{B}}T}{3\pi\eta d}$)

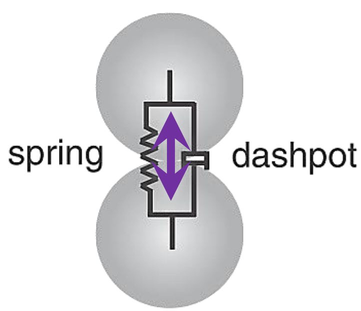


- **Vertical capillary force**: $\boldsymbol{F}^{\mathrm{cpl}}$

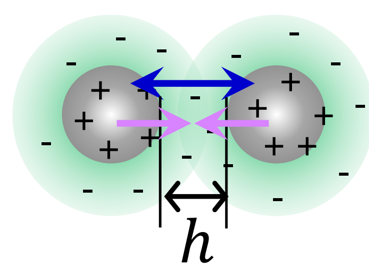


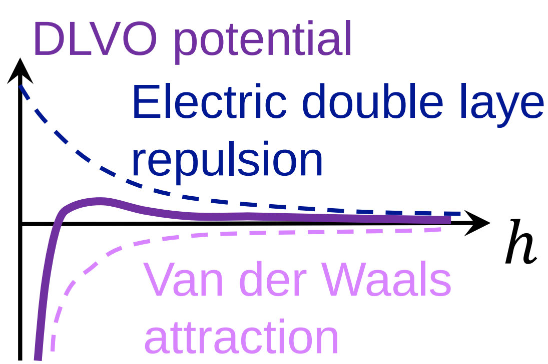
Contact angle $\alpha = 0$

- **Contact force**: $\boldsymbol{F}^{\mathrm{cnt}}$



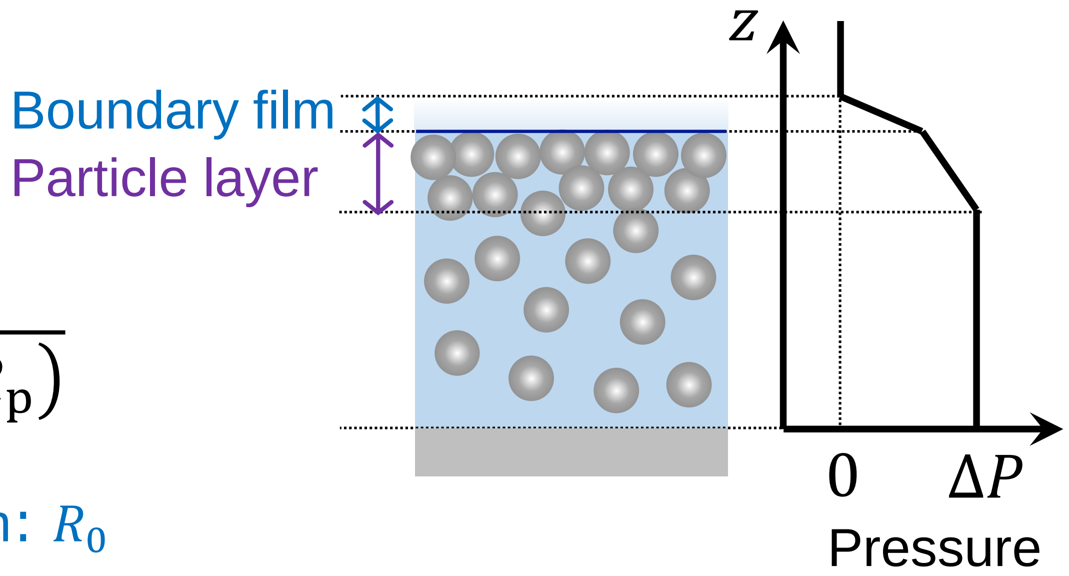
- **DLVO force**: $\boldsymbol{F}^{\mathrm{DLVO}}$





→ **Dispersion / Aggregation**

Drying Rate



Darcy's law

Drying rate: $U = \dfrac{\Delta P}{\eta\left(R_0 + R_\mathrm{p}\right)}$

Resistance of evaporation: R_0

Resistance of particle layer: R_p

Viscosity of liquid: η

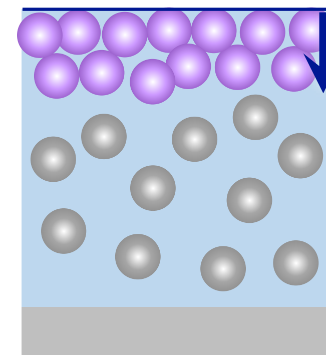
$$\rightarrow \quad \frac{U}{U_0} = \frac{R_0}{R_0 + R_\mathrm{p}}$$

Initial drying rate: $U_0 = \dfrac{\Delta P}{\eta R_0}$

(Constant drying period)

Resistance of Particle Layer

Drying rate: $$\frac{U}{U_0} = \frac{R_0}{R_0 + R_\mathrm{p}}$$



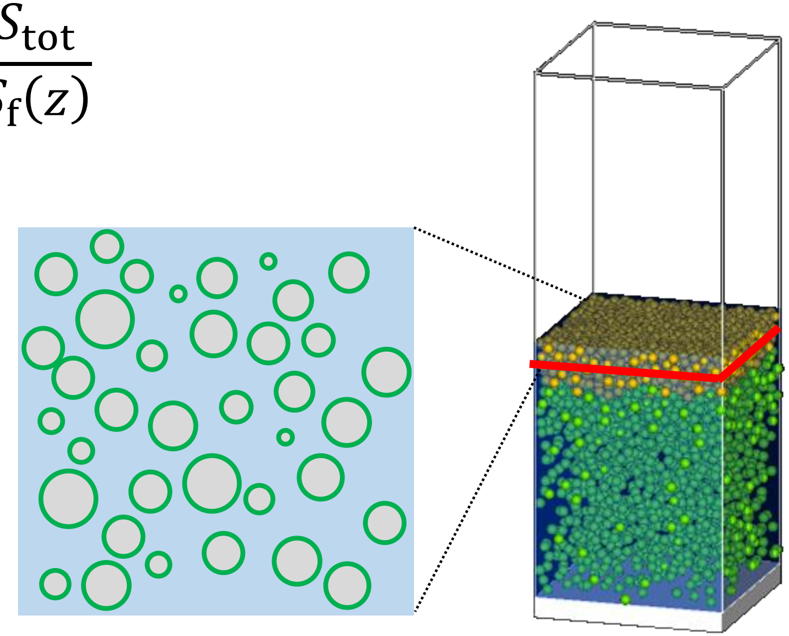
Particle layer = Aggregation moving with free surface

$$R_\mathrm{p} = \int_P r(z)\mathrm{d}z \qquad r(z) = \frac{80}{[D_\mathrm{H}(z)]^2}\frac{S_\mathrm{tot}}{S_\mathrm{f}(z)}$$

Hydraulic diameter: $D_\mathrm{H} = \dfrac{4S_\mathrm{f}}{L_\mathrm{f}}$

Cross-sectional area of the flow: S_f

Wetted perimeter: L_f



Cross-section

Simulation Conditions

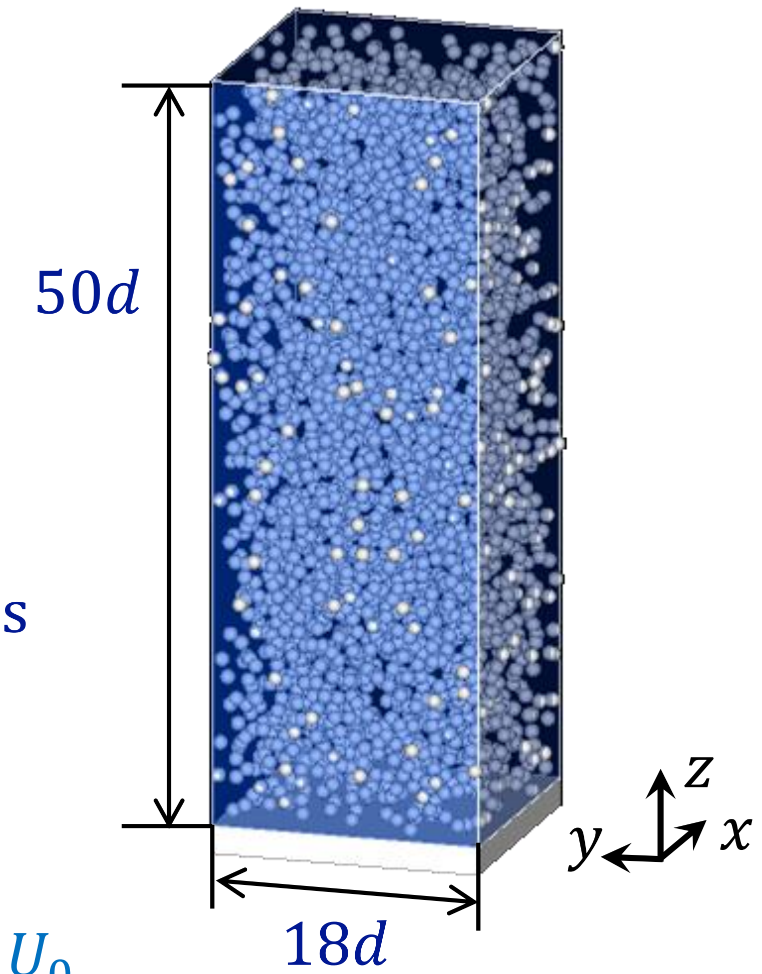
<u>Particles</u>

- diameter $d = 100\ \mathrm{nm}$
- Initial volume particle fraction 0.1
- Zeta potential $30\ \mathrm{mV}$

<u>Medium</u>

- Water
- Initial drying rate $U_0 = 5 \times 10^{-3}\ \mathrm{m/s}$
- Ion concentration

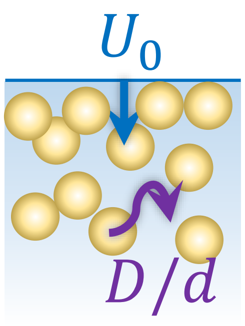
  $5 \times 10^{-4} - 1 \times 10^{-2}\ \mathrm{M}$



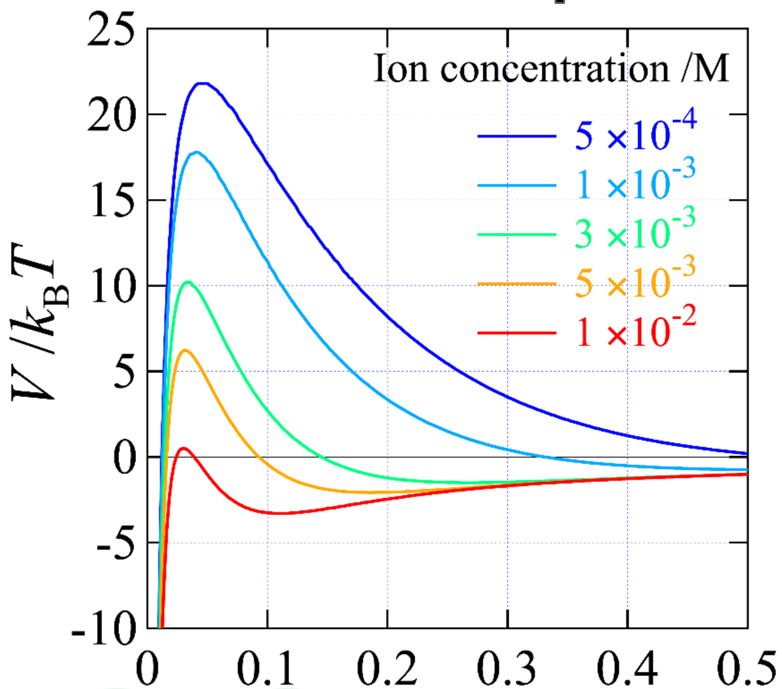
Periodic boundaries x, y

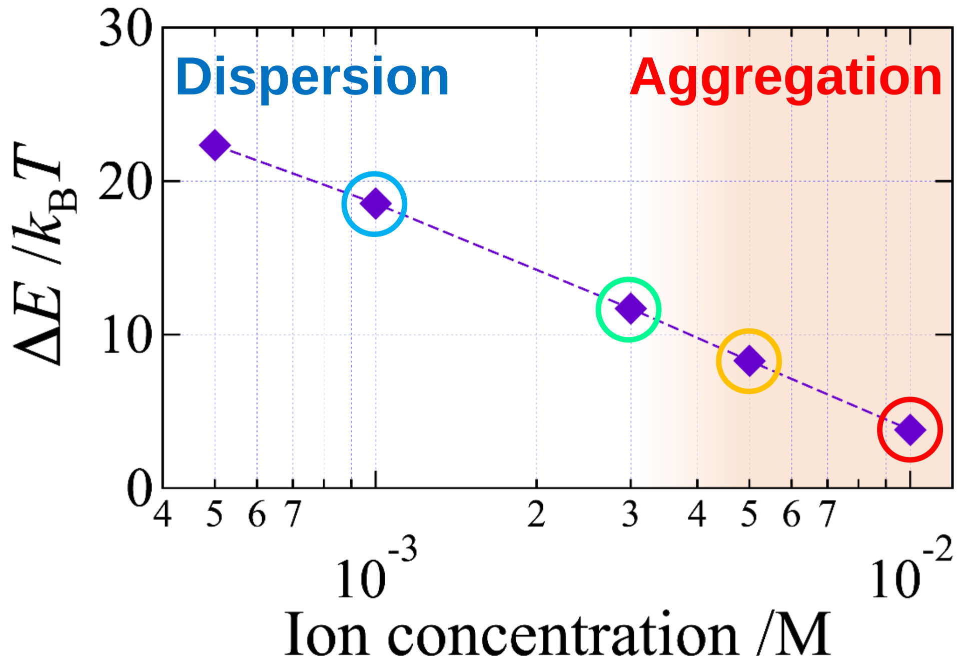
Initial particle drying Péclet number

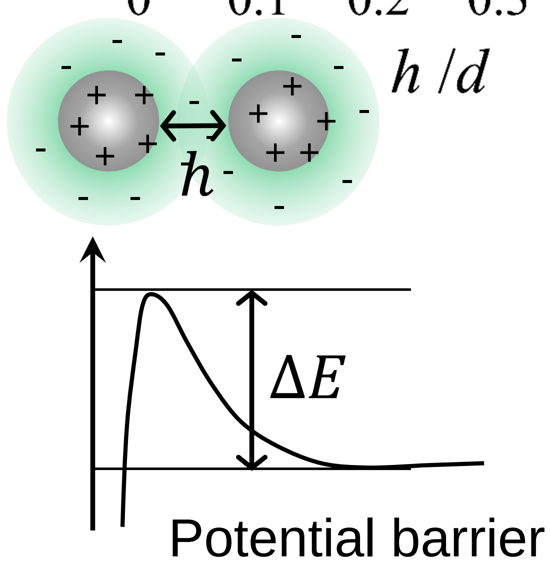
$$\mathrm{Pe}_0 = \frac{(\text{Drying rate})}{(\text{Diffusion rate})} = \frac{U_0}{D/d} = 100$$

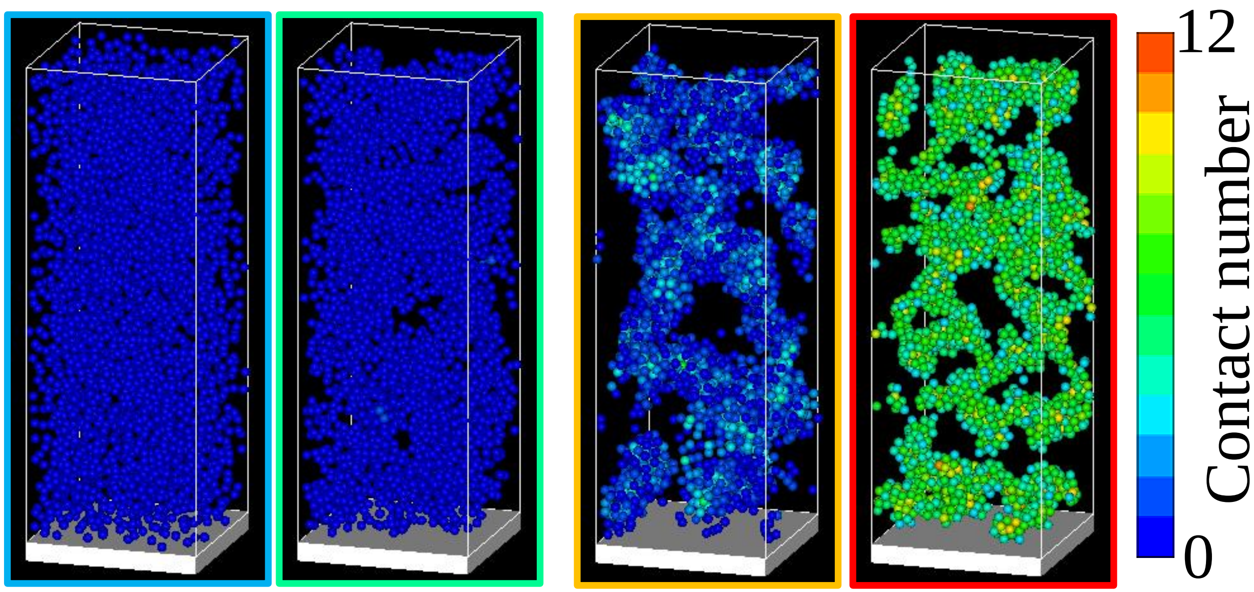


Interparticle DLVO potential

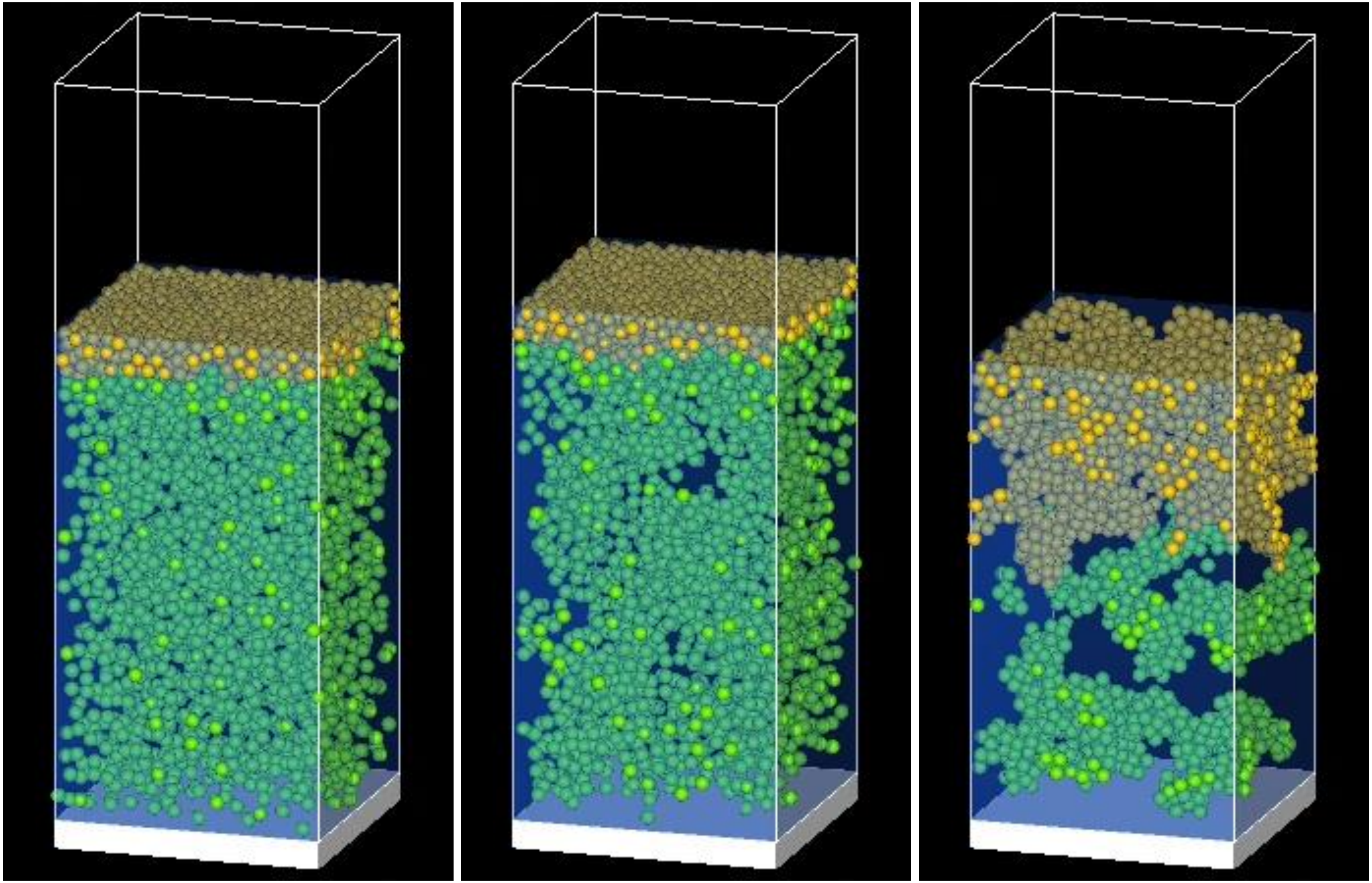






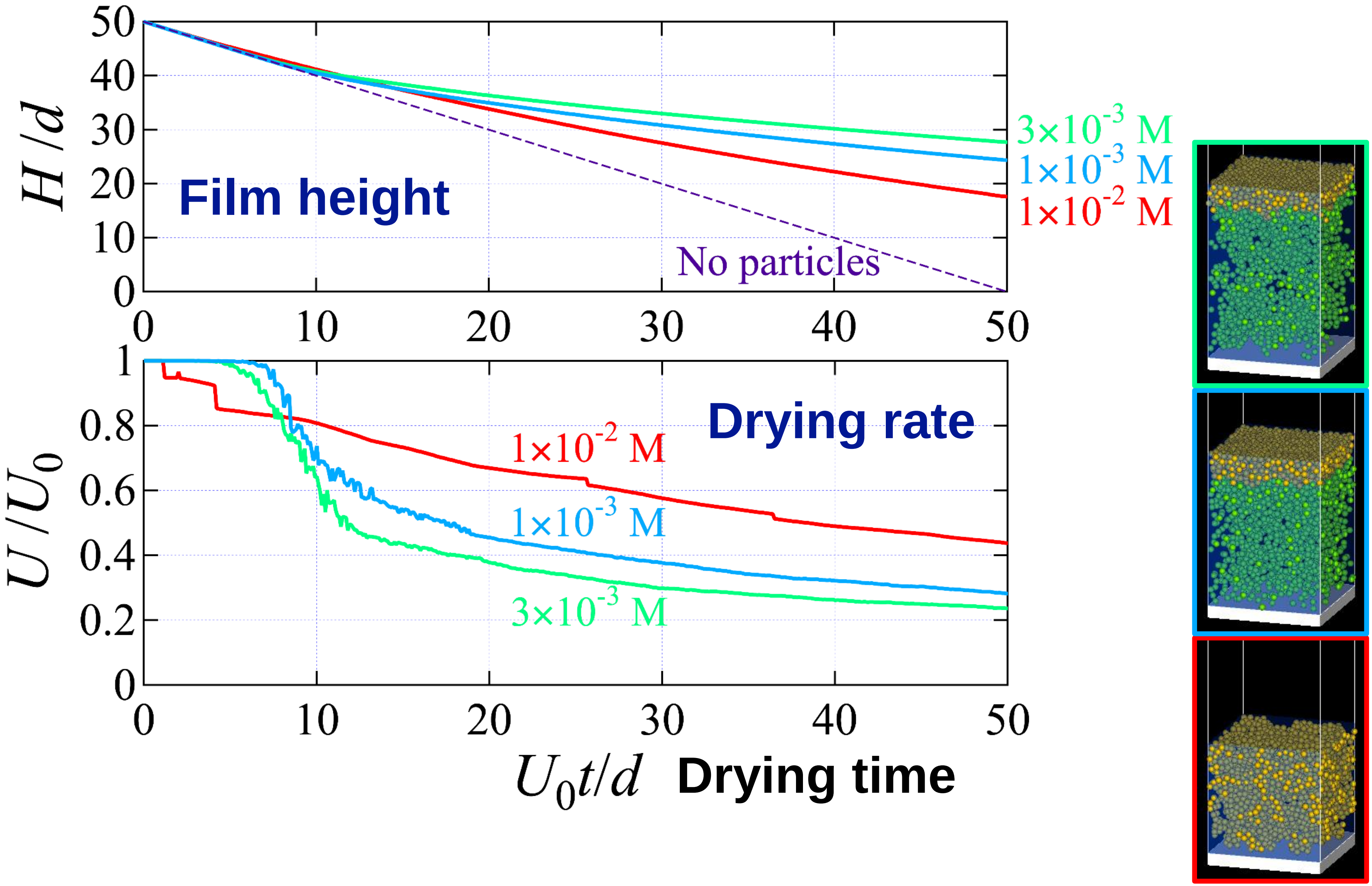


Particle Distribution

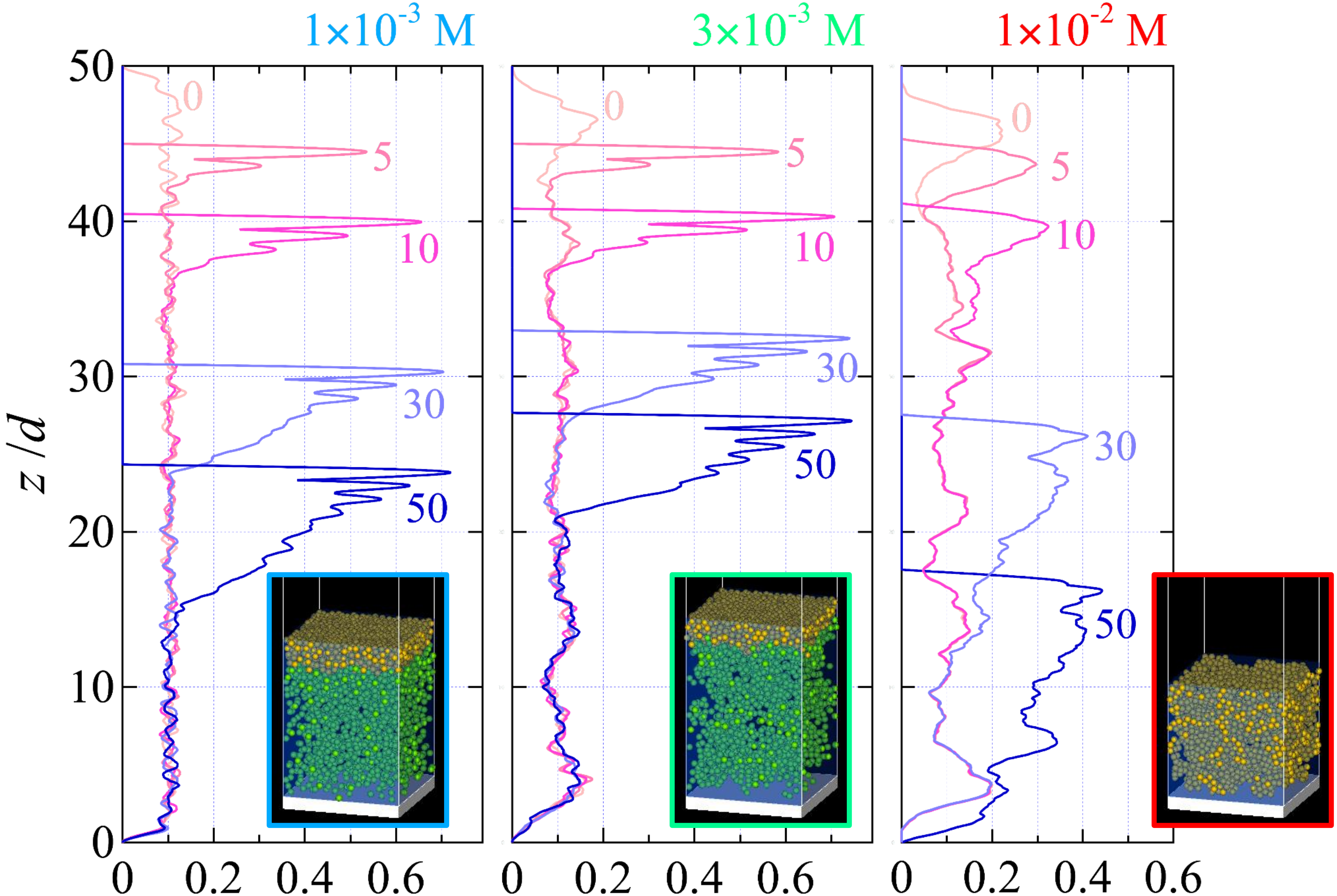


1×10^{-3} M　　3×10^{-3} M　　1×10^{-2} M

Drying Characteristics

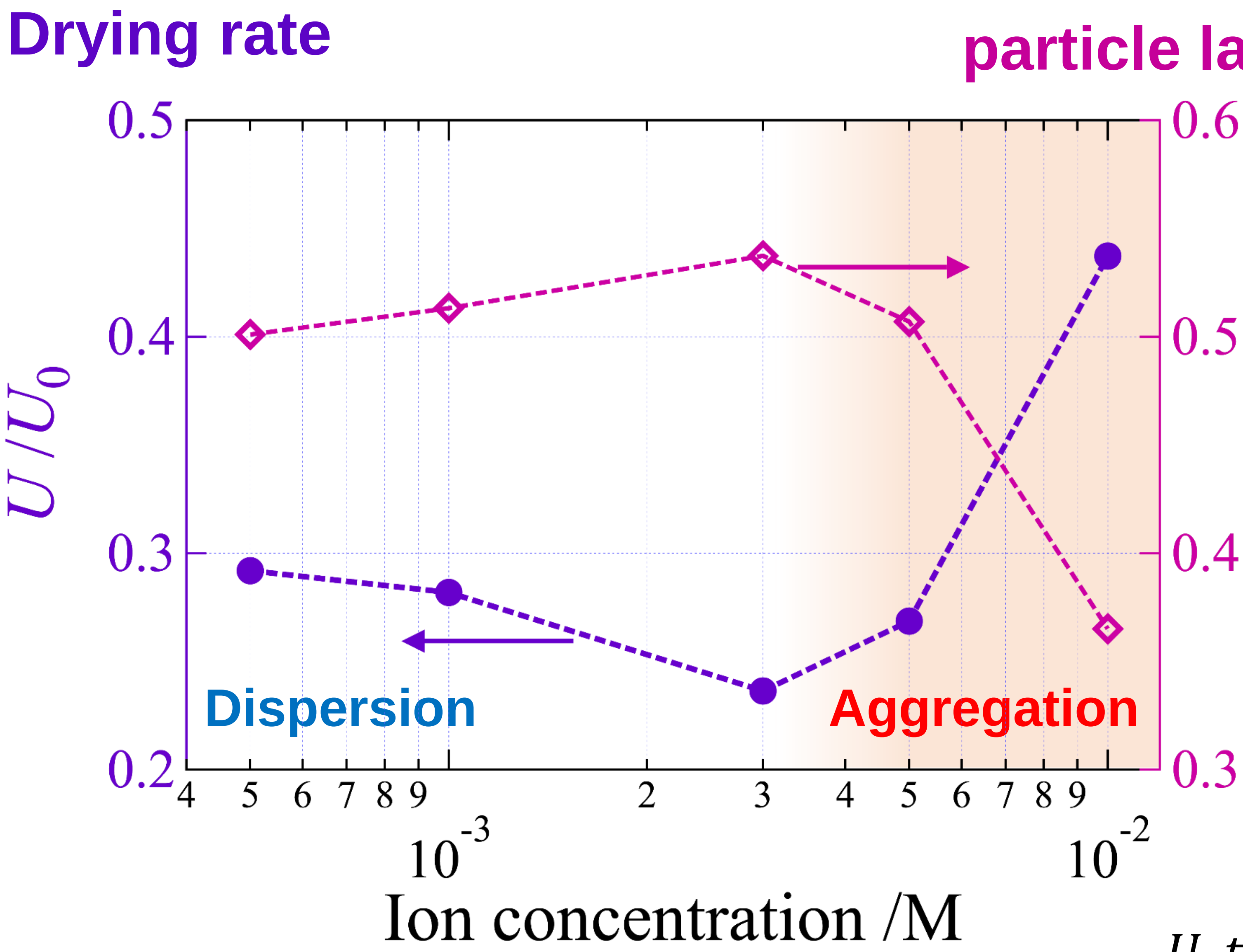


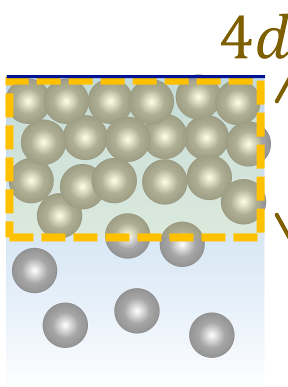
Particle Distribution



時刻 $U_0 t/d$ を表示

Summary





$U_0 t/d = 50$

Summary

◆ How to prevent skinning

- Drying characteristics → Temperature control

- Dispersion/aggregation control to reduce drying time

  Aggregation: higher porosity → higher drying rate

  Dispersion: slower particle layer growth
  → higher drying rate