Experiment and simulation of quasistatic fluid invasion resulting in pressure-saturation (p-s) hysteresis

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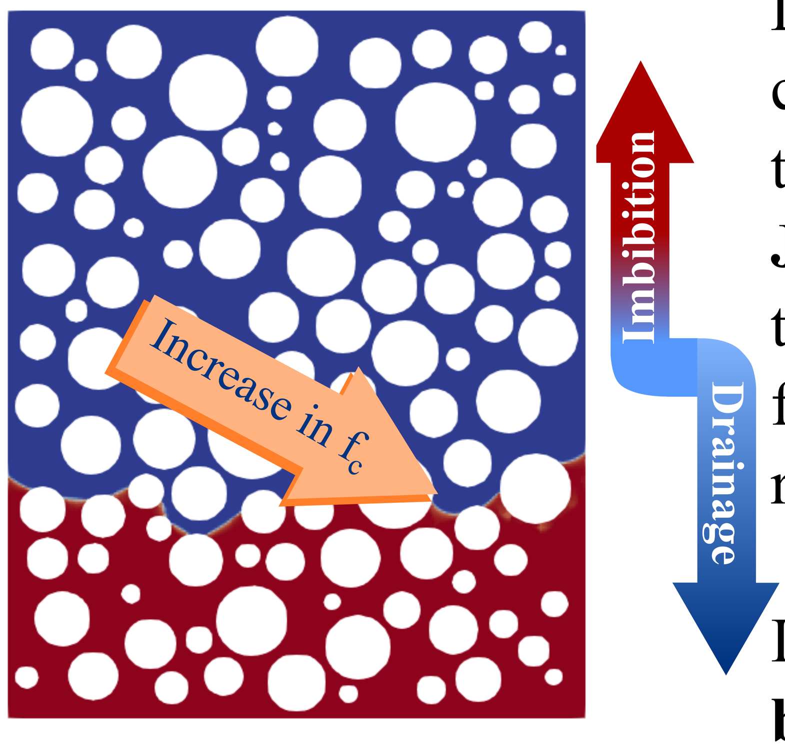
Introduction



During imbibition, fluid-fluid interface at the inlet of a constriction experiences an increase in capillary force (f_c) that results in rapid fluid invasion known as **Haines Jump [2]**. During drainage, the interface gets pinned at the end of the constriction that causes p-s trajectories to follow different paths during imbibition and drainage resulting in **p-s hysteresis**.

In our study, we seek to understand p-s behaviour in **ink-bottle** and **porous media** setups.

Objectives:

- To understand pore-scale pressure-saturation behaviour in quasistatic imbibition-drainage cycles
- To link pore-scale capillary physics to large-scale fluid displacements (Haines-Jump) resulting in p-s hysteresis

Importance: To derive upscaled model for p-s hysteresis in porous media

Methods

- 2D simulations were run in OpenFOAM
- Volume of fluid (VOF) [3] was used to differentiate two phases
- Navier-Stokes (N-S) and continuity equations were solved

N-S Equation

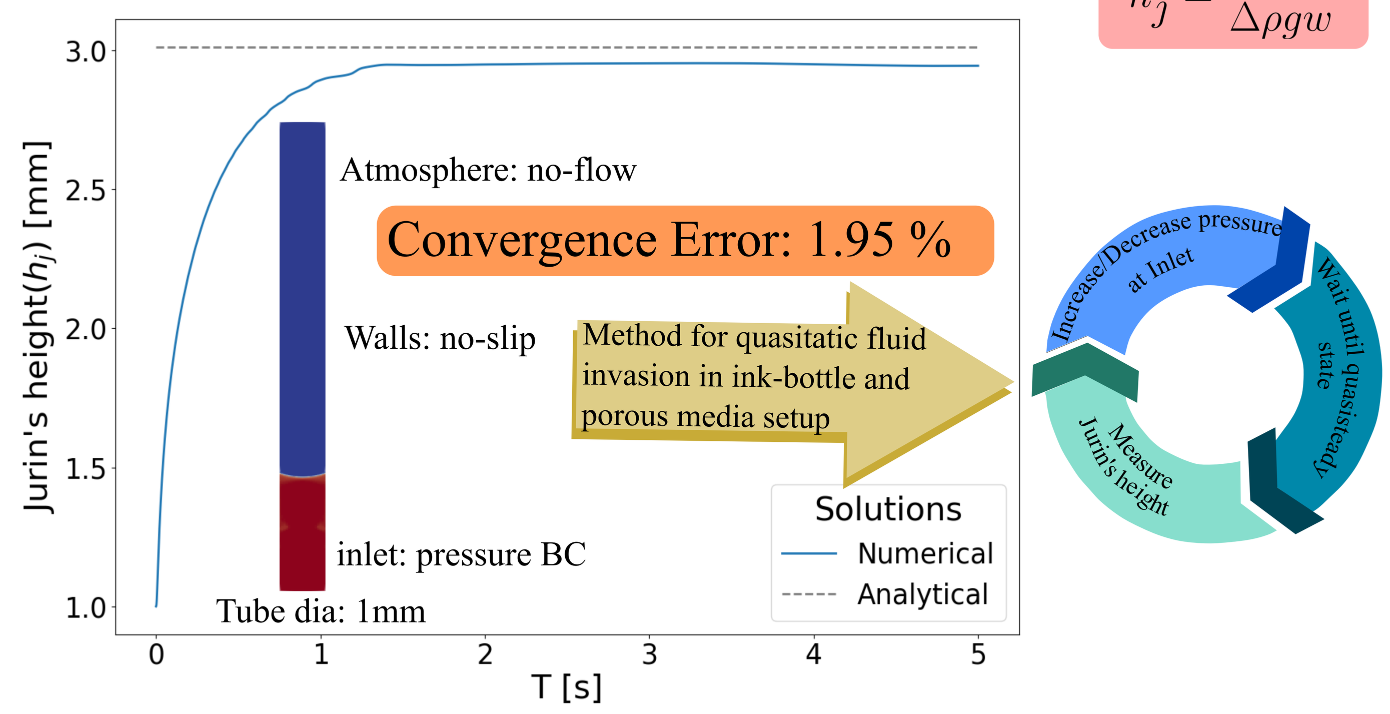
$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla\cdot(\rho\mathbf{v}\mathbf{v}) = -\nabla p + \nabla\cdot[\mu(\nabla\mathbf{v}+\nabla\mathbf{v}^{\mathbf{T}})] + \rho\mathbf{g} + \mathbf{F}_{st}$$

Where $F_{st} = \sigma\kappa\nabla\alpha$

Surface tension (F_{st}) is estimated using Continuum Surface Force (CSF) [1] model

Solver Validation

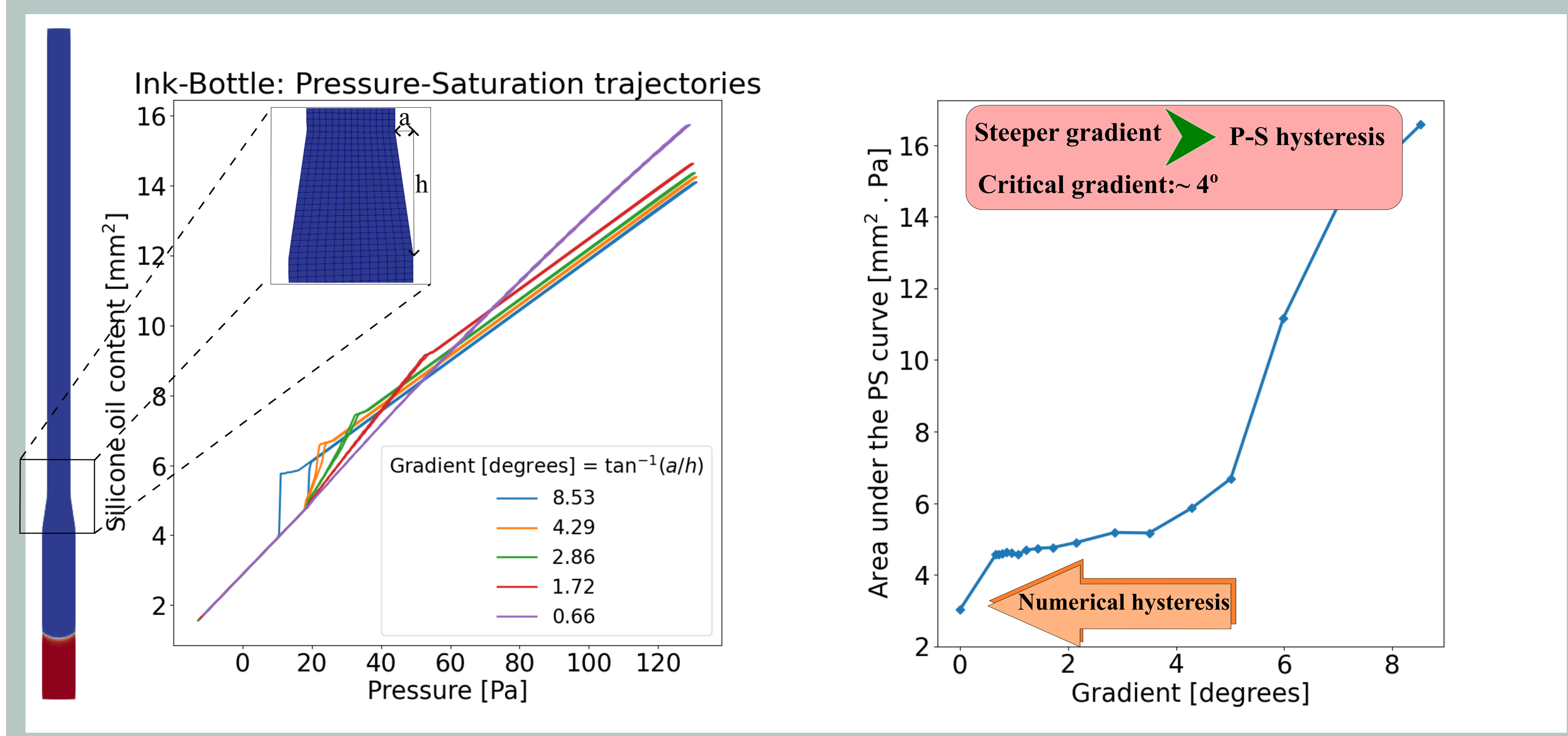
Liquid rise in a 2D capillary tube is : $h_j = \frac{\sigma\cos\theta}{\Delta\rho g w}$



Ink-Bottle

I. Simulation: P-S hysteresis in 2D Ink-bottle

Quasistatic capillary rise in a tube is analyzed for p-s hysteresis.
Problem setup wetting fluid is silicone oil, non-wetting fluid is air.
Pressure at the inlet is varied quasistatically.



II. Analytical Solution

Analytical solution to obtain Jurin's height in a tube with a constriction is derived using **Young-Laplace equation**.

At interface equilibrium,

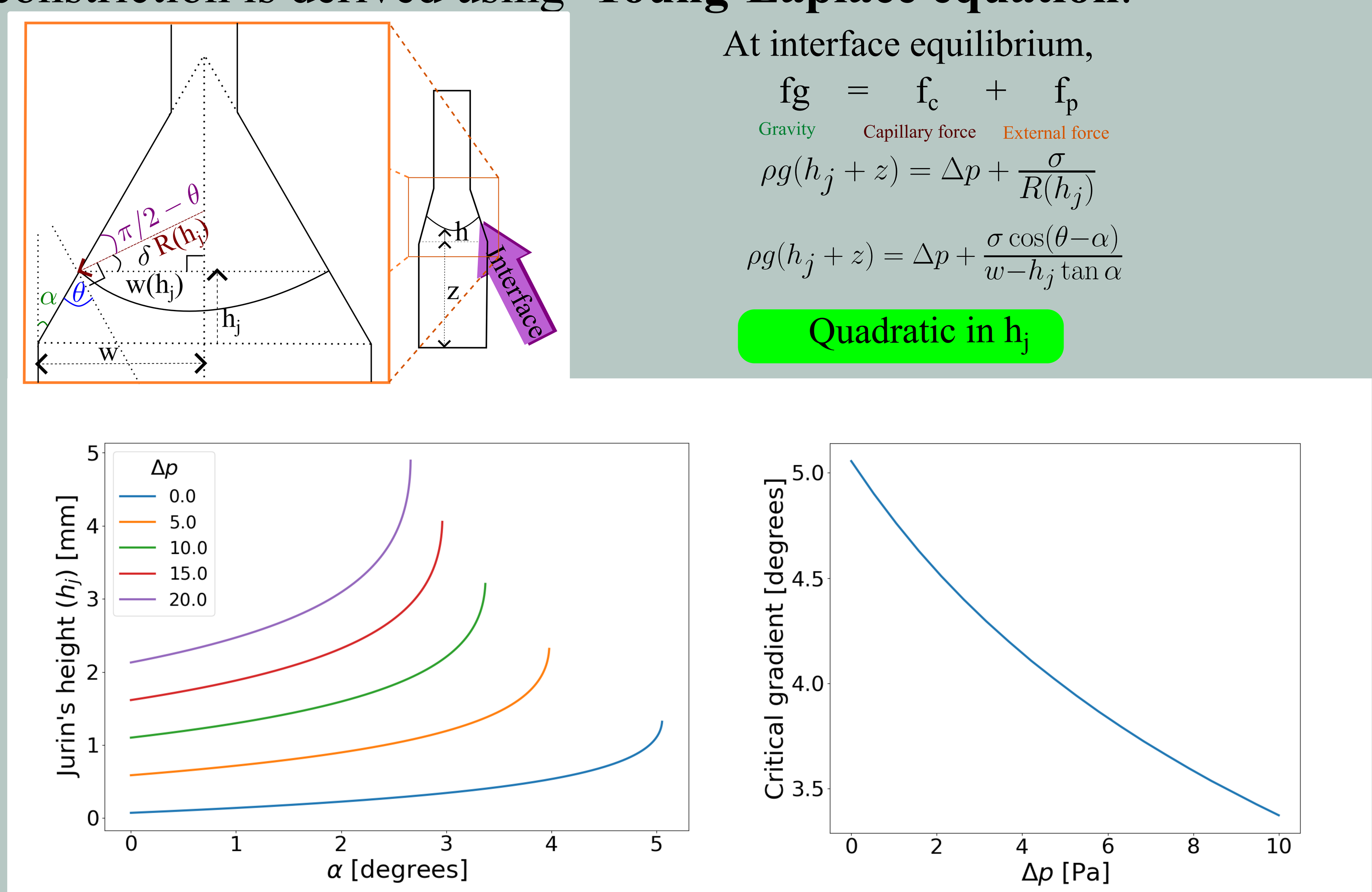
$$f_g = f_c + f_p$$

(Gravity, Capillary force, External force)

$$\rho g(h_j + z) = \Delta p + \frac{\sigma}{R(h_j)}$$

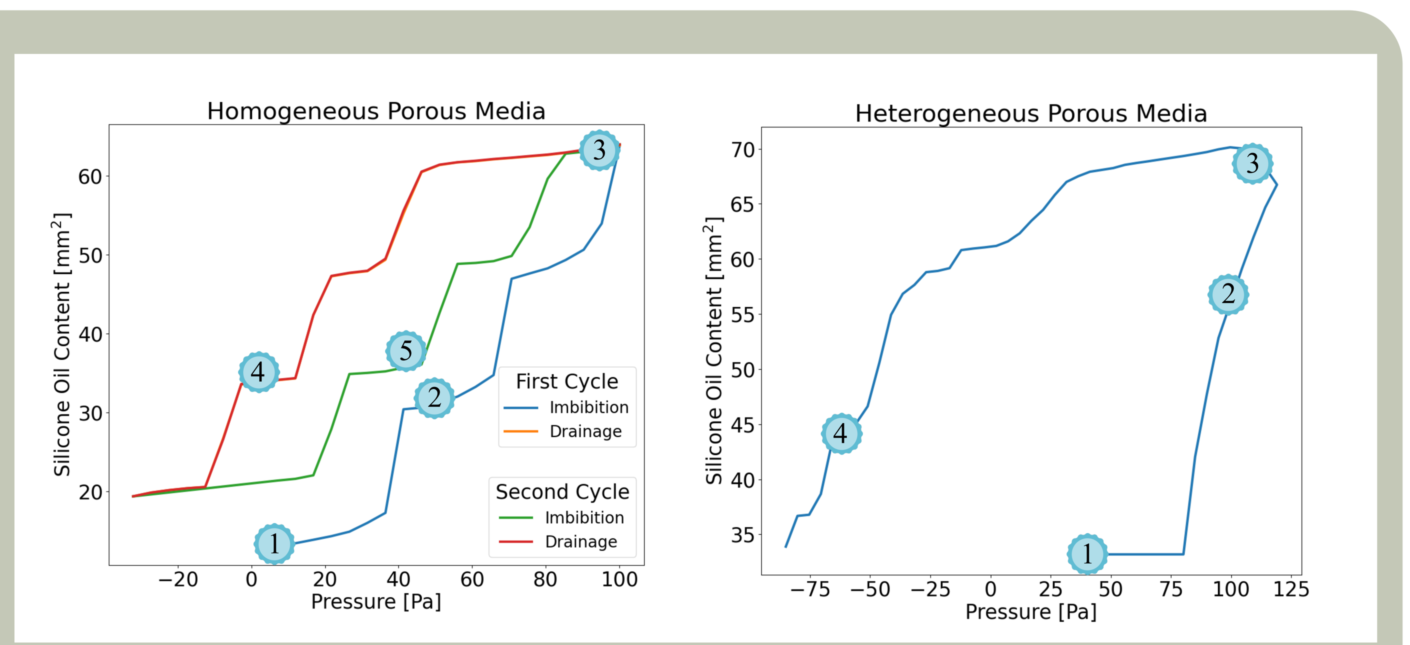
$$\rho g(h_j + z) = \Delta p + \frac{\sigma\cos(\theta-\alpha)}{w - h_j\tan\alpha}$$

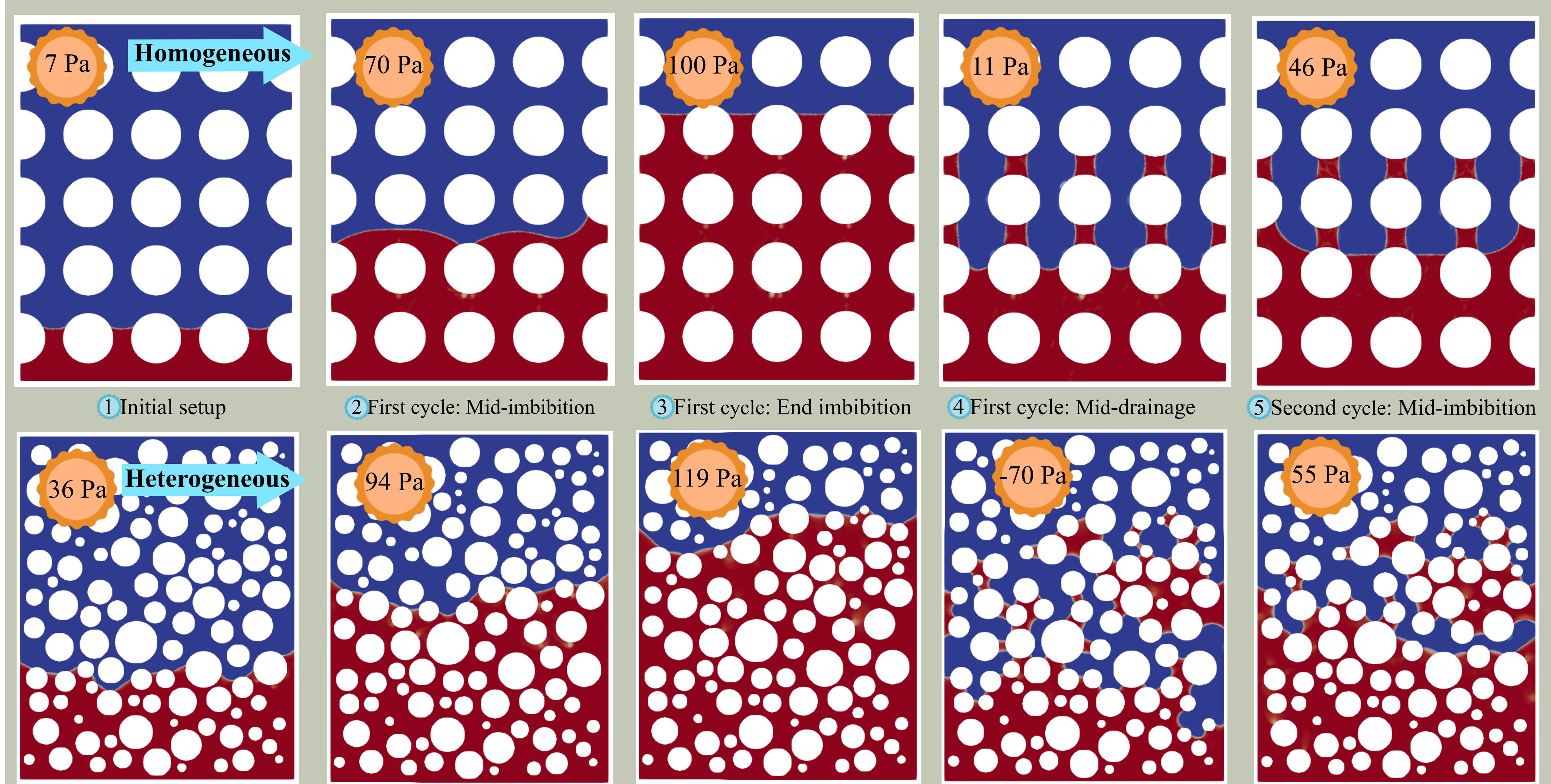
Quadratic in h_j



Porous Media

Quasistatic fluid invasion is analyzed in homogeneous and heterogeneous porous media. We analyzed fluid invasion and retension pattern during imbibition-drainage cycles resulting in p-s hysteresis. **Problem setup** wetting fluid is silicone oil, non-wetting fluid is air. Pressure at the inlet is varied quasistatically. Dimension : [10mm X 12mm]





Conclusions

- Haines jump in ink-bottle depends on cross-section gradient and pressure difference
- Fluid retained in small pores after the first imbibition-drainage cycle facilitated fluid invasion such that the fluid invaded with less pressure in subsequent cycle

References:

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[2] Haines W. B. (1930). Studies in the physical properties of soil. v. the hysteresis effect in capillary properties, and the modes of moisture distribution associated therewith. The Journal of Agricultural Science 20(1), 97–116.
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