OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

IFPRI International Fine Particle Research Institute

Modelling porosity development during drying of liquids and slurries

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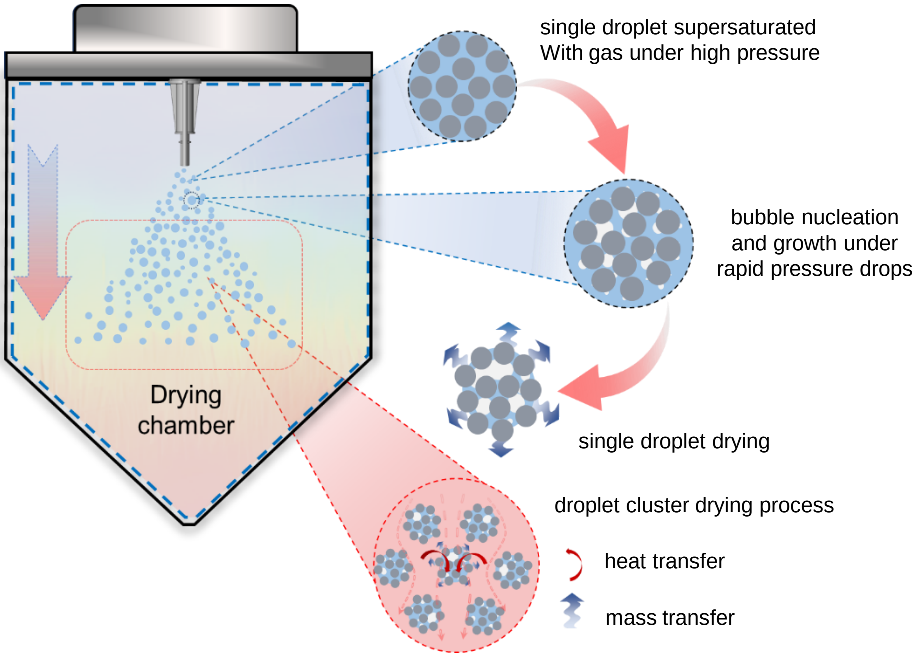
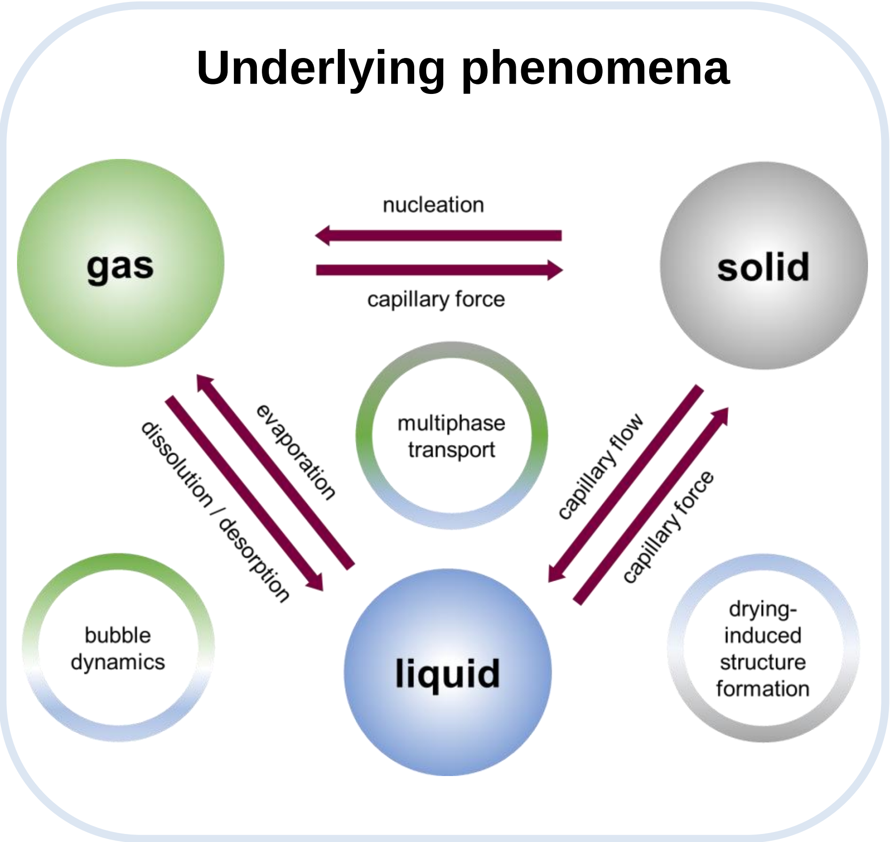
Context and key phenomena





Existing studies:

- ❑ rely on empirical data; product-specific
- ❑ lack a solid theoretical framework
- ❑ limit of their broader applicability

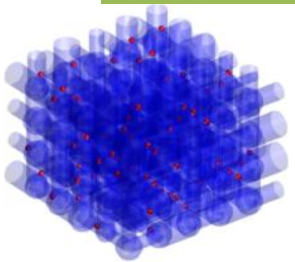
Progress: Past and present

- ❑ **bubble dynamics**
  - **bubble nucleation**
  - **bubble growth**
  - **bubble invasion**

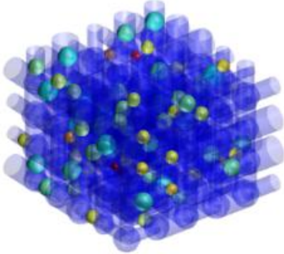
two-way coupling

- ❑ **drying process**
  - **liquid transport**
  - **vapor transport**

Previous work

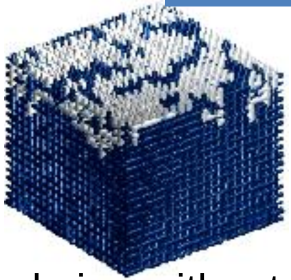


nucleation

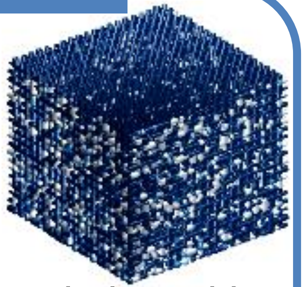


bubble growth

Current work



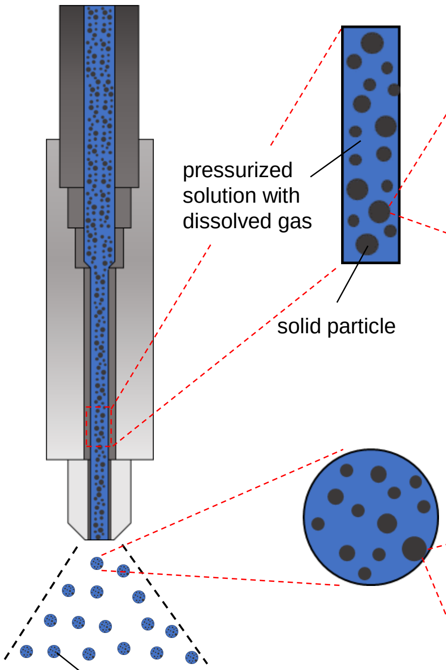
drying without bubbles

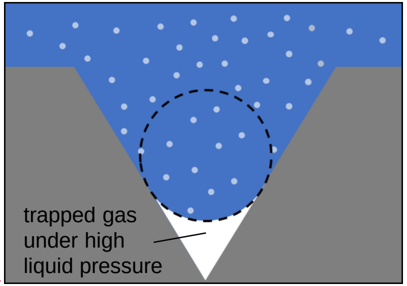


drying with bubbles

Bubble modeling approach: Discrete rules

bubble nucleation

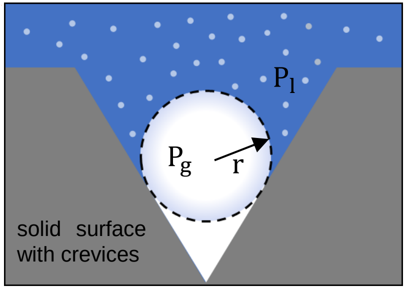




nucleation after pressure drop

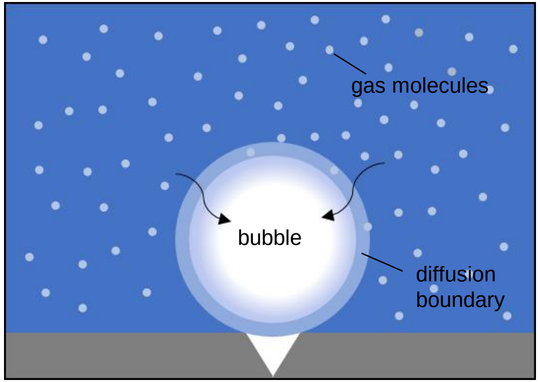
$$P_g = P_l - \frac{2\sigma}{r} \quad \text{(concave)}$$

$$P_g = P_l + \frac{2\sigma}{r} \quad \text{(convex)}$$



spraying liquid feed saturated with inert gas from pressure nozzle to drying chamber

bubble growth

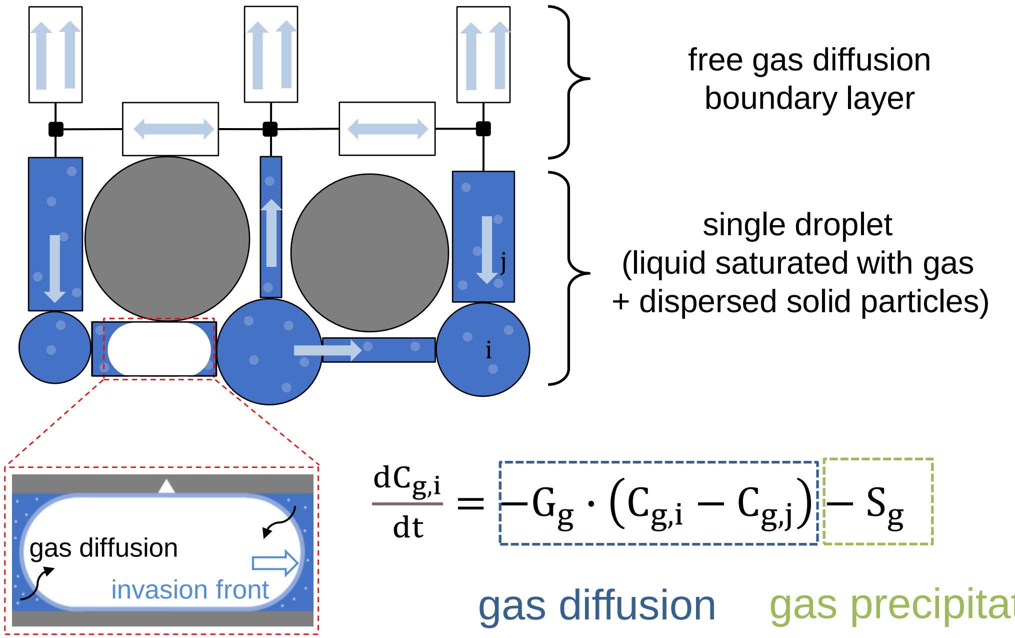


governing equations

$\frac{dn}{dt} = A_b \cdot D \cdot Sh \cdot \frac{(C_g - C^*)}{R_b}$	gas diffusion (Fick's law)
$C^* = \frac{P_g}{H}$	Henry's law
$P_g V_b = nRT$	ideal gas law
$P_g = P_l + \frac{2\sigma}{r}$	Young–Laplace equation

Bubble modeling approach: Discrete rules

dissolved gas diffusion

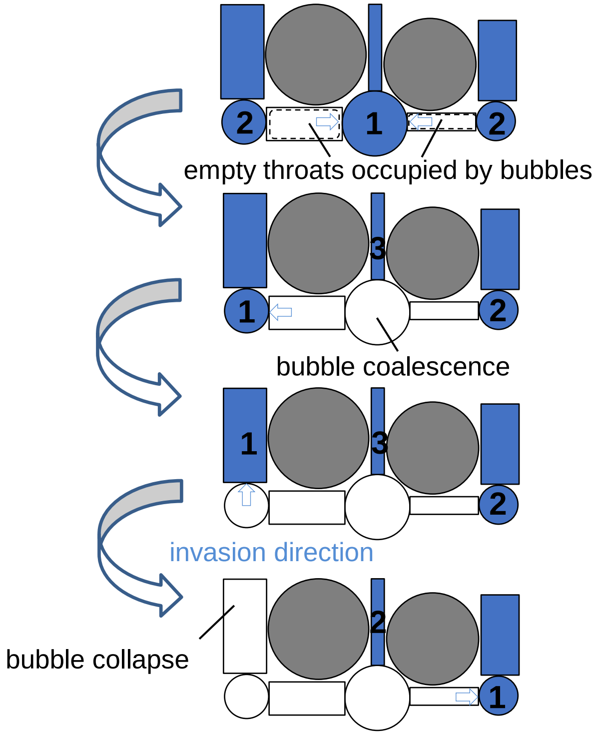


$$\frac{dC_{g,i}}{dt} = \boxed{-G_g \cdot (C_{g,i} - C_{g,j})} \boxed{- S_g}$$

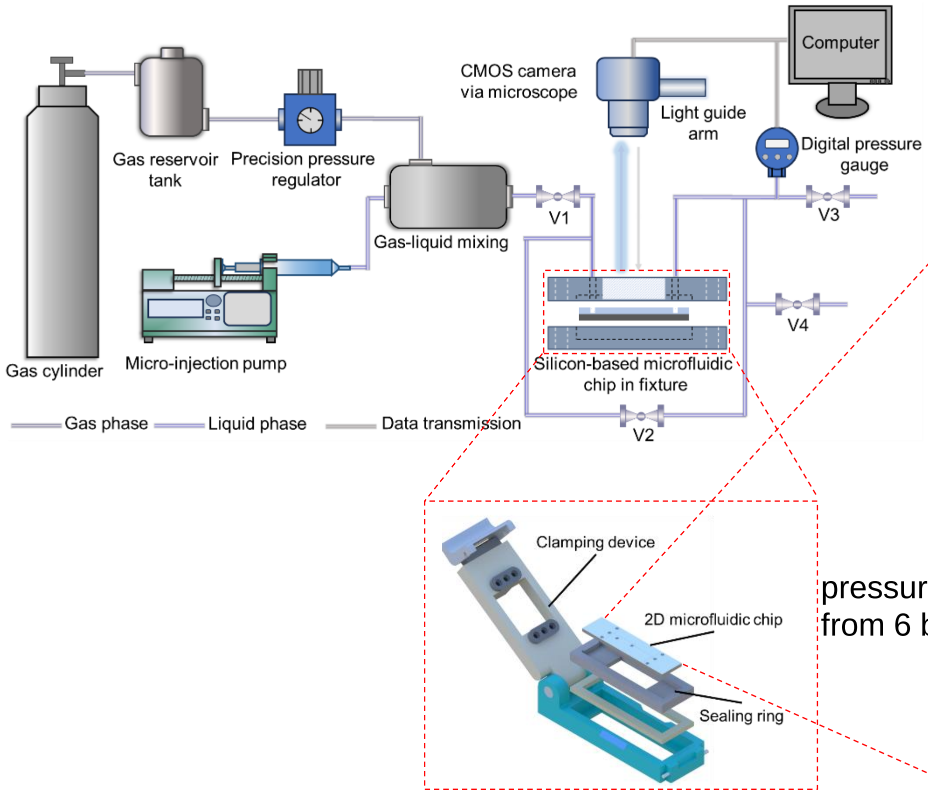
gas diffusion gas precipitation

$$S_g = A_b \cdot Sh \cdot D \cdot \frac{(C_g - C^*)}{2R_b}$$

bubble invasion in PNM



Preliminary microfluidic observation of bubbles

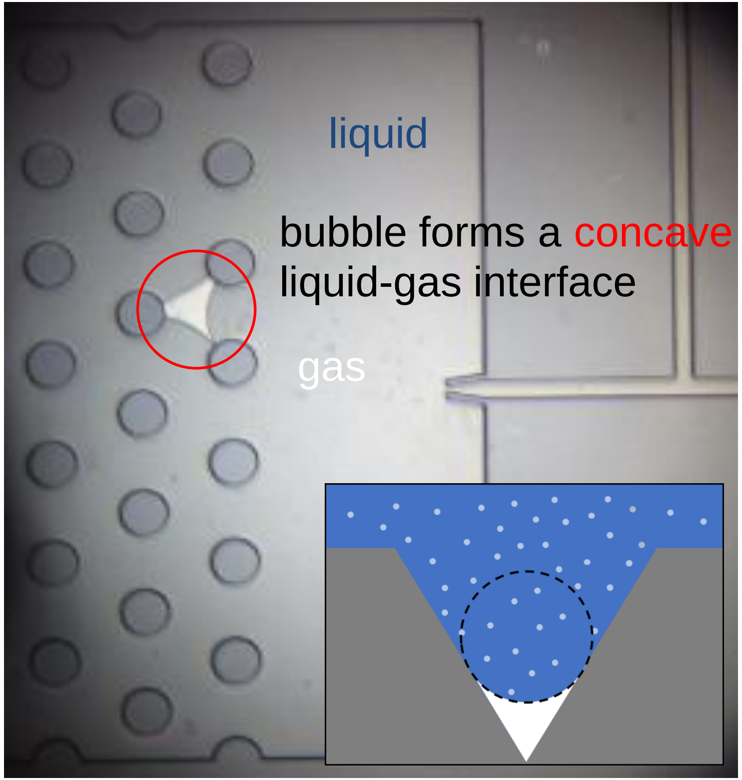


2D microfluidic system

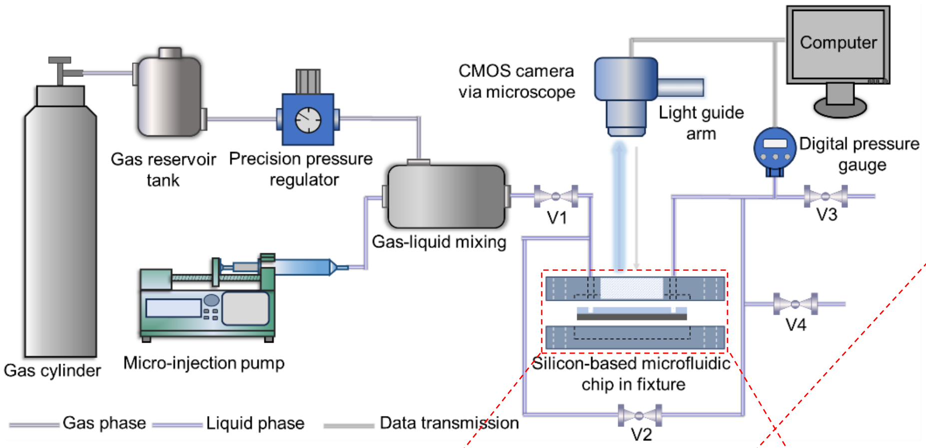
pressure drops from 6 bar to 1 bar

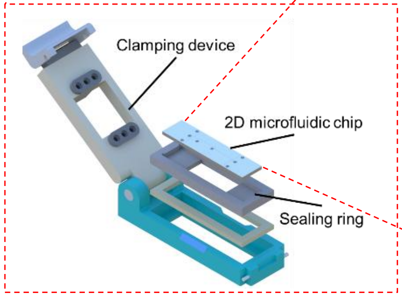
0 s

under high pressure



Preliminary microfluidic observation of bubbles

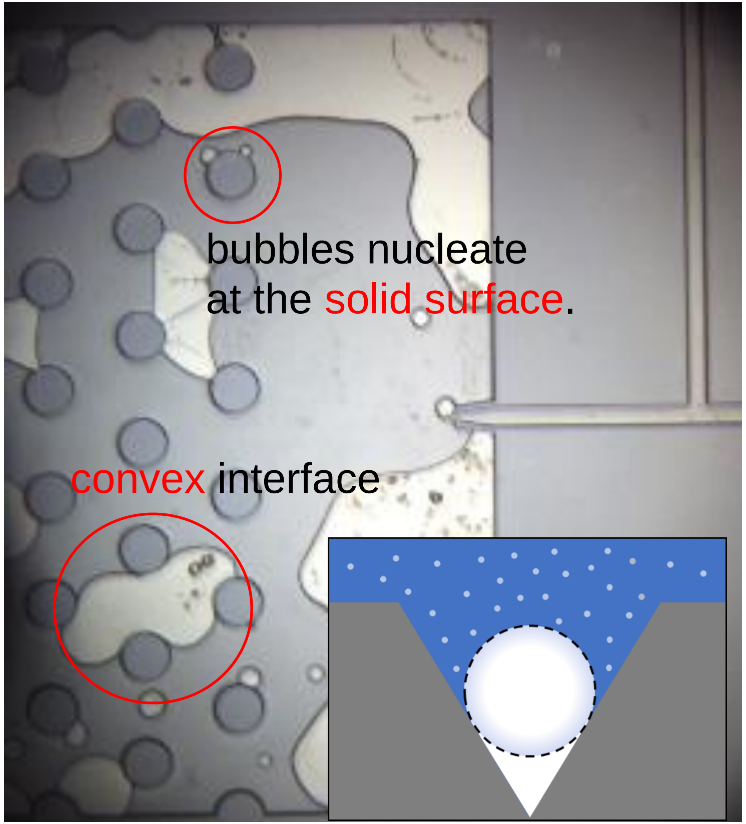




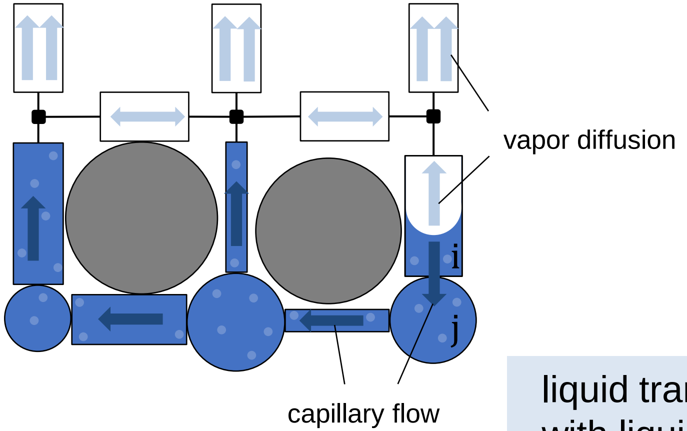
2D microfluidic system

after pressure drop

5 s



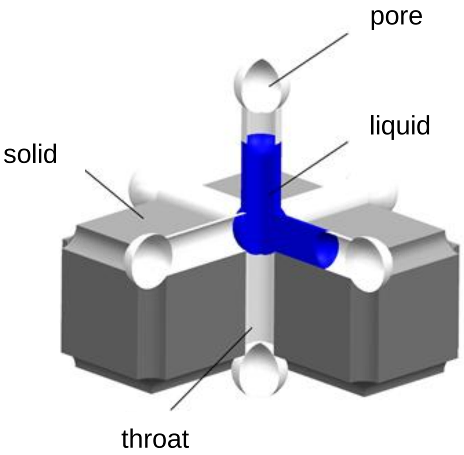
Drying modeling approach: Discrete rules



vapor diffusion: Stefan flow

$$\dot{M}_{v,ij} = -g_{v,ij} \cdot P \cdot \ln\left(\frac{P - P_{v,j}}{P - P_{v,i}}\right)$$

$$g_{v,ij} = \frac{D_{va}\tilde{M}_v A}{\tilde{R}T \cdot \delta}$$

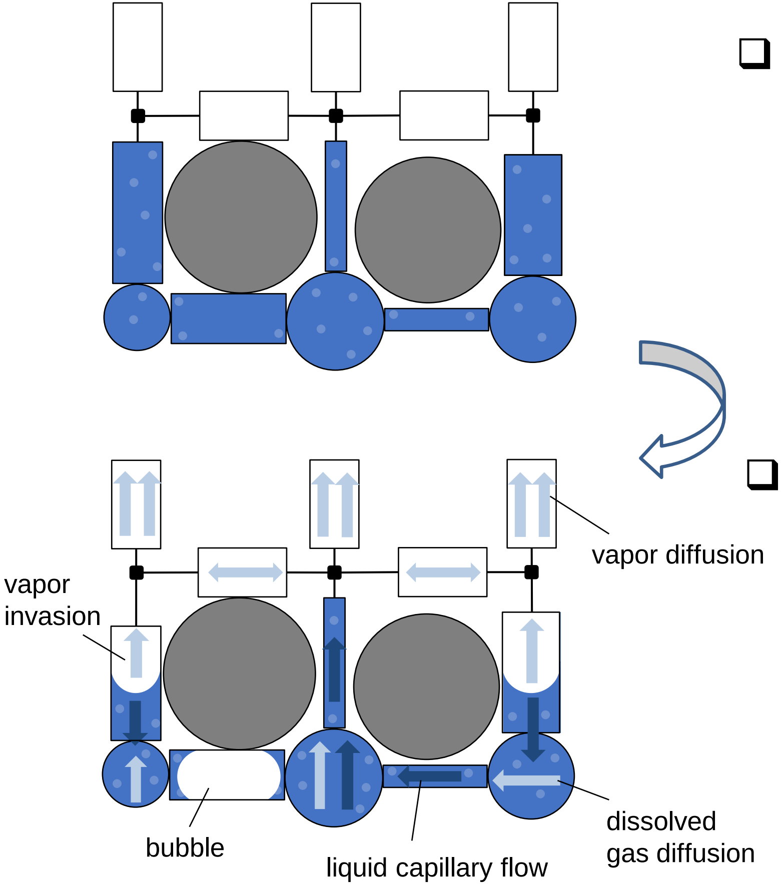


liquid transport: Capillarity combined with liquid flow resistance

$$\dot{M}_{w,ij} = -g_l \cdot \left(P_{l,j} - P_{l,i}\right)$$

$$g_l = \frac{\pi \rho_l A}{8\mu \cdot \delta}$$

Drying process coupled with bubble formation



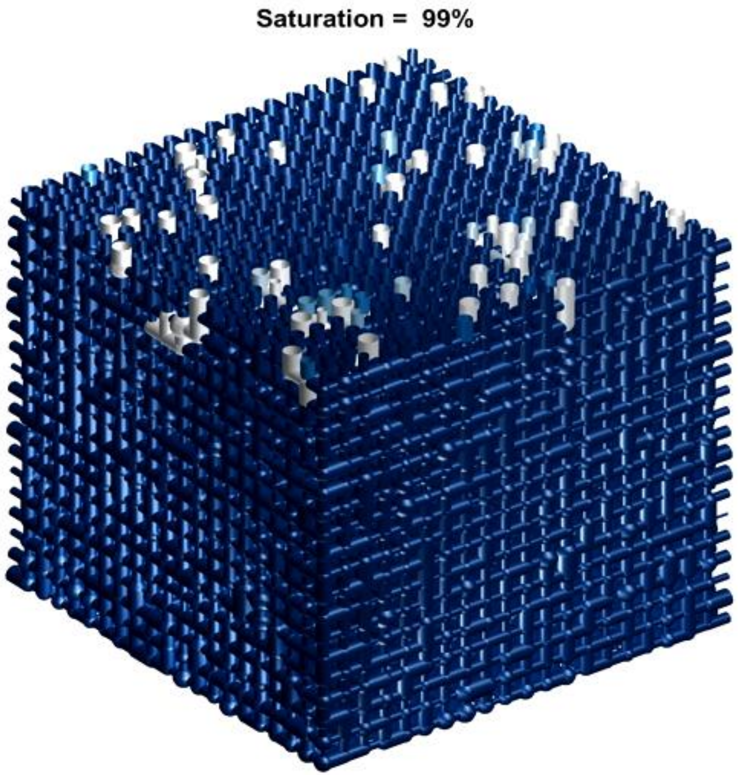
❑ effects of bubble on drying process:

- enhance capillary pumping
- increase the liquid transport resistance
- redistribute liquid

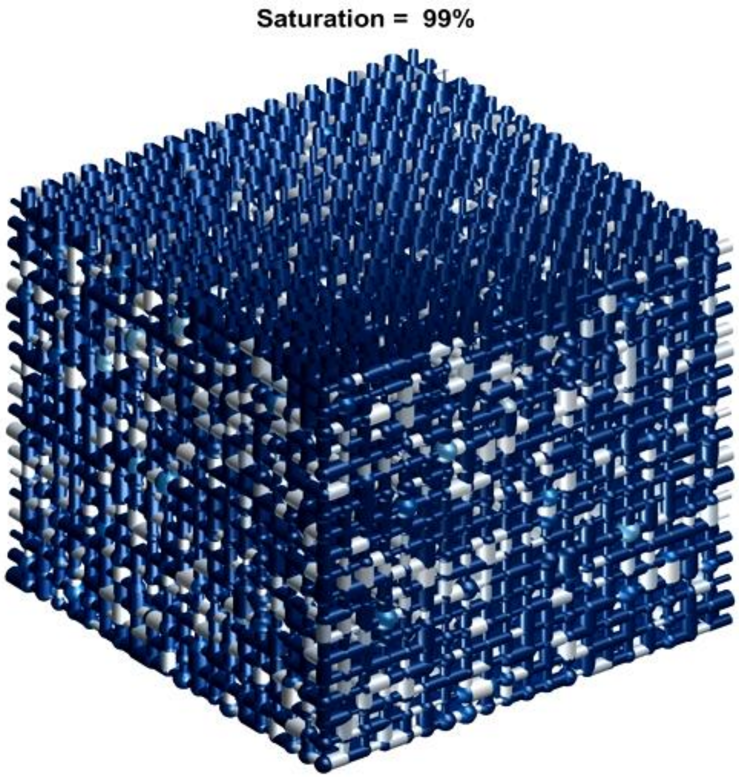
❑ effects of drying on bubble dynamic:

- bubble collapses when vapor invades
- gas concentration distribution affected by drying
- bubble growth or bubble shrinkage

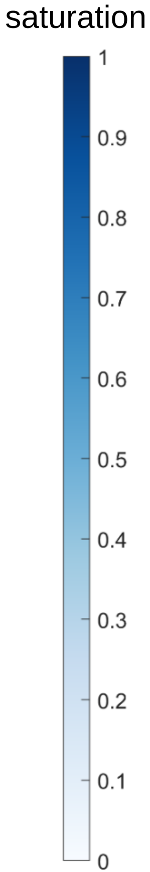
Drying simulations without and with bubbles



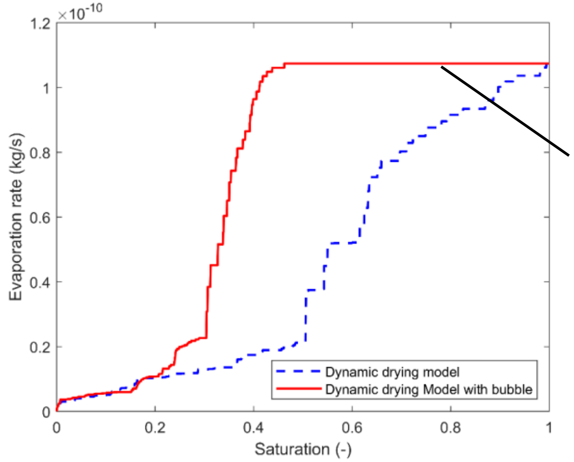
without bubbles



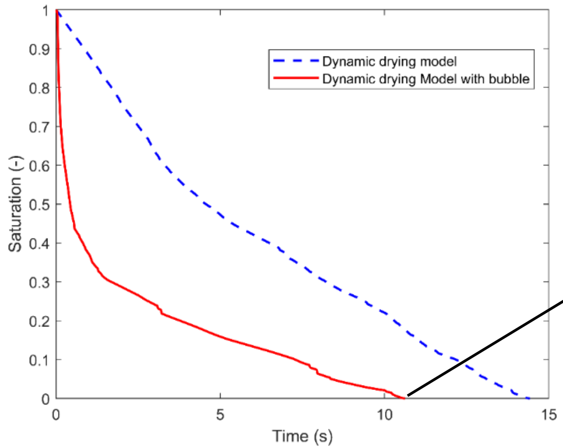
with bubbles



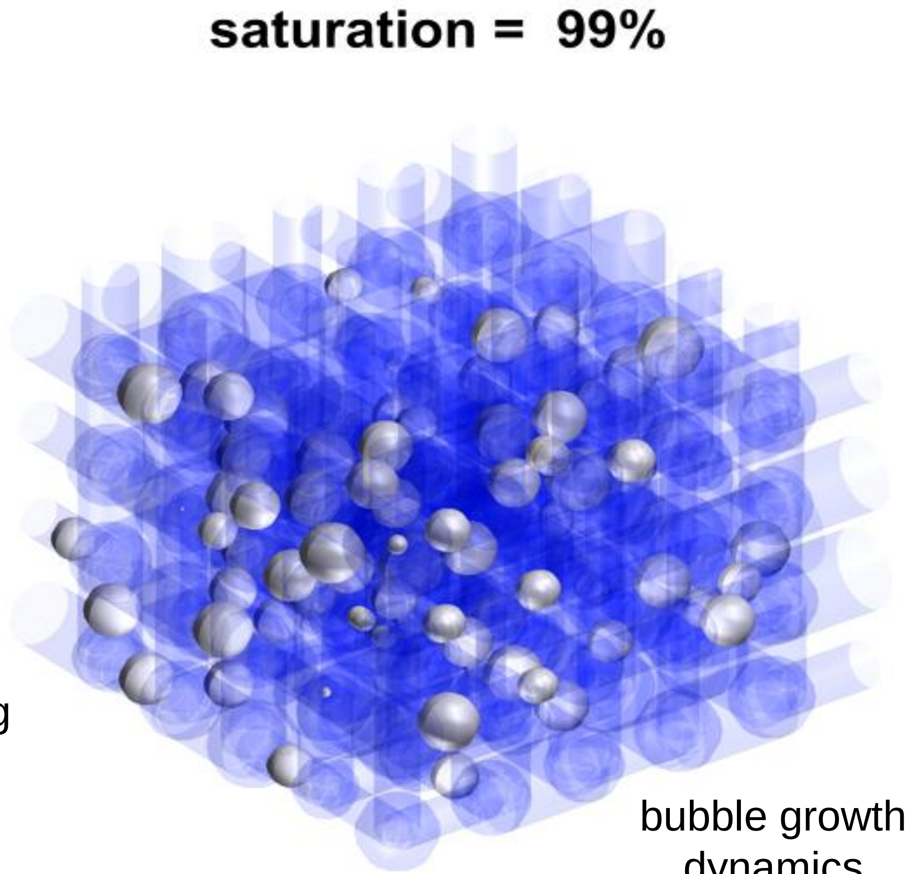
Drying kinetics and bubble growth dynamics



extended first drying period

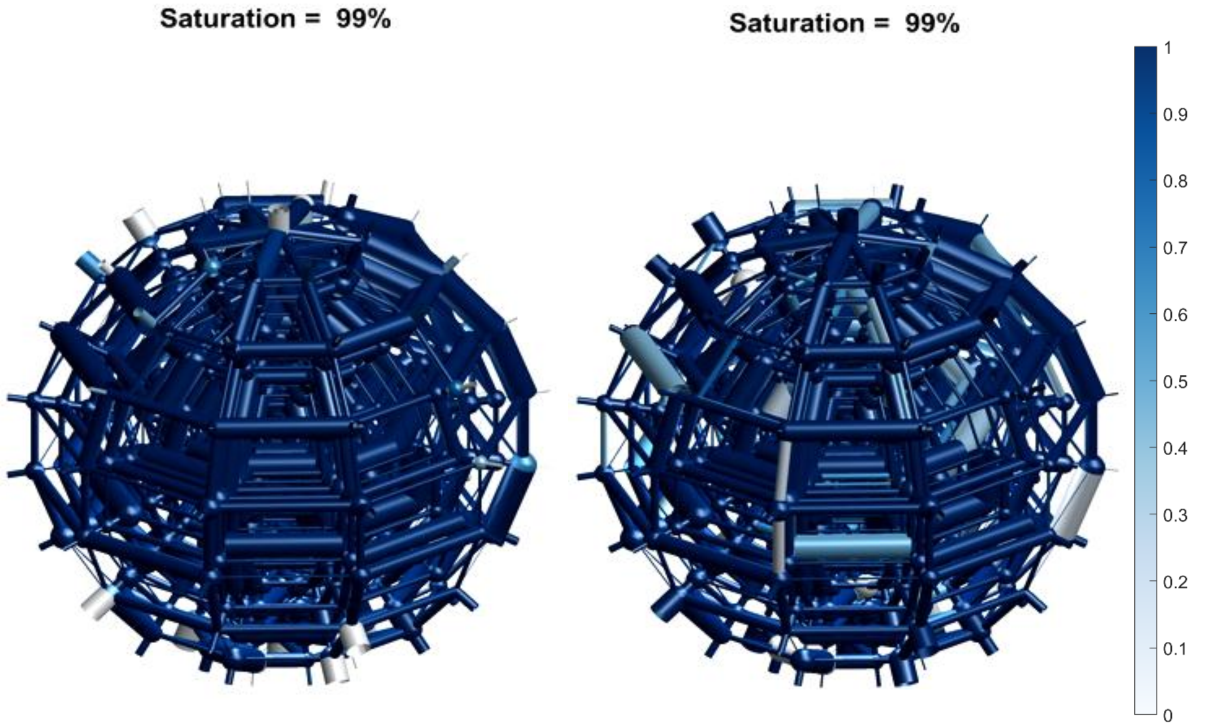


reduced drying time



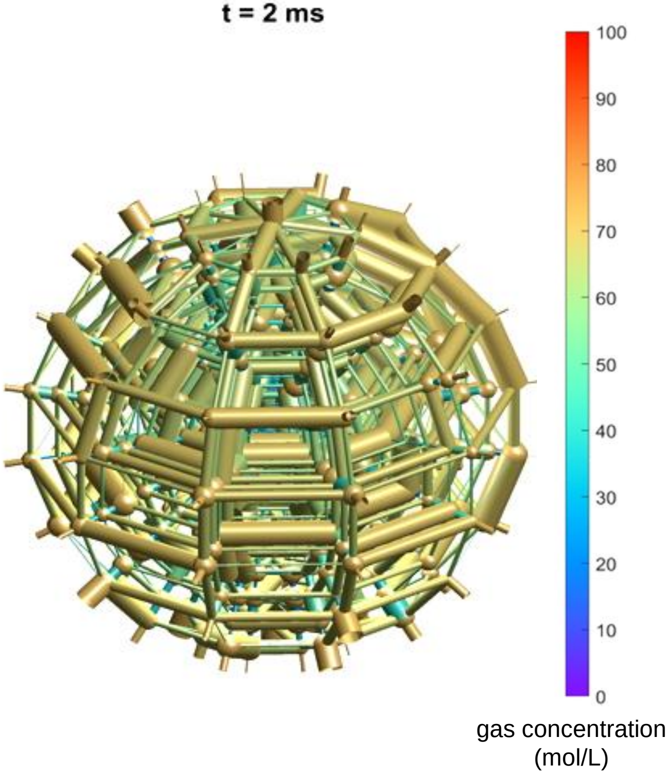
bubble growth dynamics

Drying simulations: Irregular and spherical pore networks



without bubbles

with bubbles



Summary

- Discrete rules for bubble formation and drying dynamics have been successfully formulated and implemented.
- 2D microfluidic experiments support for our bubble formation model.
- Both cubic and spherical pore network models are employed to simulate the coupled dynamics of bubble evolution and drying.
- The presence of bubbles reduces drying time, supporting the rationale for using foaming in spray drying.

On-going work

- Until now: Fixed structure, focus on drying kinetics with bubbles
- Next: Model morphology evolution and its impact on drying kinetics.