SCEJ 83rd Annual Meeting

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Modeling of the drying characteristics of colloidal suspensions

粒子系の乾燥特性モデル

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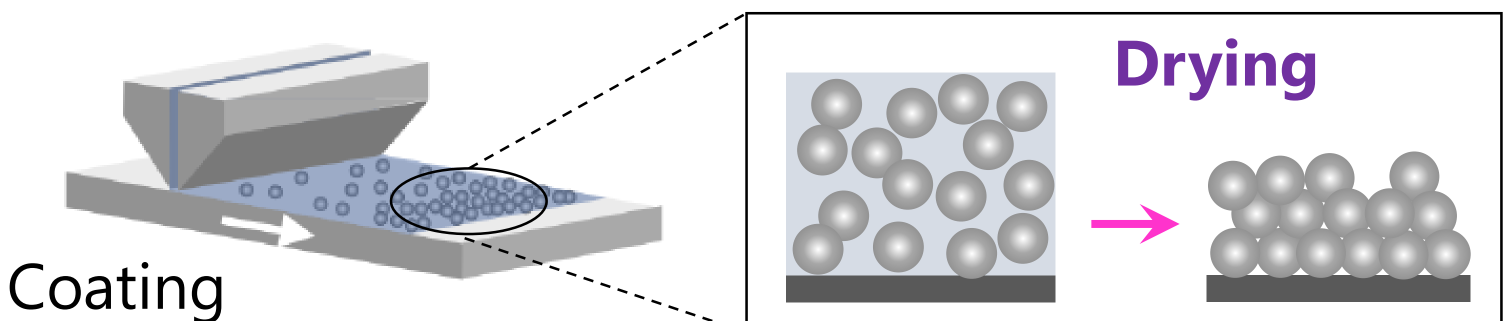
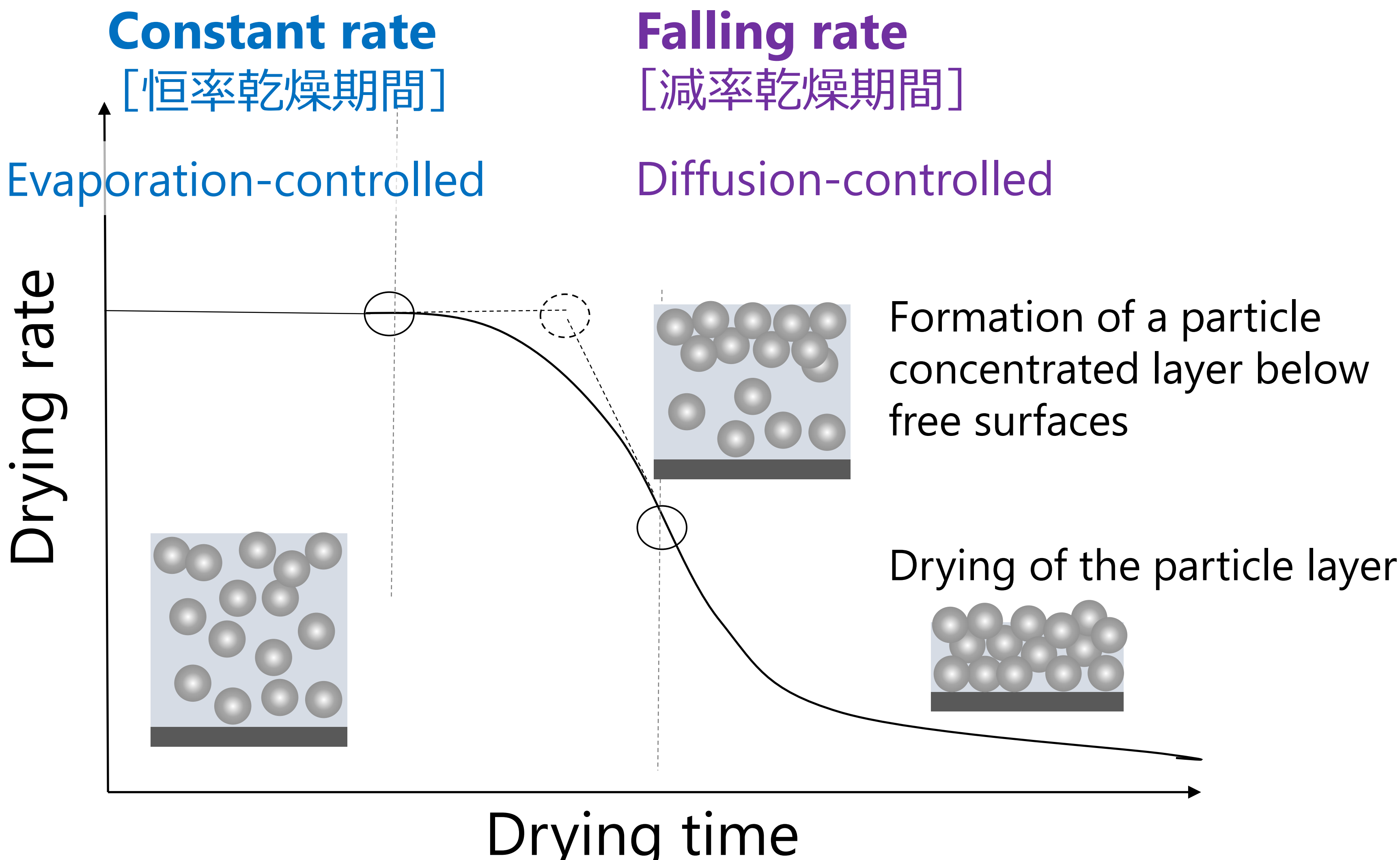
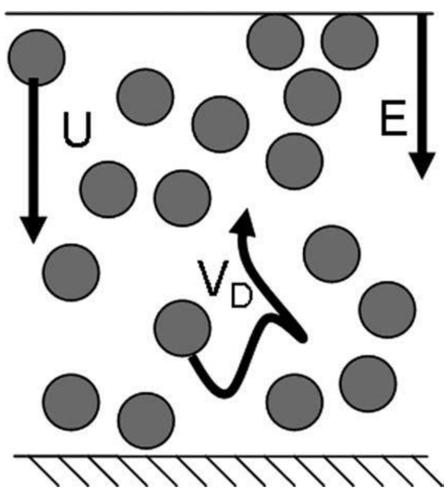


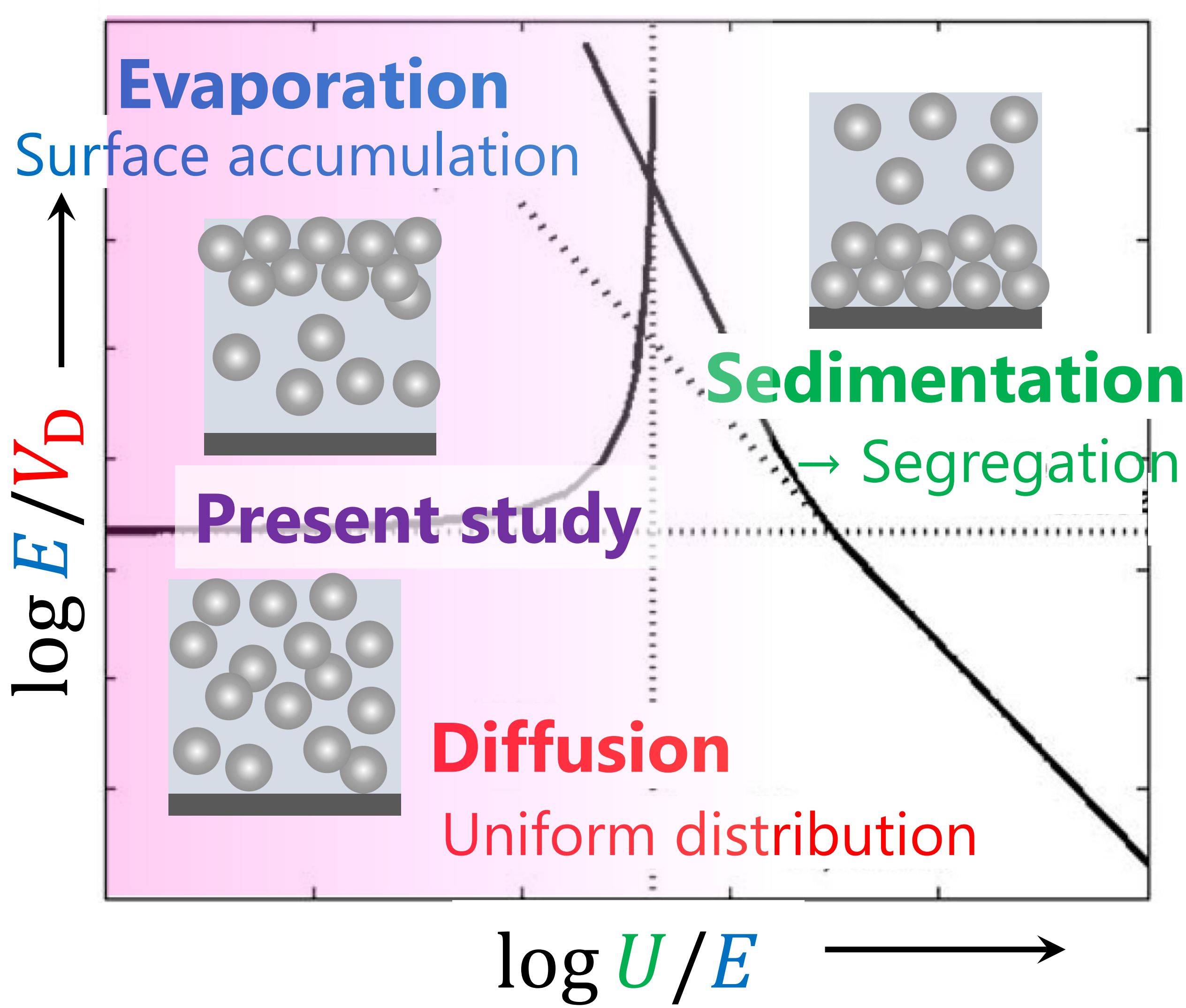
Drying Curve of Colloidal Suspensions



山口由岐夫，「ものづくりの化学工学」(2015).

Particle Distribution during Drying





Evaporation rate: E

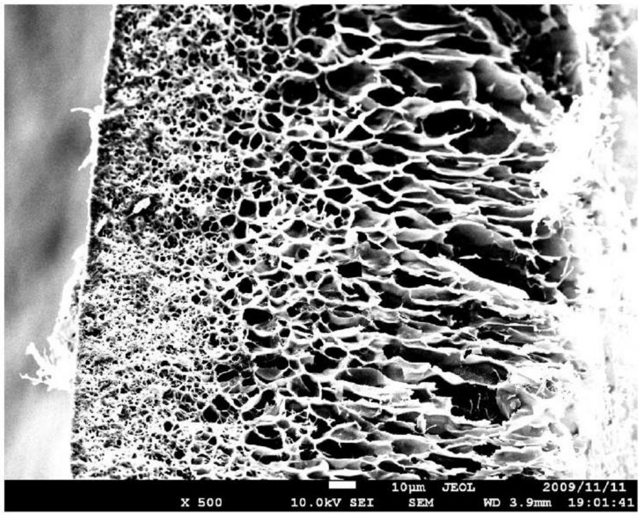
Brownian diffusion rate: V_D

Sedimentation velocity: U

Cardinal et al., AIChE J. (2010).

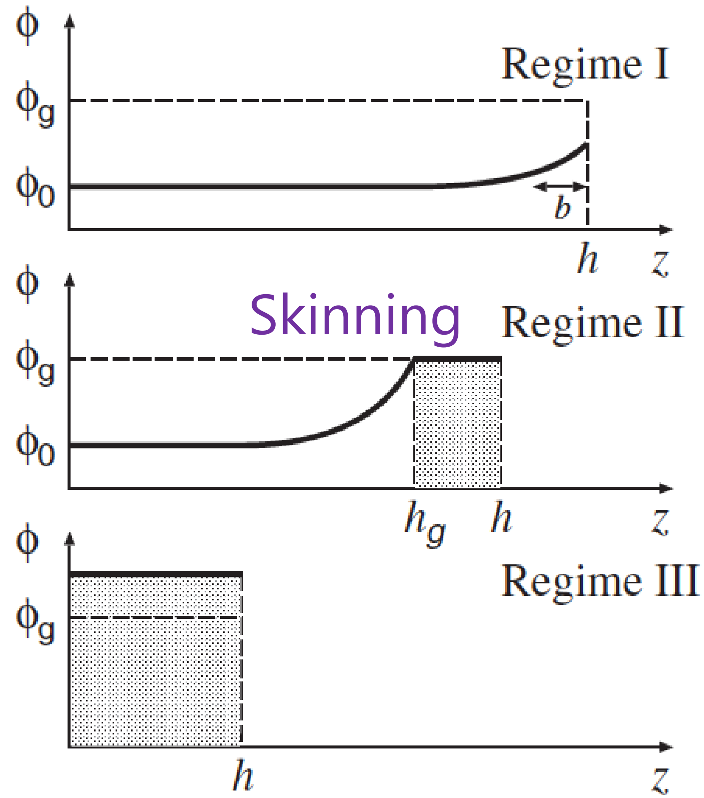
Skinning

Formation of a gel-like layer at the free surface



Yuba (Vertical section)

Y. Chen & T. Ono, J. Agric. Food Chem. (2010).



- Inhibition of drying
- Inhomogeneity of density
- Defects: Surface roughness, Crack

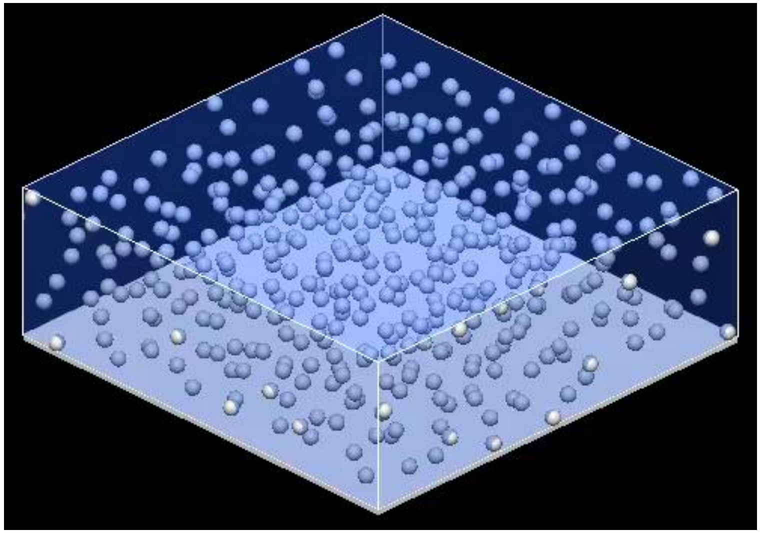
1D advection-diffusion eq.

T. Okuzono, K. Ozawa, and M. Doi, Phys. Rev. Lett. (2006).

Objective

- Prediction of the drying curve of colloidal suspensions

- Analysis using a simple model
  - Particles: Equation of motion (Langevin eq.)
  - Free surface receding with a constant rate
  - Drying rate: Estimation from the permeability



Equation of Particles' Brownian Motion

Langevin equation

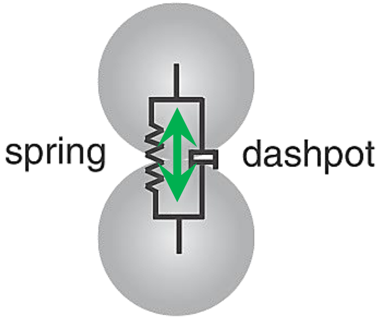
$$M_i \dot{\boldsymbol{V}}_i = -\xi \boldsymbol{V}_i + \boldsymbol{F}_i^{\mathrm{R}} + \boldsymbol{F}_i^{\mathrm{cnt}} + \boldsymbol{F}_i^{\mathrm{cpl}}$$

Drag force: $-\xi \boldsymbol{V}_i$ Stokes' law: $\xi = 3\pi\eta d$

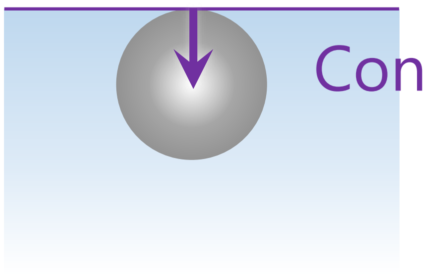
Random force: $F_{i\alpha}^{\mathrm{R}}(t) \sim N(0, 2\xi k_{\mathrm{B}} T)$ Stochastic variables obeying the Gaussian dist.

→ **Brownian Diffusion**: $D = \dfrac{k_{\mathrm{B}} T}{3\pi\eta d}$ Diffusion coefficient in infinite dilution

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

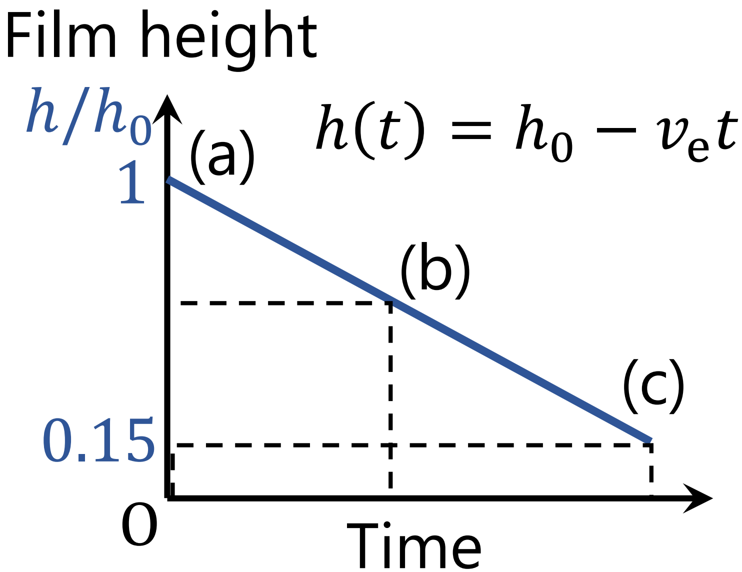


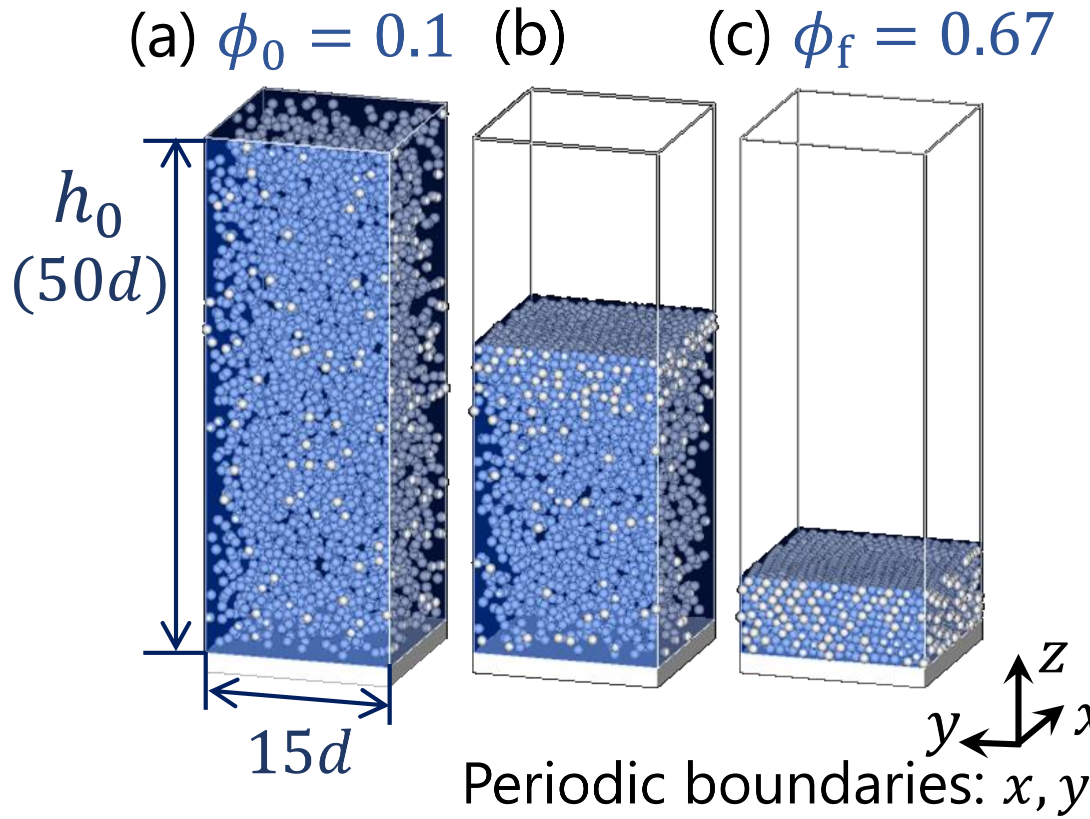
Vertical capillary force: $\boldsymbol{F}_i^{\mathrm{cpl}}$



Contact angle $\alpha = 0$

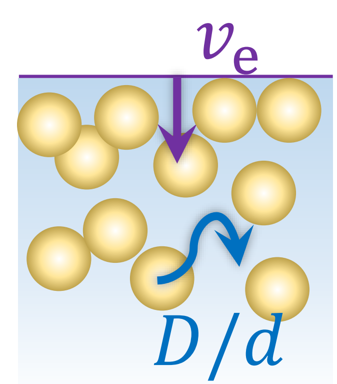
Simulation Conditions





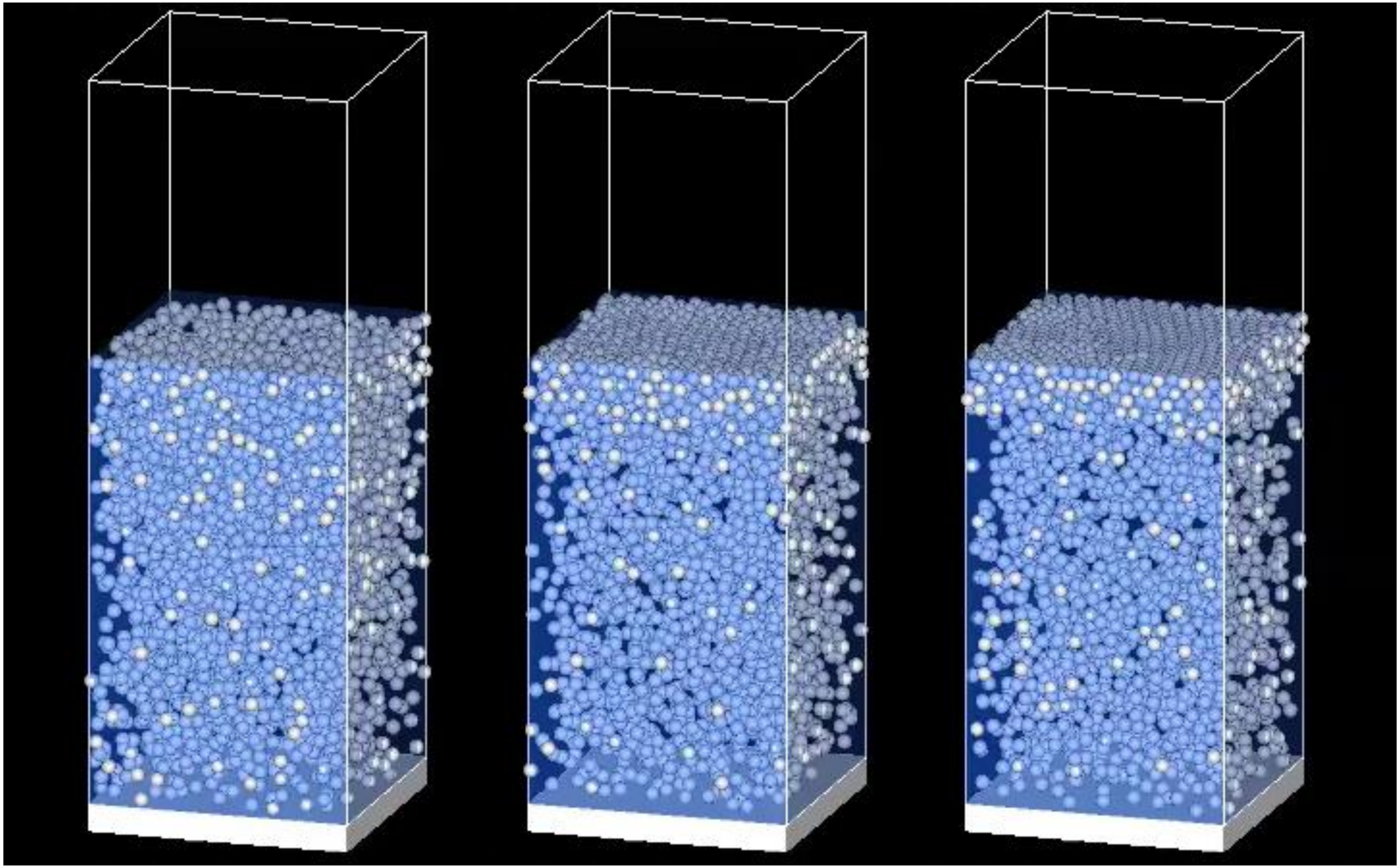
- Particle diagram d
- Particle drying Péclet number

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



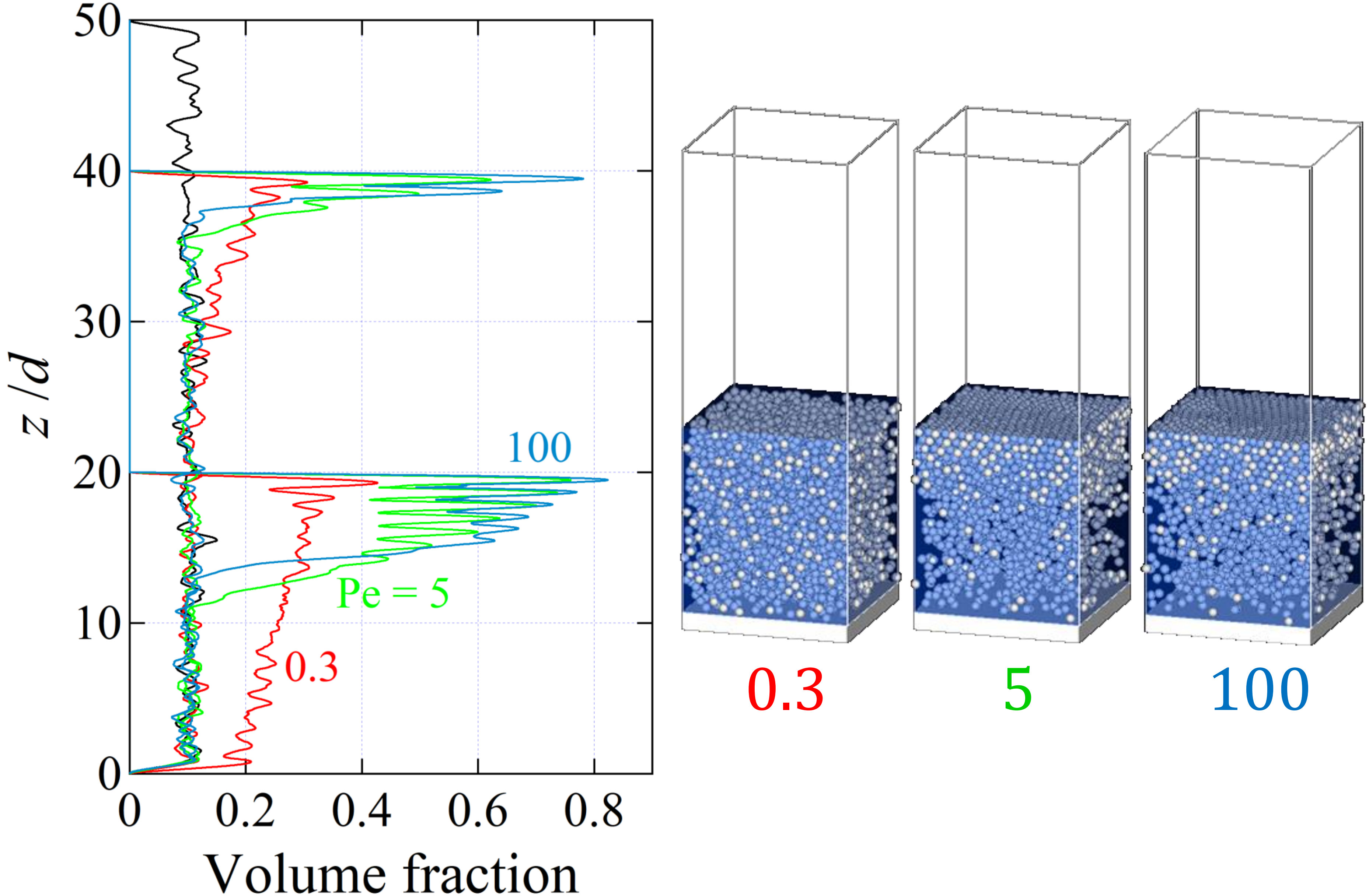
Simulation: $\mathrm{Pe} = 0.3,\ 5,\ 100,\ \infty$

Particle Distribution



$\mathrm{Pe} = 0.3$ 5 100

Particle Distribution



Permeability

Darcy's law $u = K\Delta p$

$$K(h) = \left[\int_0^h r(z)\mathrm{d}z\right]^{-1}$$

Pressure drop: Δp

Superficial velocity: u = Drying rate (Falling rate period)

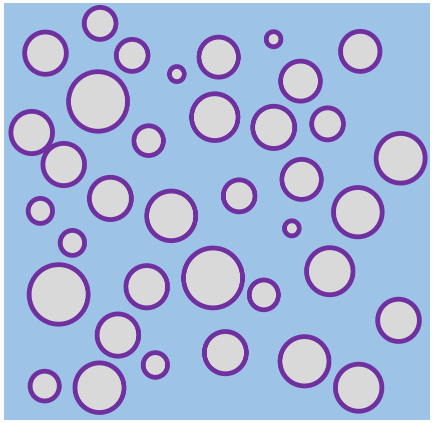
Pressure gradient

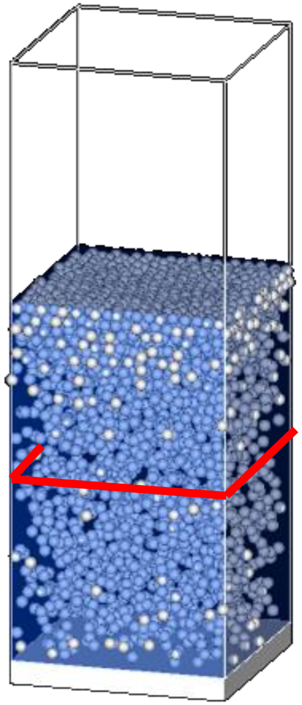
$$\frac{\mathrm{d}p}{\mathrm{d}z} = r(z)u \qquad r(z) = \frac{k\eta}{[D_\mathrm{H}(z)]^2}\frac{S_\mathrm{tot}}{S_\mathrm{f}(z)}$$

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

Cross-sectional area of the flow: S_f

Wetted perimeter: L_f



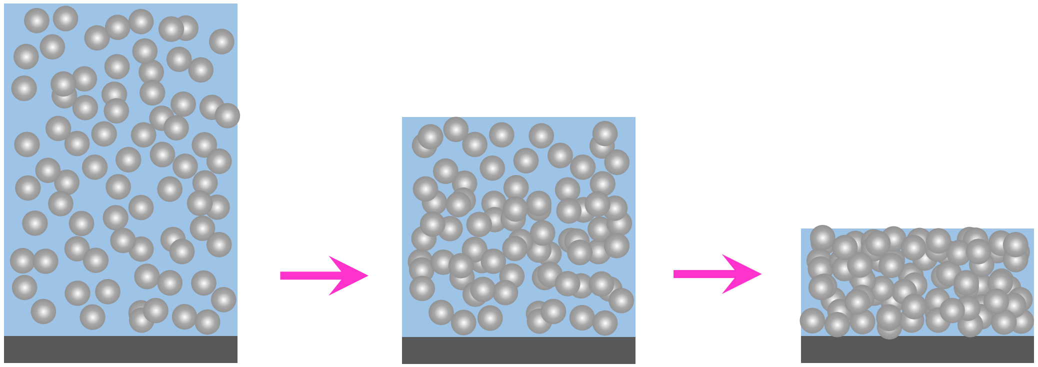


Permeability

Kozeny-Carman eq.

$$r_{\mathrm{KC}} = \frac{9}{4}\frac{k\eta}{d^2}\frac{\phi^2}{(1-\phi)^3} \qquad K_{\mathrm{KC}}(h) = \frac{1}{r_{\mathrm{KC}} h}$$

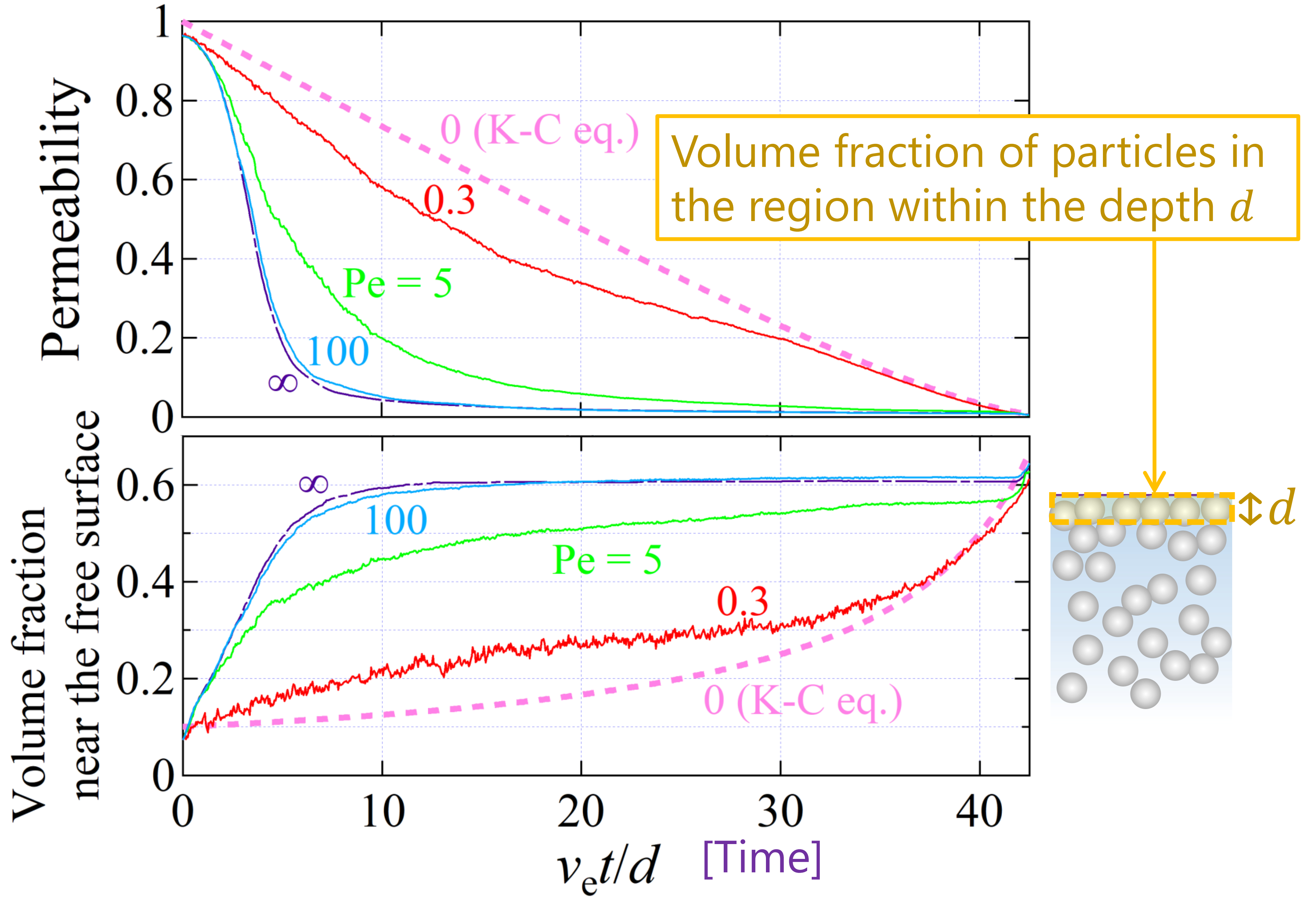
Homogeneous particle distribution



Quasi-static compression: Pe → 0

Volume fraction of particles: $\phi = \phi_0 \dfrac{h_0}{h}$

Permeability: $K(h)/K_{\mathrm{KC}}(0)$

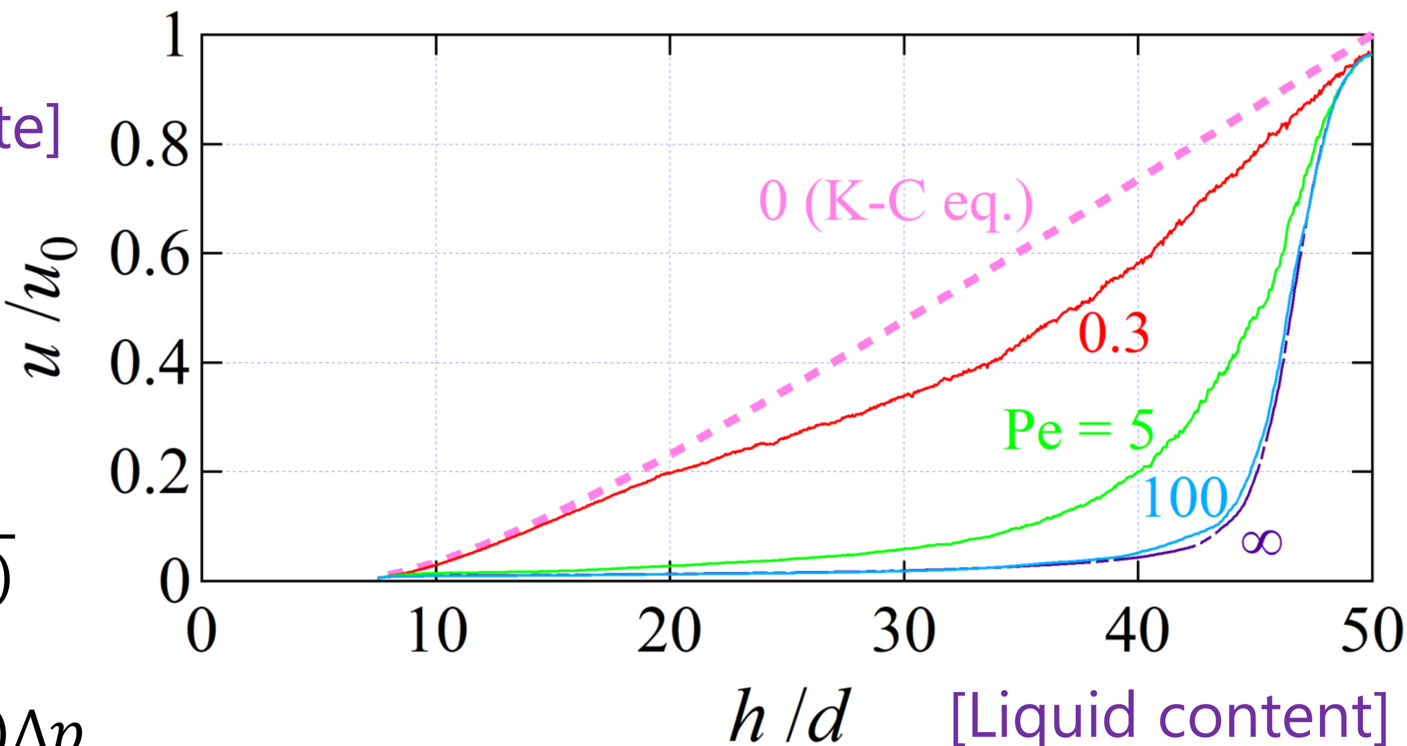


Drying Curve: $u = u(h)$

Assumption

- Constant pressure drop Δp during drying
- Falling drying rate period: Drying rate = u ($< v_e$)

[Drying rate]



[Liquid content]

$$\frac{u}{u_0} = \frac{K(h)}{K_{KC}(0)}$$

$$u_0 = K_{KC}(0)\Delta p$$

Initial drying rate estimated by K-C eq.

Drying Curve: $u = u(t)$

Recession rate of the free surface

$$u(h) = -\frac{\mathrm{d}h}{\mathrm{d}t} = K(h;\mathrm{Pe})\Delta p$$

Time when the free surface arrives at the height h

$$t = \int_{h_0}^{h} \frac{\Delta p}{K(h';\mathrm{Pe})}\mathrm{d}h'$$

→ Drying curve: $u = u(t)$

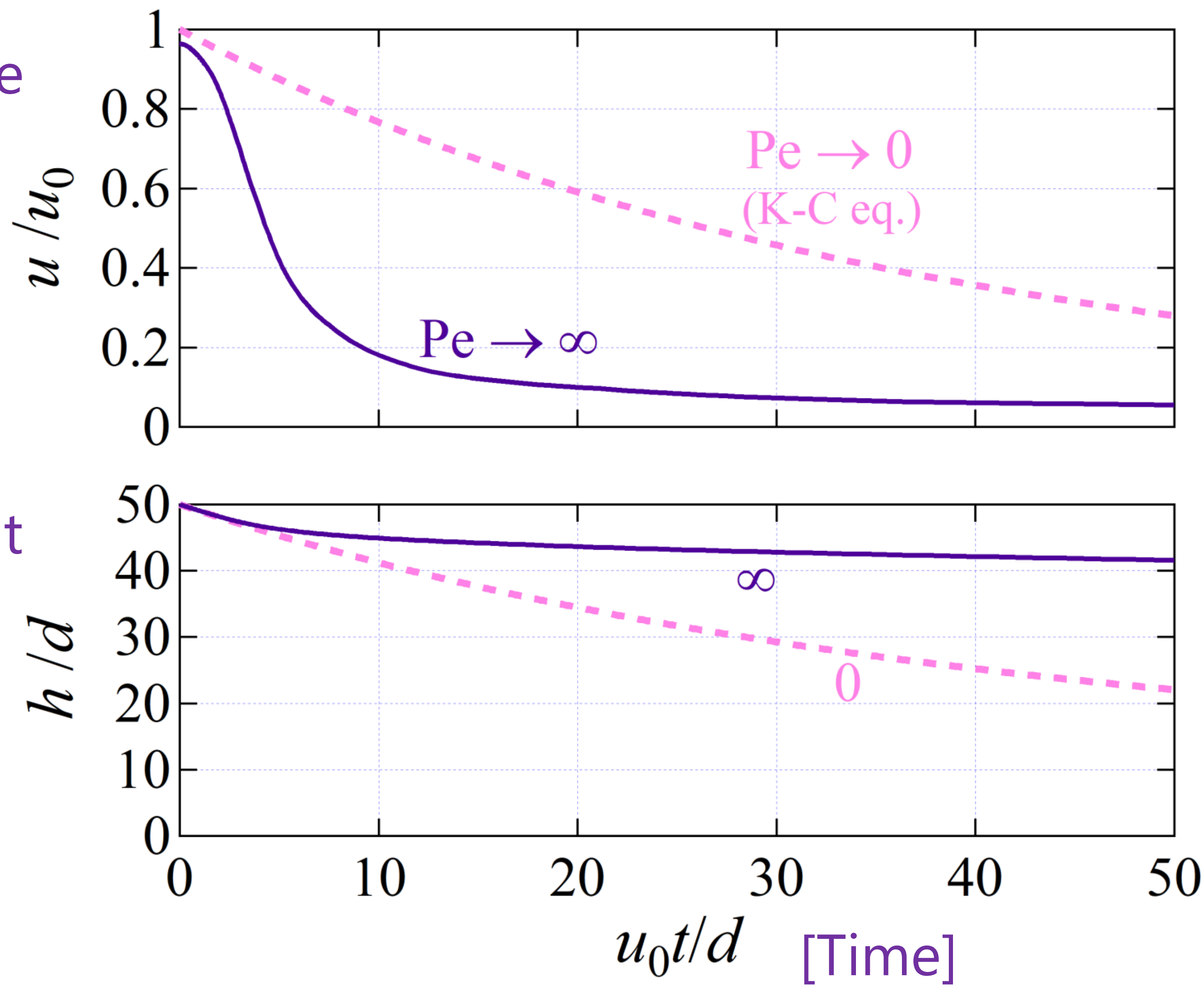
- Pe decreases during drying.
- $K(h;\mathrm{Pe})$ almost converges uniformly at $\mathrm{Pe} > 100$.

→ Drying curves at $\mathrm{Pe} \to 0$ and $\mathrm{Pe} \to \infty$ can be obtained.

Drying Curve: $u = u(t)$

Drying rate

Film height



[Time]

Summary

- The present simple model enables us to estimate the following:
  - Permeability dependent on the Péclet number
  - Drying curve at low/high Péclet number limit

- Future work: Prediction of the drying curve at a finite Péclet number

  ← Free surface receding with a time-varying rate