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NTNU-UiO Porous Media Laboratory

Norwegian Centre of Excellence
The Research Council of Norway

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Norwegian University of Science and Technology

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Impact of gravity on pore-scale steady-state flow patterns

Fredrik K. Eriksen, PoreLab Oslo

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Introduction

Steady-state, simultaneous two-phase flow in porous media: An experimental study

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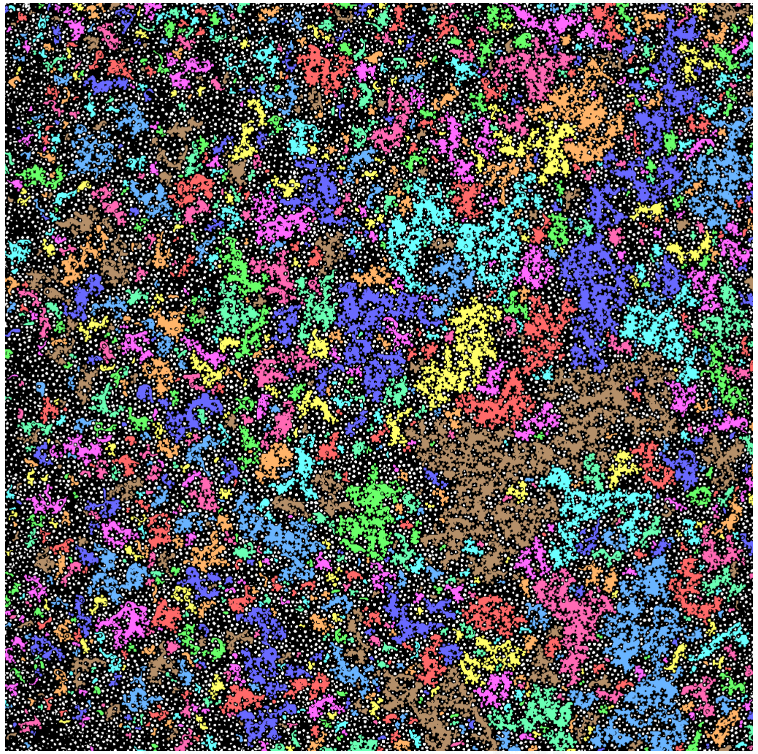
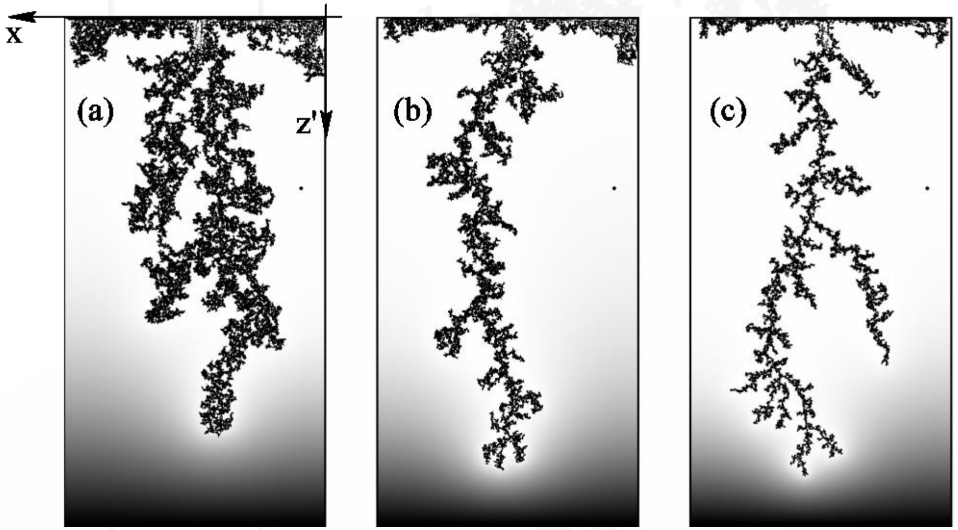
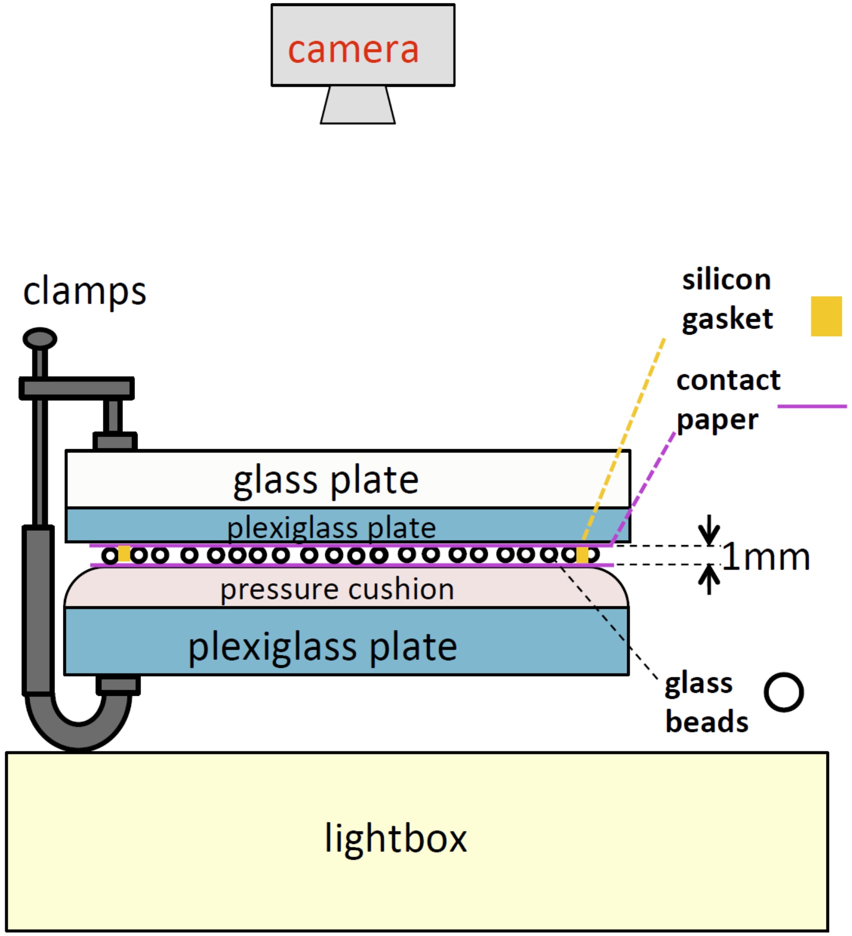
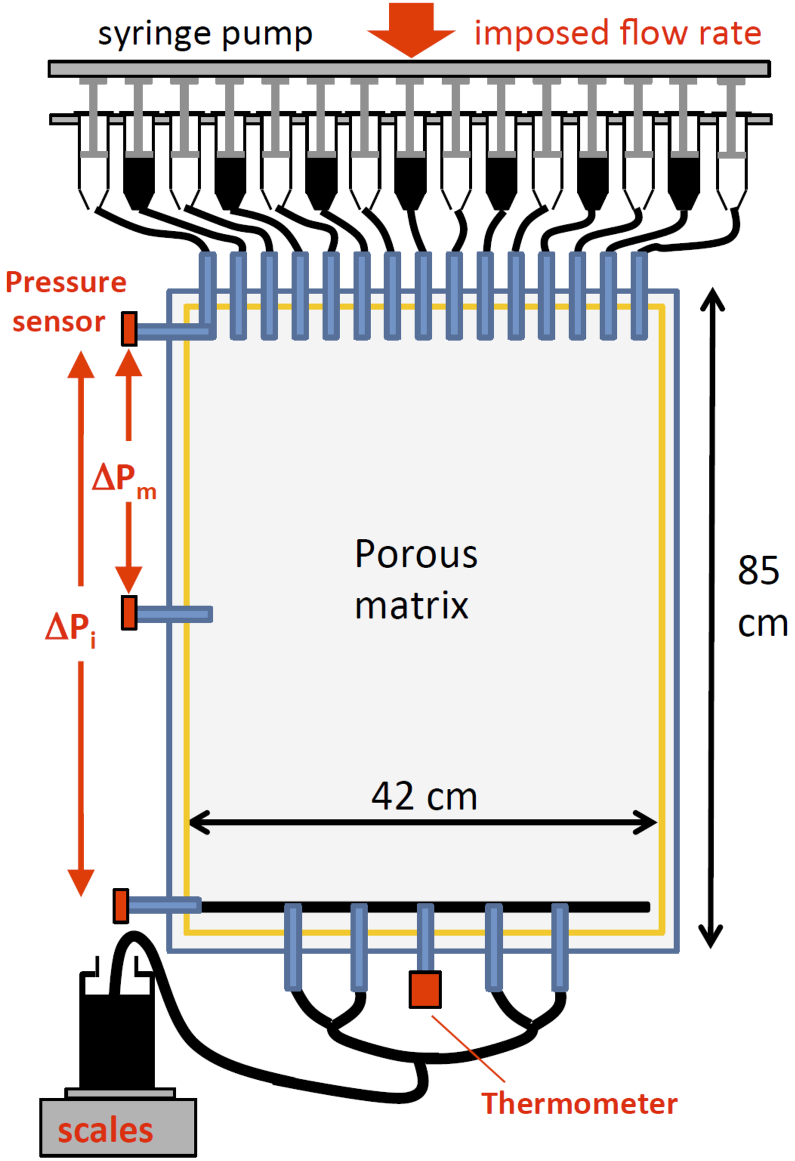




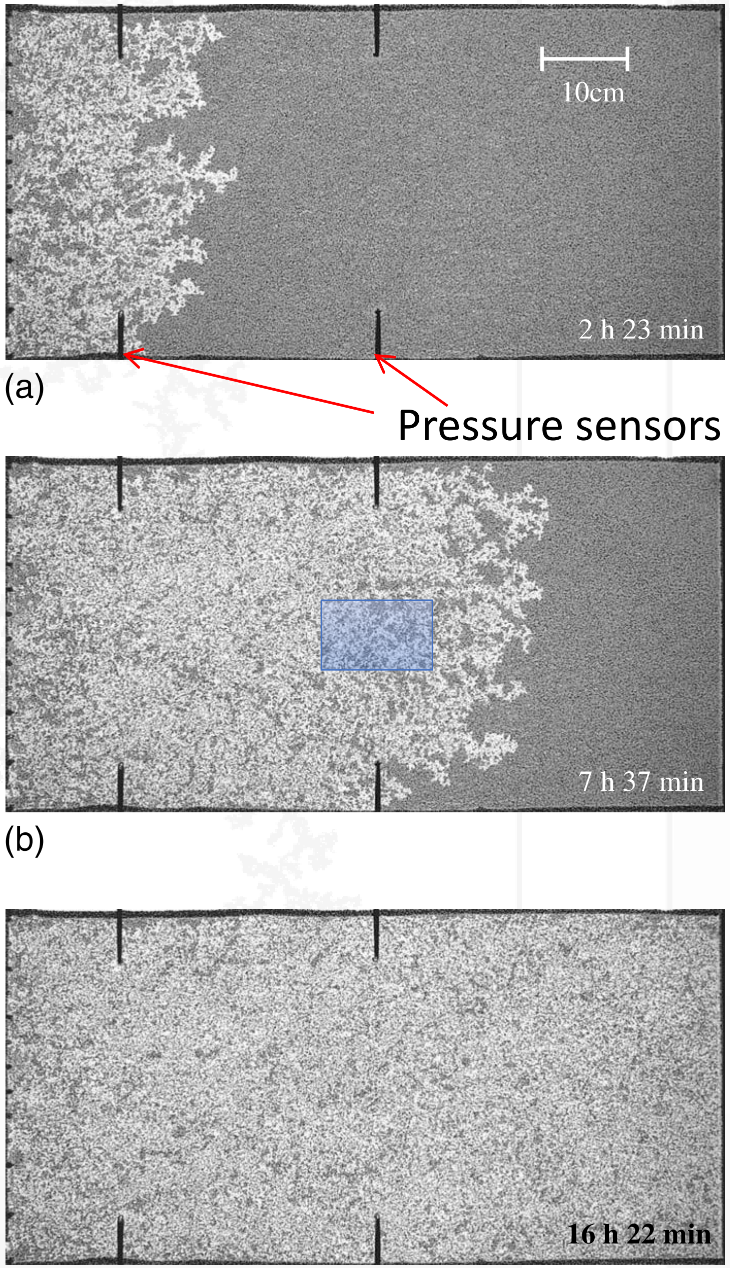
Experimental setup





- Quasi-2-D porous medium
- Wetting fluid:
  85 % Glycerol – 15 % Water
- Non-wetting fluid:
  Air

Typical evolution of experiments



Early transient regime, initial drainage

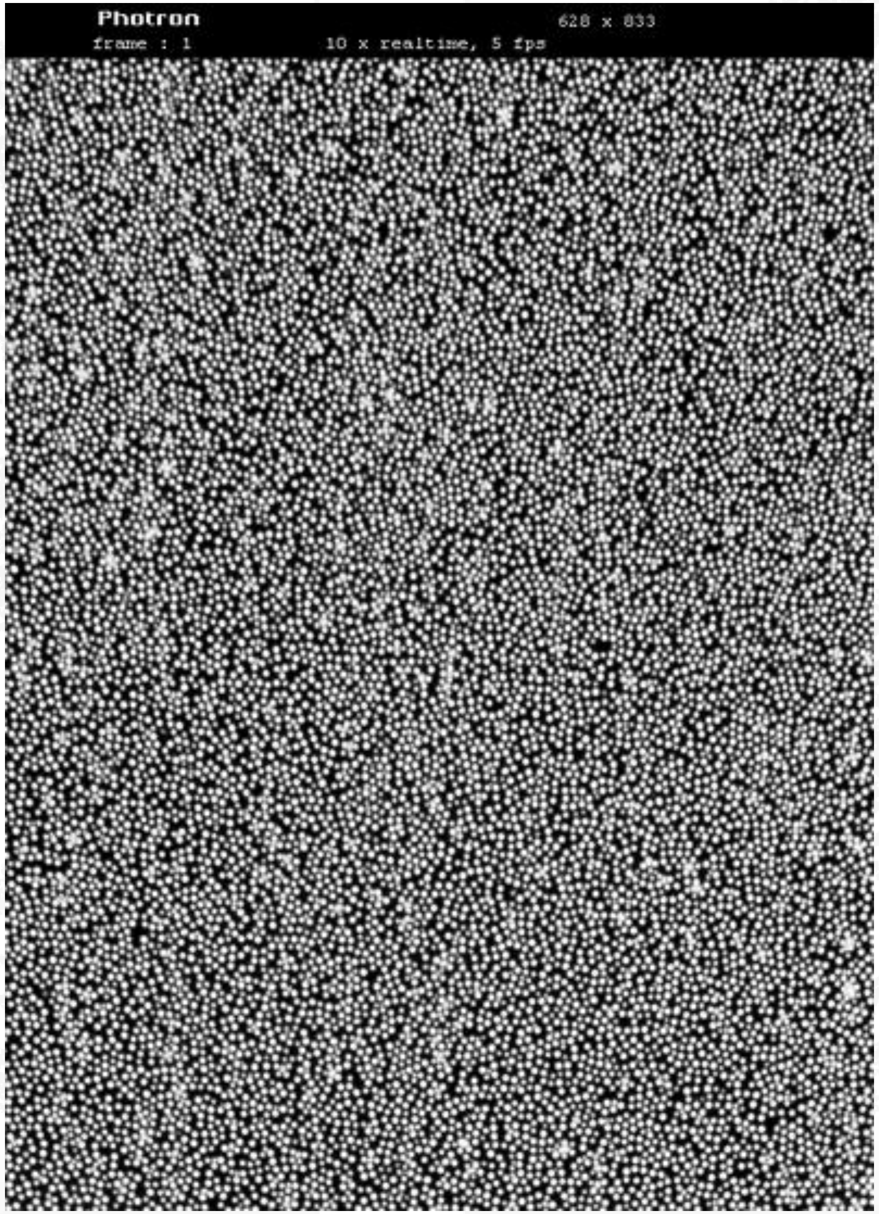
Front: Transient regime

Behind: Steady-state regime

Fully developed steady-state regime

Ca = 0.0079

Steady state experiments



Fast experiment.

10 times real time, Ca = 0.090

10cm x 15 cm section in the middle of the model.

Non-wetting phase:
- Trapped clusters
- Mobile clusters
- Dynamic coalescence and fragmentation

Wetting phase:
- Flows through narrow channels between non-wetting clusters

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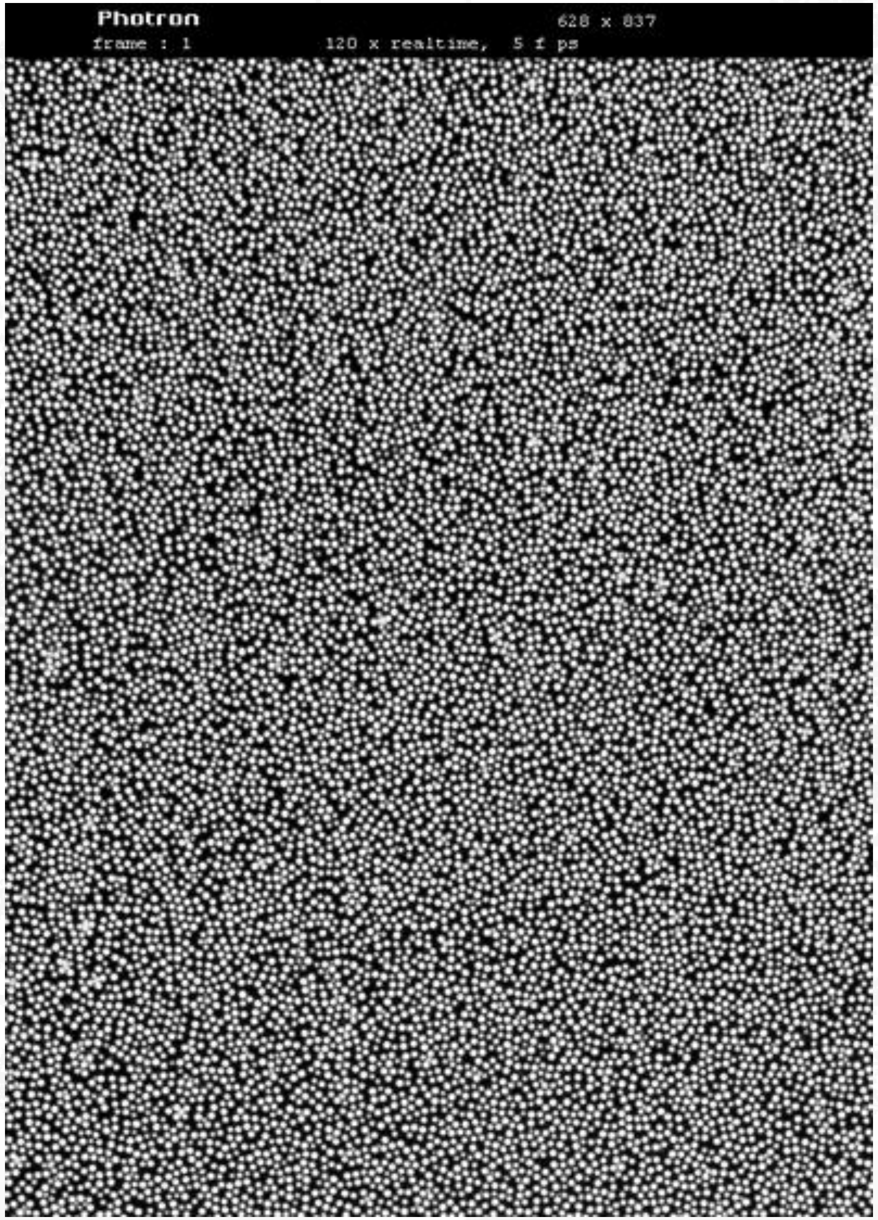
Steady state experiments



Slow experiment.

120 times real time, Ca = 0.0079

10cm x 15 cm section in the middle of the model.

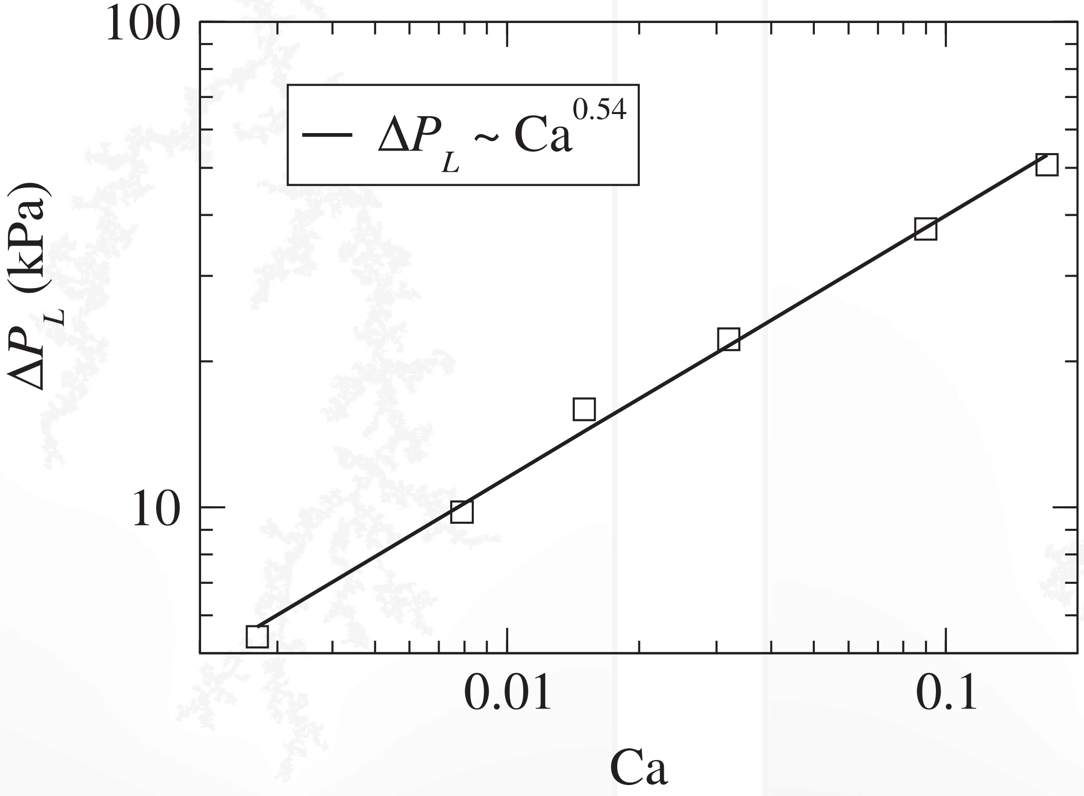
Non-wetting phase:
- Trapped clusters
- Mobile clusters
- Dynamic coalescence and fragmentation

Wetting phase:
- Flows through narrow channels between non-wetting clusters

Background

In a given steady-state regime, parameters such as the pressure drop, non-wetting cluster size distribution and saturation are found to be statistically stable

Pressure dependence on capillary number Ca



Tallakstad et al PRL **102,** 0742, (2009)

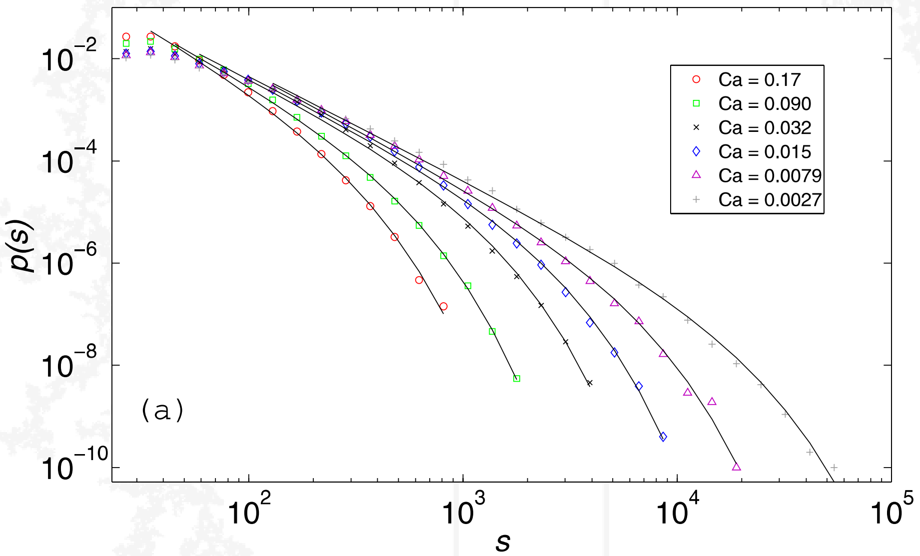
$$\mathrm{Ca} = \frac{\mu_w Q_w a^2}{\gamma \kappa_0 A}$$

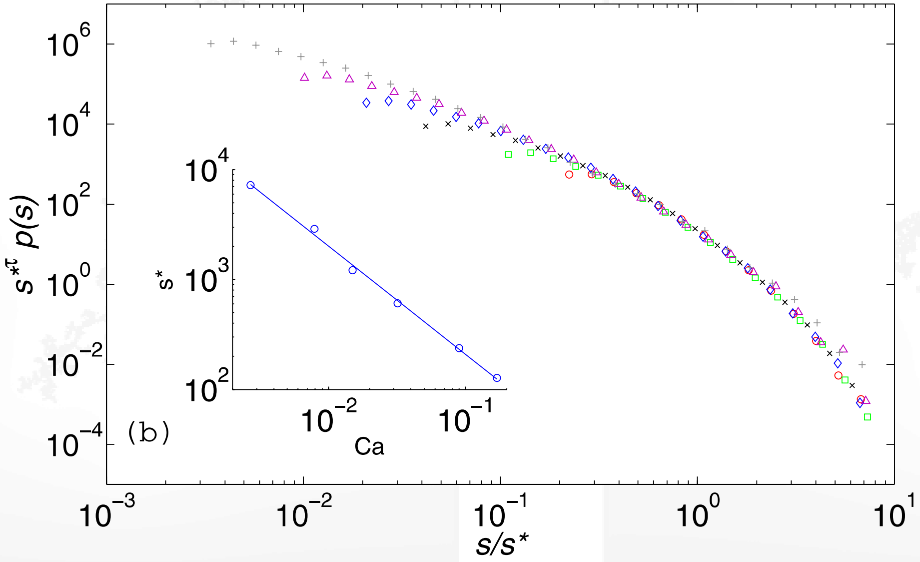
PHYSICAL REVIEW E **80**, 036308 (2009)

$$\Delta P_{ss} \propto \mathrm{Ca}^{\beta}$$
$$\beta = 0.54 \pm 0.08$$

Background

Cluster size distribution





$$p(s) \propto s^{-\tau} \exp(-s/s^*),$$

$\tau = 2.0 \pm 0.2$

$$s^* \propto \mathrm{Ca}^{-\zeta},$$

$\zeta = 0.98 \pm 0.07.$

Tallakstad et al. PRE **80**, 036308 (2009)

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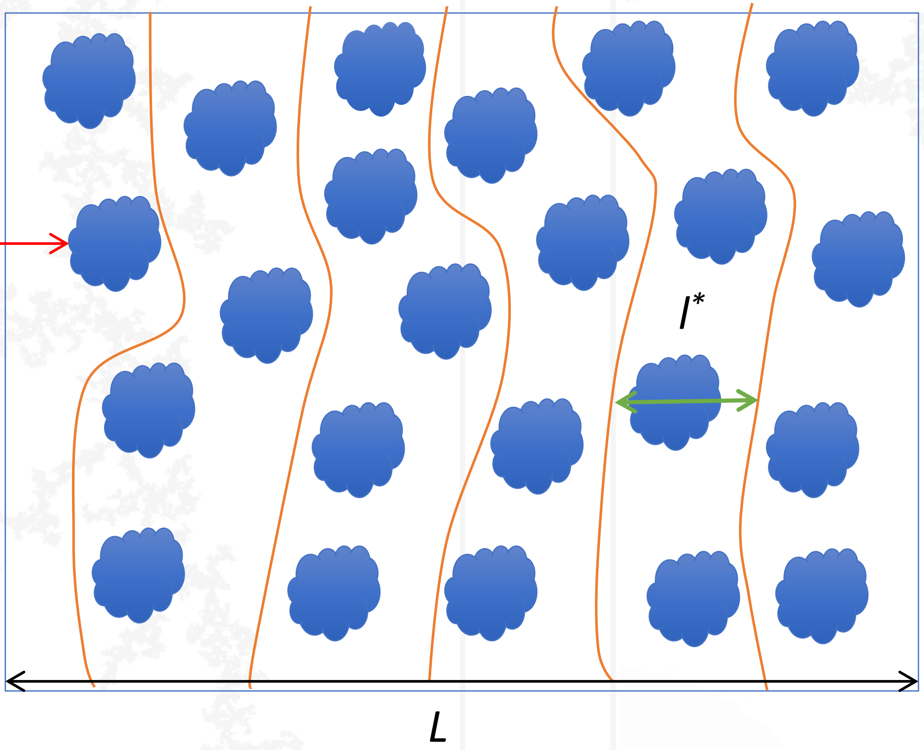
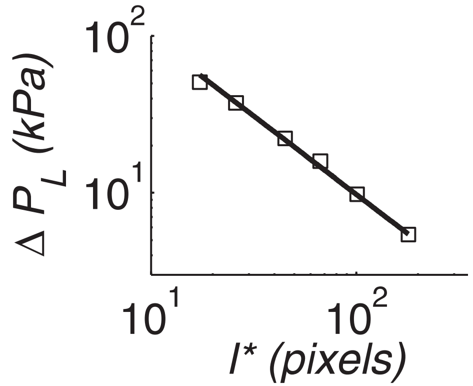
Background

Trapped air cluster



Assumption:
Flow restricted to narrow channels separated a distance corresponding to the characteristic cluster size.



Total flux of wetting fluid:

$$Q = q \cdot N = a^2 \cdot \frac{a^2}{\mu}\frac{\Delta P}{L} \cdot \frac{L}{l^*}$$

$$N = L/l^*$$

Balance between viscous pressure and capillary threshold.

$$l^* \frac{\Delta P}{L} = \Delta P_c = P_d - P_i$$

$$\Delta P \propto Q^{1/2} \propto Ca^{1/2}$$

Theory by Eirik G. Flekkøy

$$l^* \propto s^{*\beta_i}, \ \beta_i = 0.57 \pm 0.05$$

Summary – horizontal experiments

$$\Delta P_{ss} \propto \mathrm{Ca}^{\beta}$$
$$\beta = 0.54 \pm 0.08$$

The steady-state pressure drop scales as the square root of the Ca-number:
the effective permeability increases with Ca

$$p(s) \propto s^{-\tau} \exp(-s/s^{*}),$$
$$s^{*} \propto \mathrm{Ca}^{-\zeta},$$
$$\zeta = 0.98 \pm 0.07.$$

The cluster size distribution follows a power law with an exponential cutoff:
s* = cutoff cluster size

s* is decreasing with increasing flow rate / Ca-number

Summary – horizontal experiments

What happens when we introduce gravity?

$$\Delta P_{ss} \propto \mathrm{Ca}^{\beta}$$
$$\beta = 0.54 \pm 0.08$$

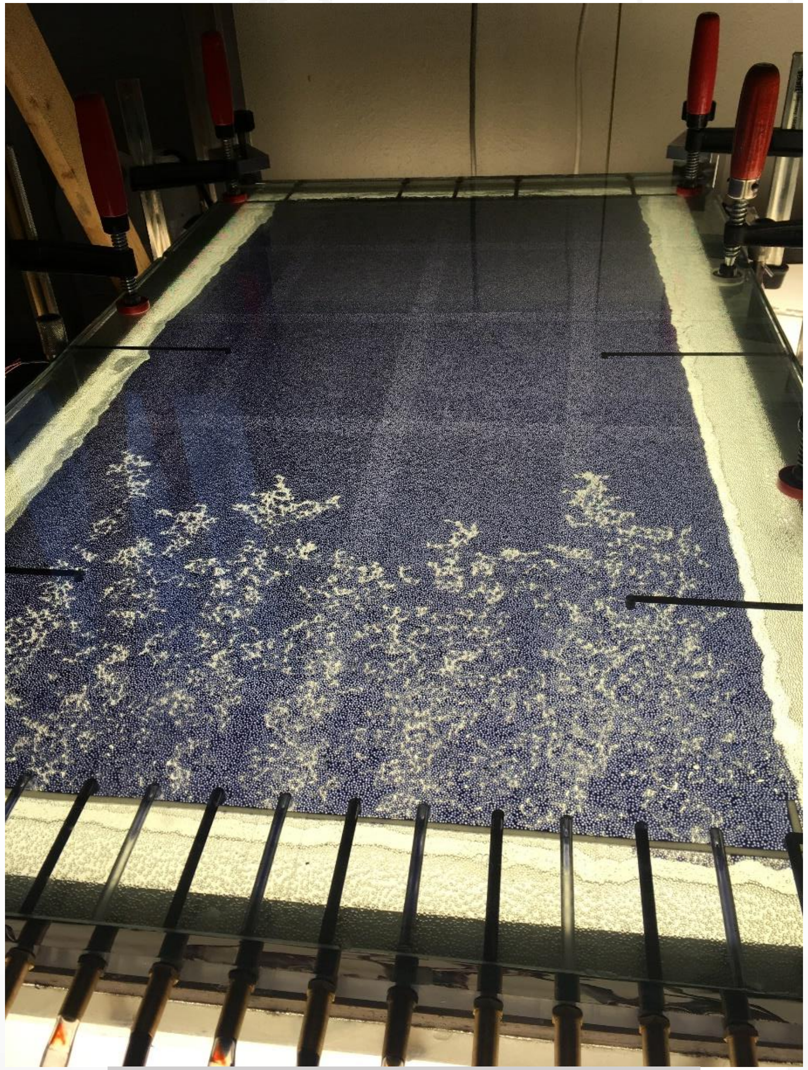
The steady-state pressure drop scales as the square root of the Ca-number:
the effective permeability increases with Ca

$$p(s) \propto s^{-\tau} \exp(-s/s^{*}),$$
$$s^{*} \propto \mathrm{Ca}^{-\zeta},$$
$$\zeta = 0.98 \pm 0.07.$$

The cluster size distribution follows a power law with an exponential cutoff:
s* = cutoff cluster size

s* is decreasing with increasing flow rate / Ca-number

Current experiments, introducing gravity



Beginning of an experiment

Summary:

Cell dimensions = 80 x 40 cm

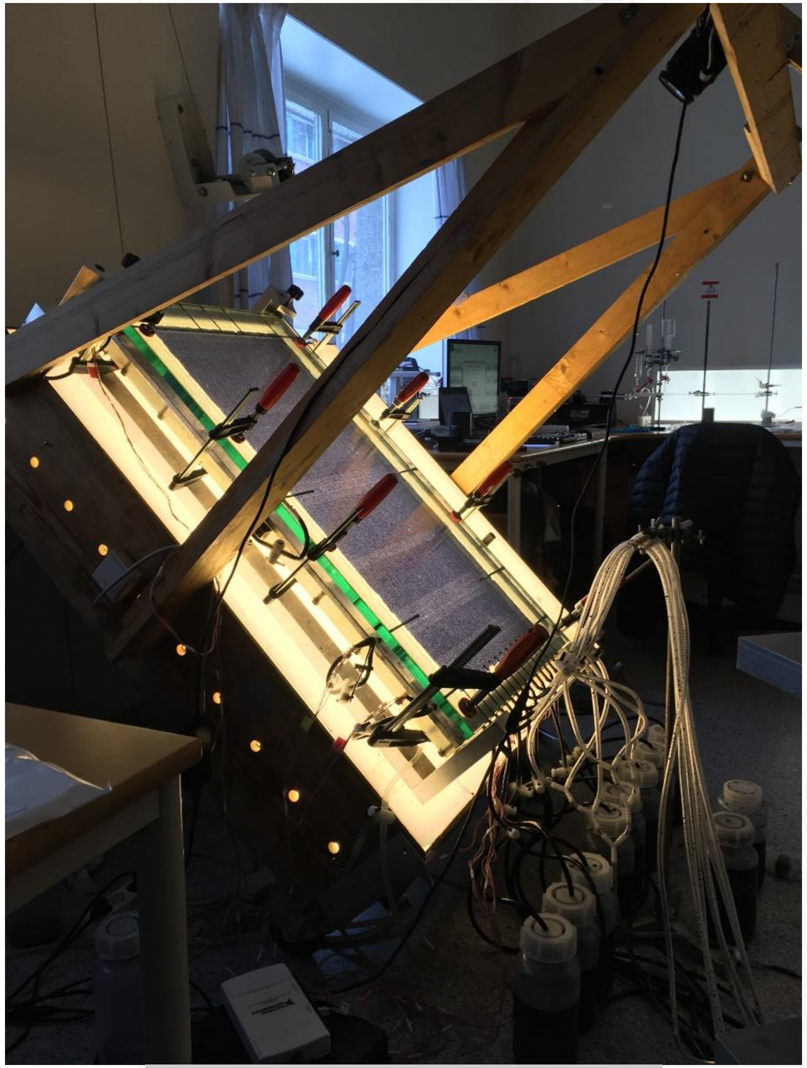
Non-deformable porous monolayer: 1 mm glass beads

Tilting angle: 0 to 45 degrees

15 fluid inlets: 8 liquid, 7 air

8 Pressure sensors

Nikon D7200 camera:
4000x6000 pixels,
time lapse images



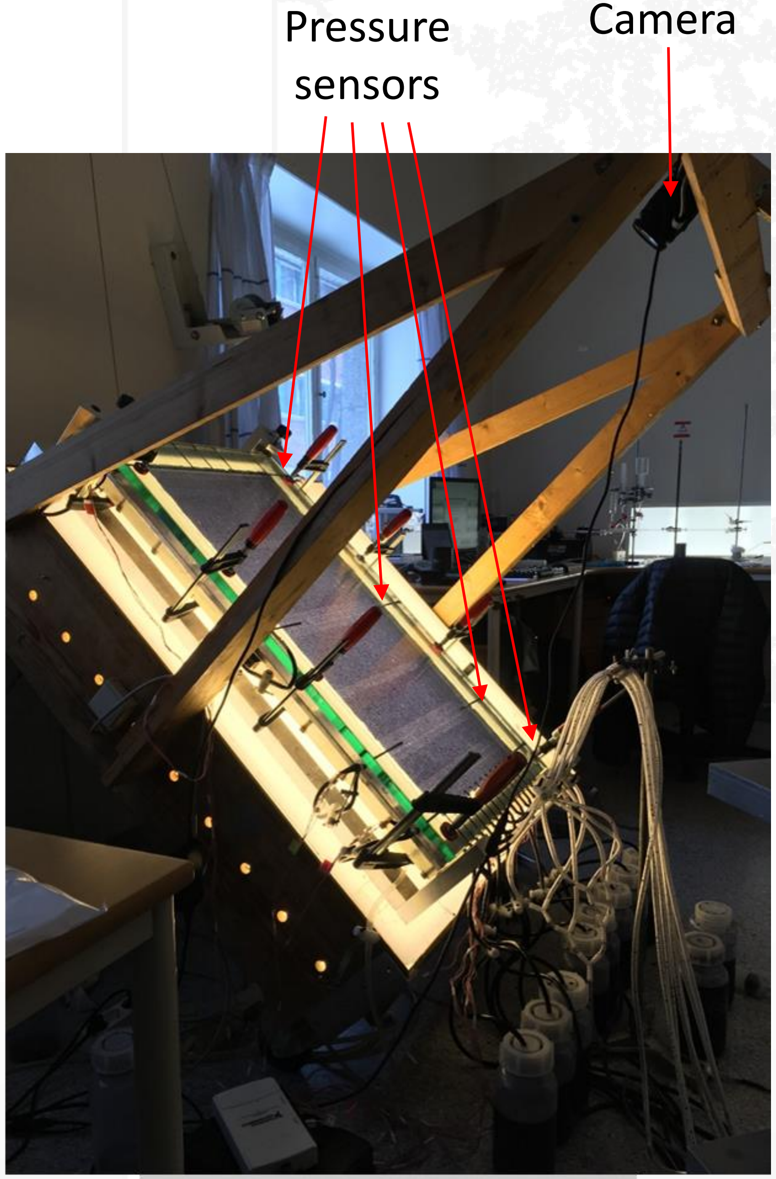
Cell is tilted 45 degrees

Impact of gravity on steady-state flow experiments

We set a constant flow rate and cell tilting angle

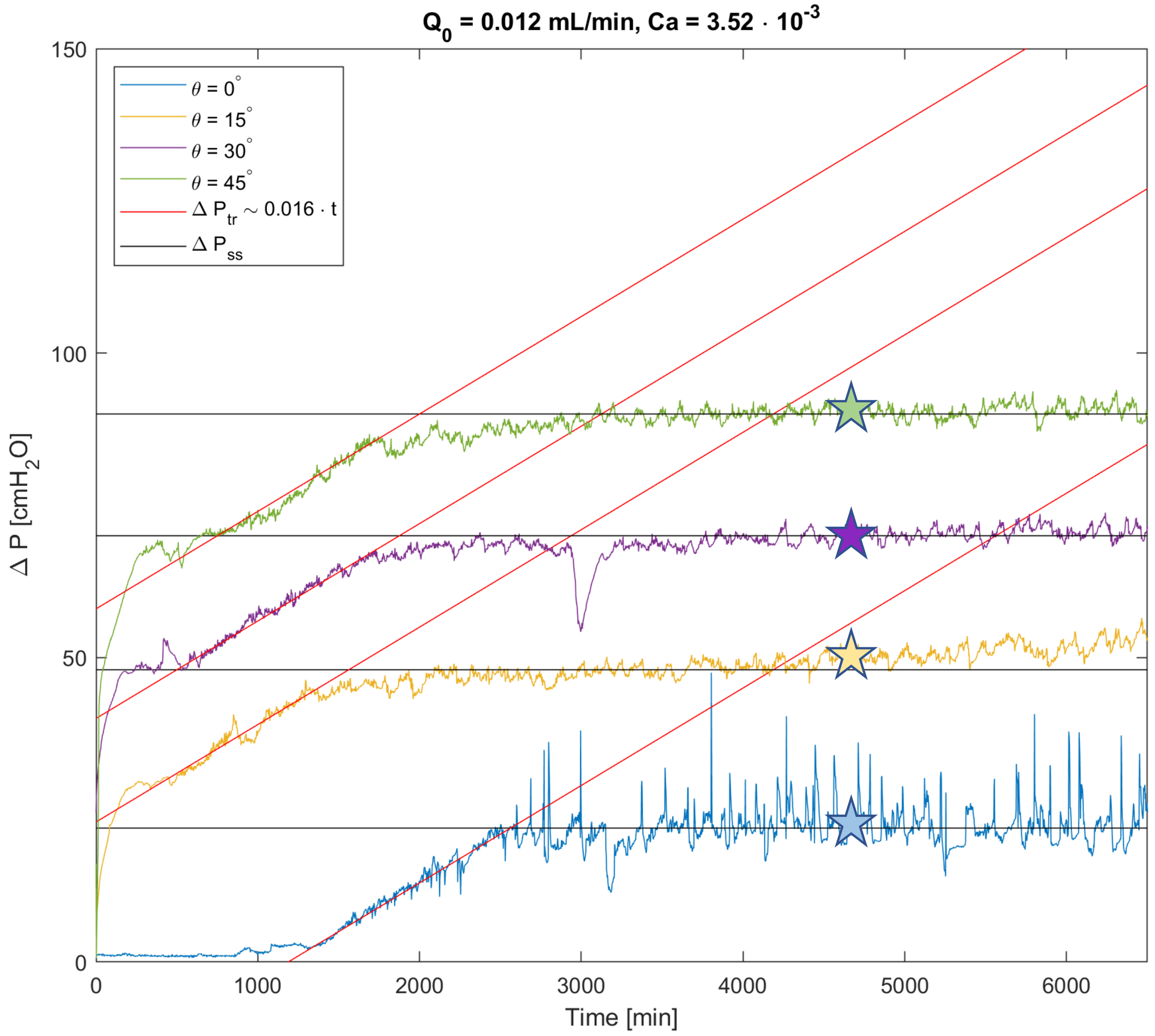
Have conducted 12 initial experiments:

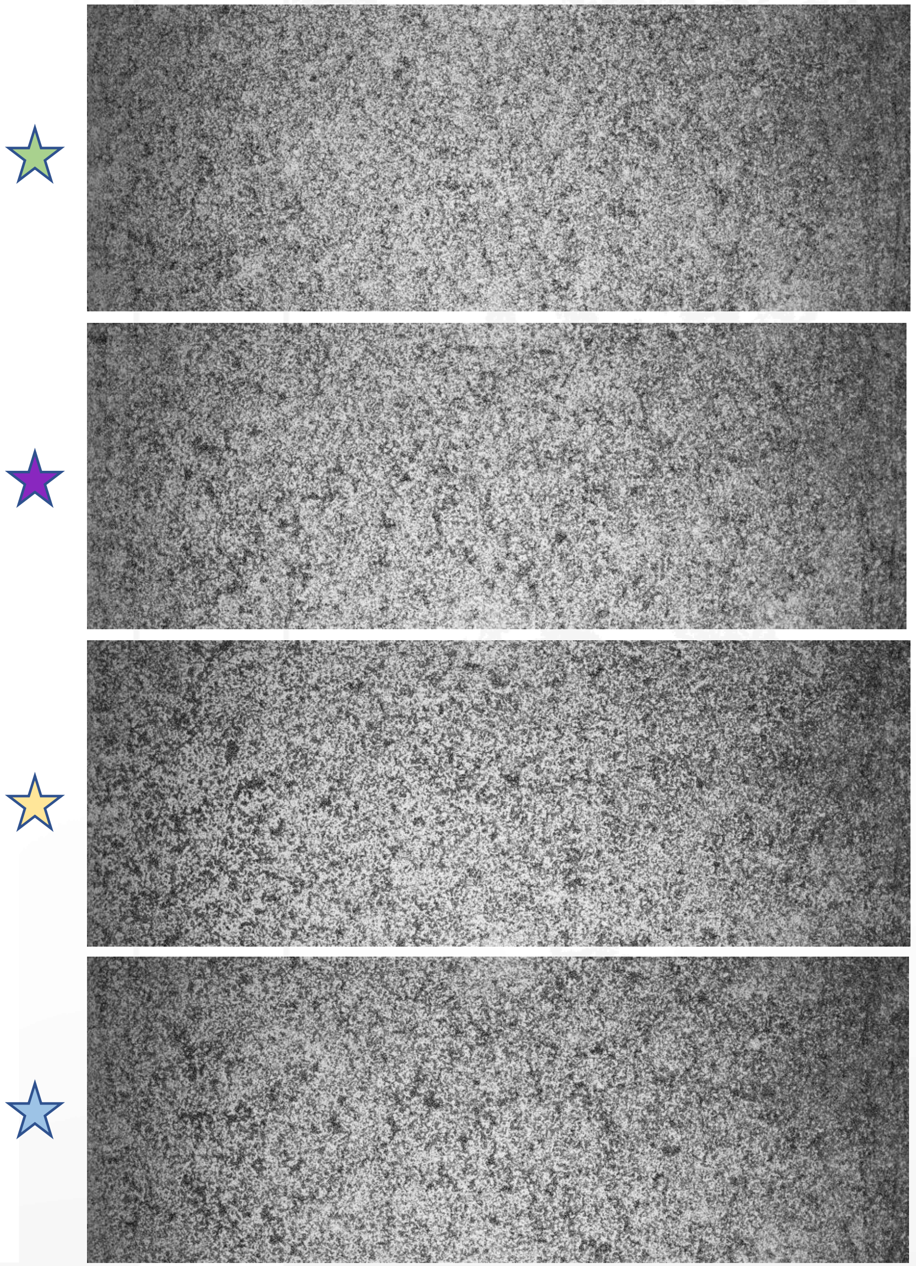
- 3 capillary numbers: Ca = 3.52e-3, 8.8e-3, 8.8e-2
- 4 tilting angles: $\theta = 0^o, 15^o, 30^o, 45^o$
- Fluid pair: 85 % Glycerol – 15 % water (wetting)
  Air (non-wetting)



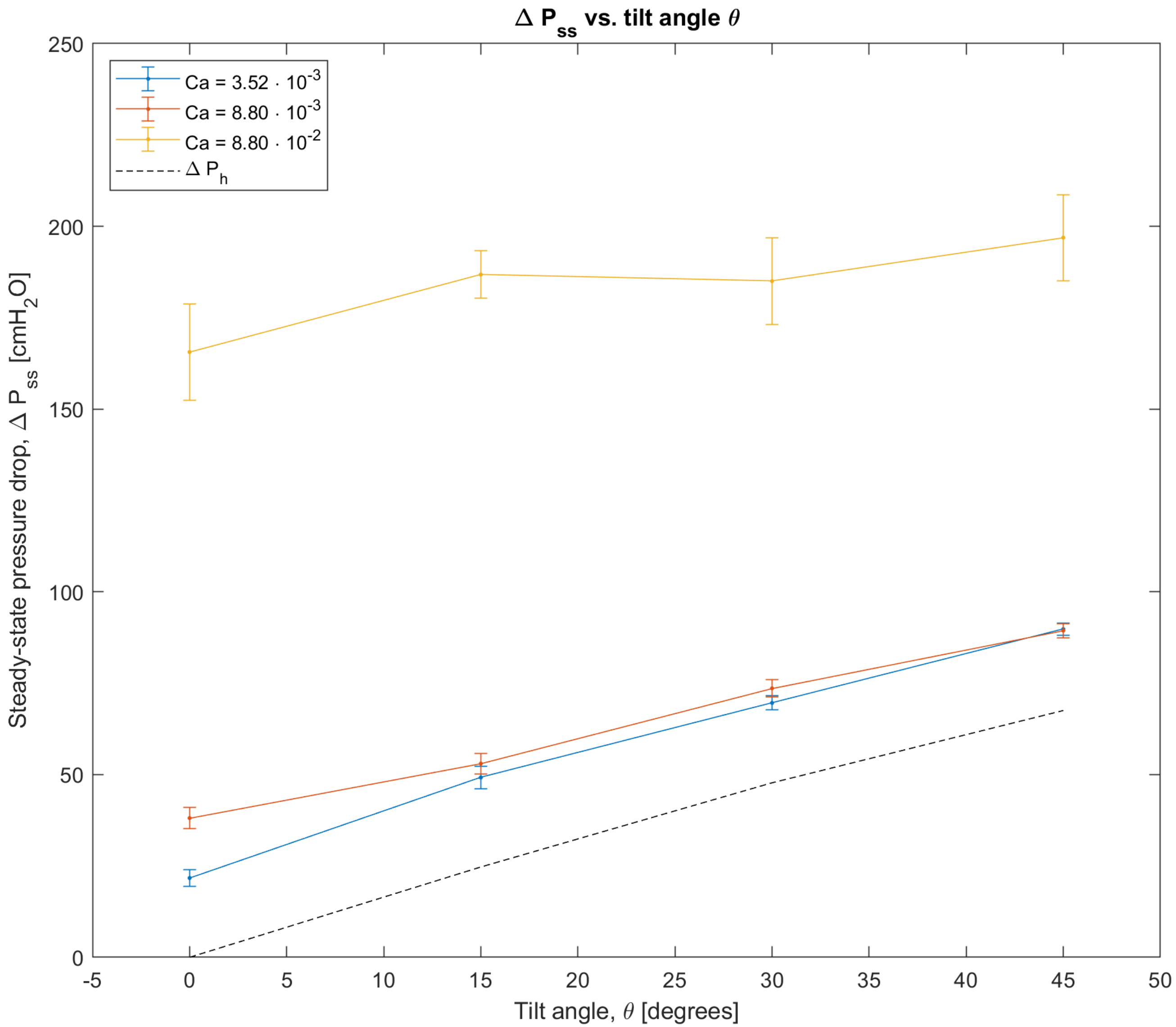
Cell is tilted 45 degrees

Pressure drop across cell – time evolution

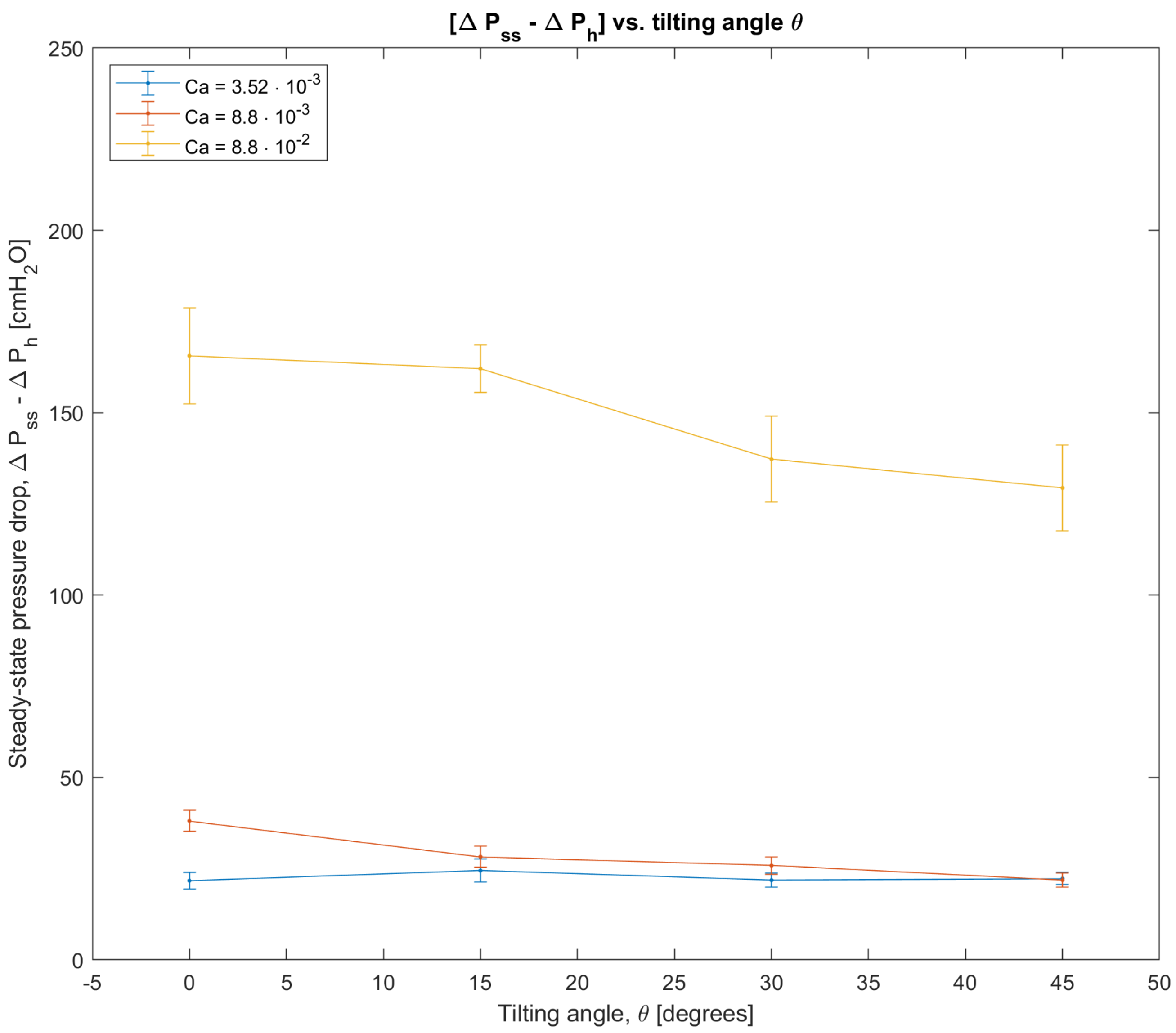




Impact of gravity on the Pressure drop



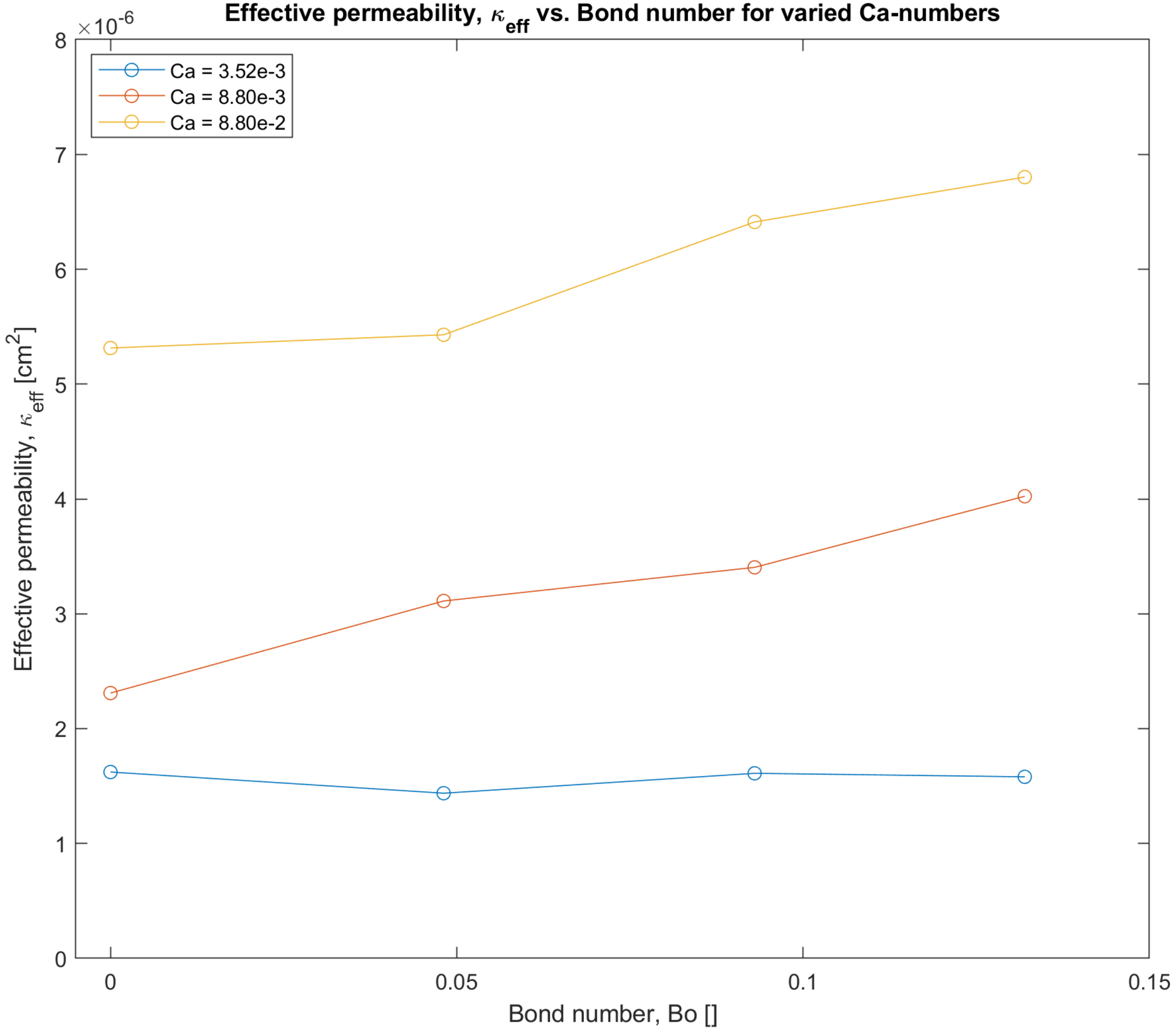
Impact of gravity on the Pressure drop



Gravity has an influence at higher flow rates

Effective permeability increases with gravity

Impact of gravity on the Pressure drop



Gravity has an influence at higher flow rates

Effective permeability increases with gravity

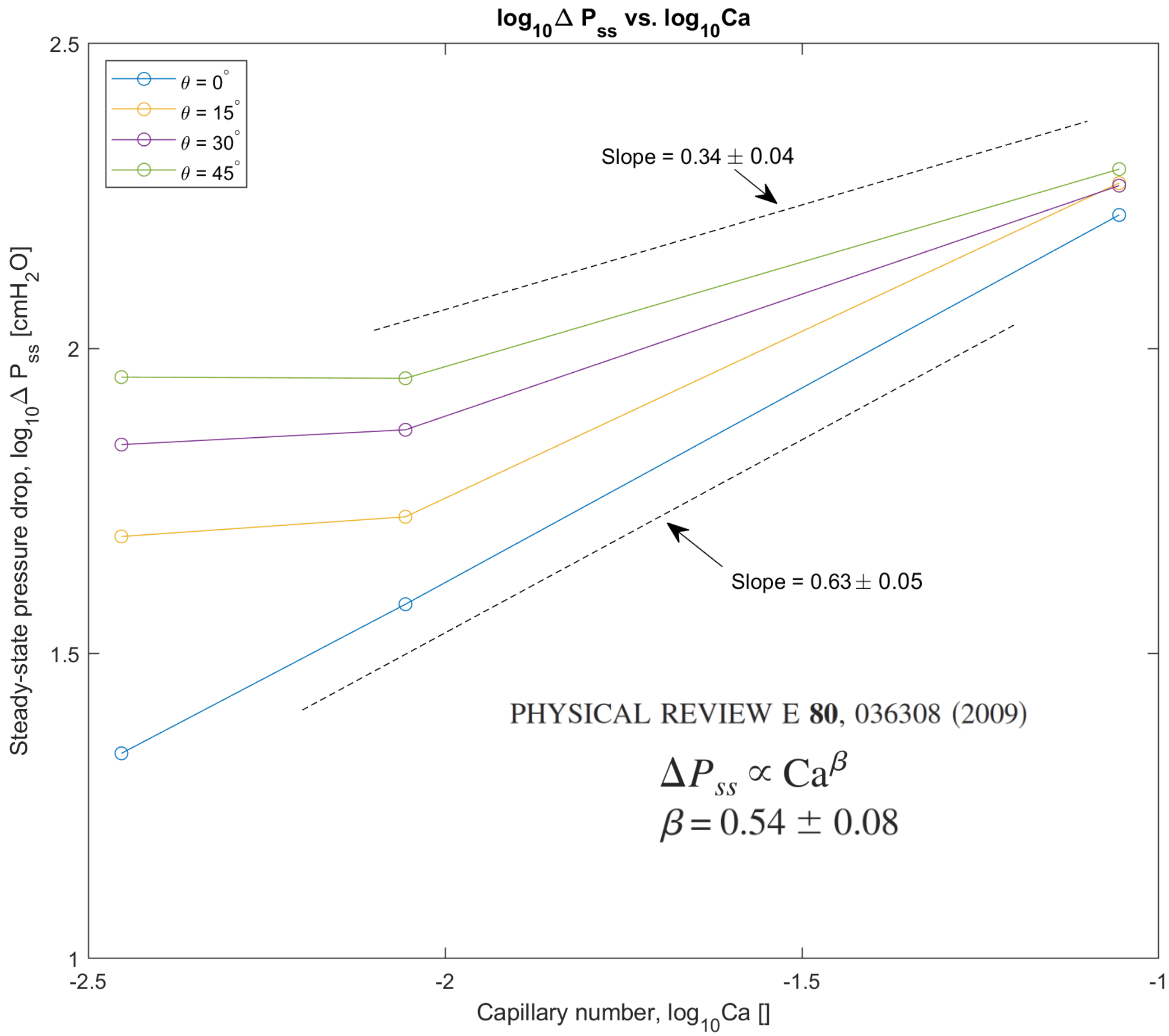
$$\frac{Q_w}{A} = -\frac{\kappa_{eff}}{\mu_w}\nabla P = \frac{\kappa_{eff}}{\mu_w}\frac{\Delta P_{ss} - \Delta P_h}{L}$$

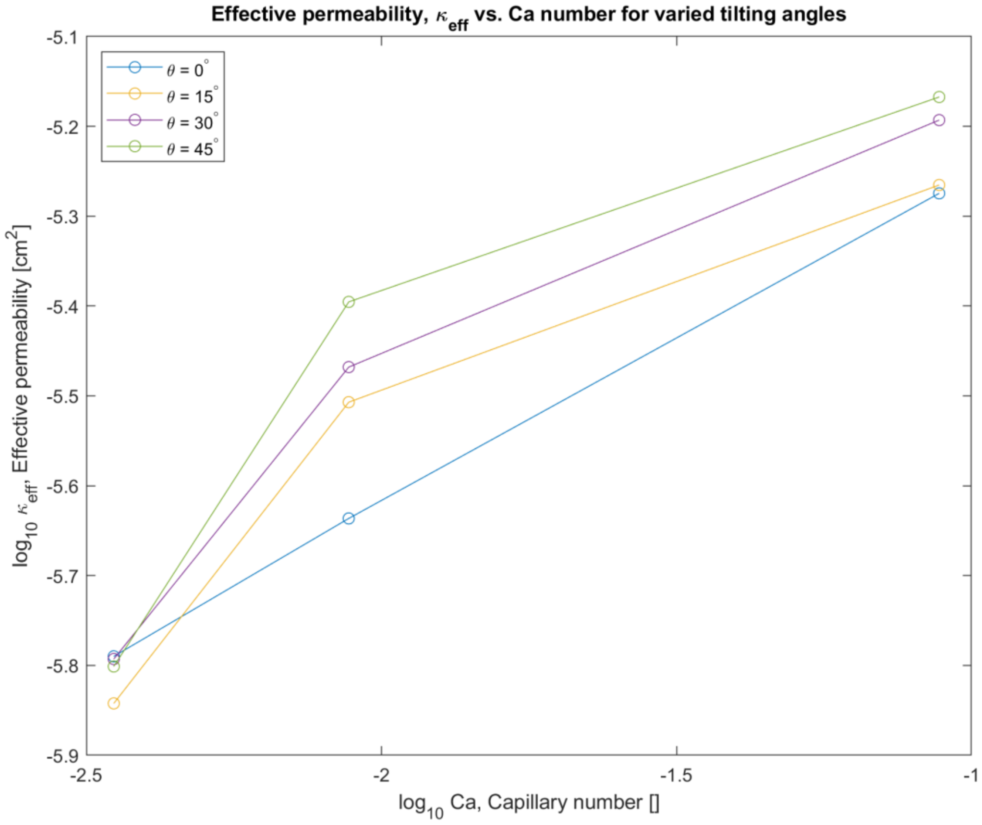
$$\Downarrow$$

$$\kappa_{eff} = \frac{\mu_w Q_w L}{(\Delta P_{ss} - \Delta P_h)A}$$

$$\mathrm{Bo} = \frac{\Delta\rho g a}{\gamma}\sin(\theta), \quad \Delta\rho = \rho_w - \rho_{nw}$$

Impact of gravity on the Pressure drop





Pressure data summary

Low flow rate experiments:

The steady state pressure drop increases with the hydraulic pressure of the wetting fluid
-> gravity does not seem to impact the effective permeability (wetting phase)

Medium and High flow rate experiments:

The steady state pressure drop increases less with Ca-number for higher tilting angle than the hydraulic pressure drop of the wetting fluid
-> gravity increases the effective permeability (wetting phase)

What do we expect from the images?

- Low Ca: no change in the cluster sizes with tilting angle?
- Medium & high Ca: Smaller clusters for increased tilting angle?
- Elongated clusters, or more mobile clusters, for higher tilt and Ca-number?

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Image processing

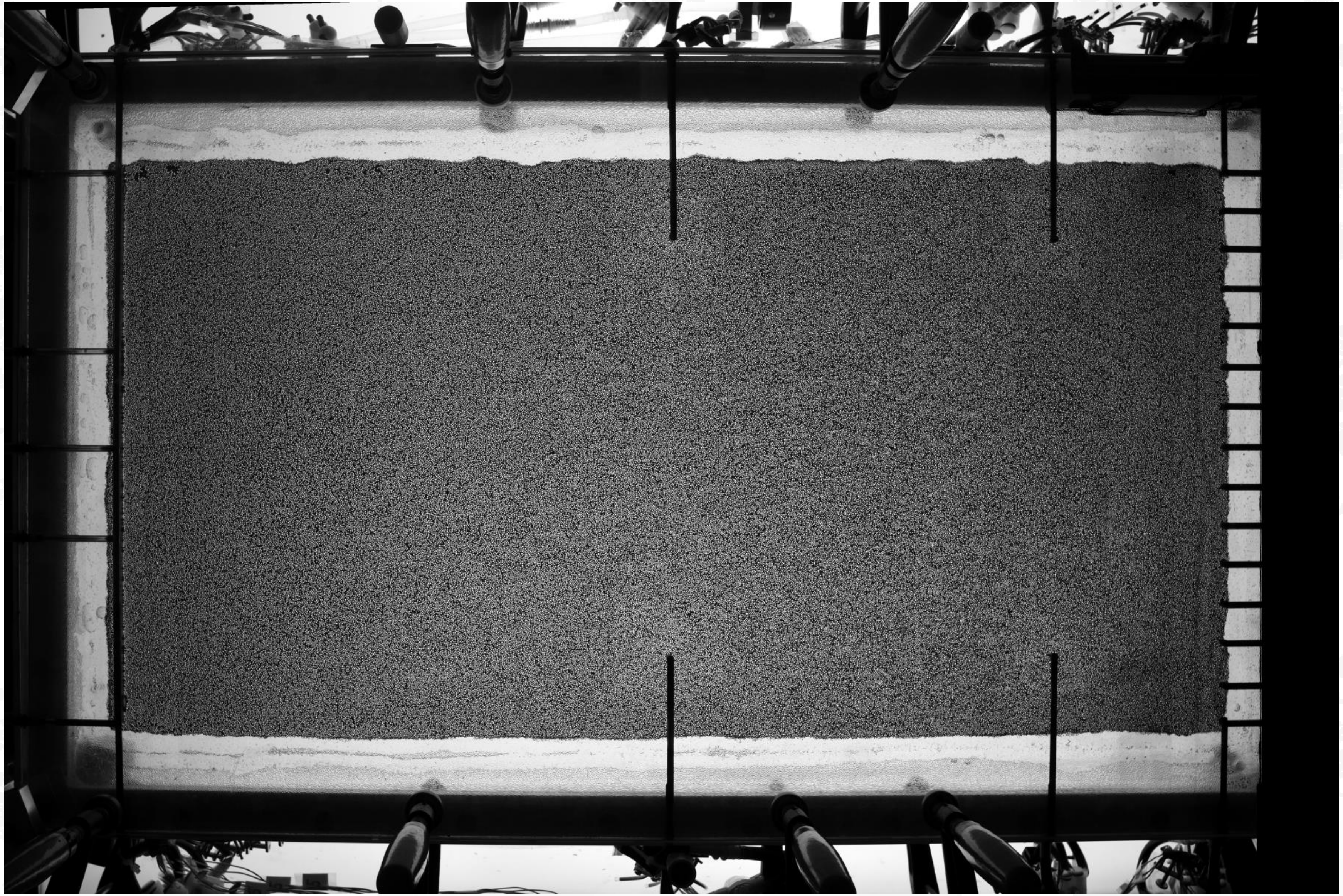


Image processing

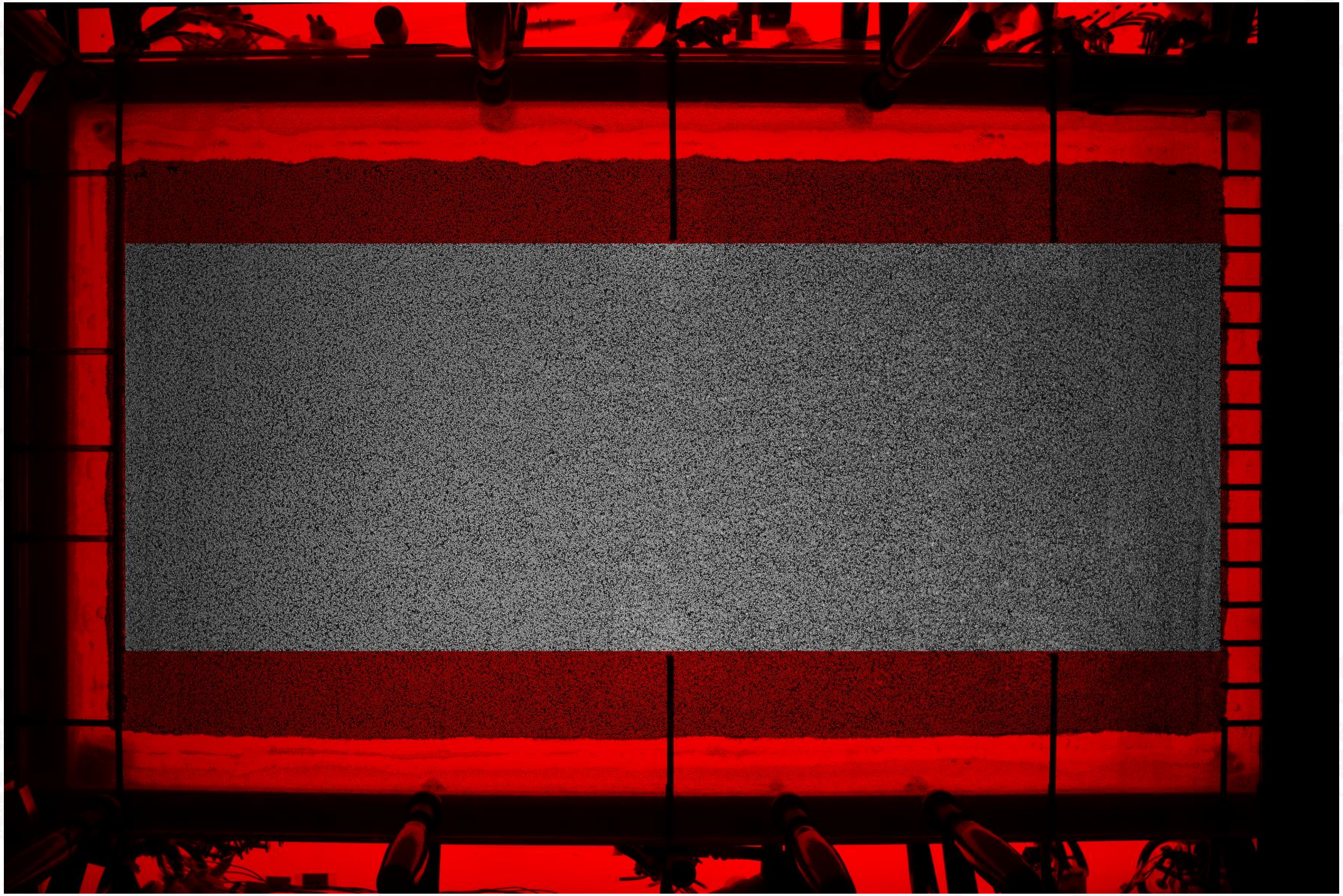
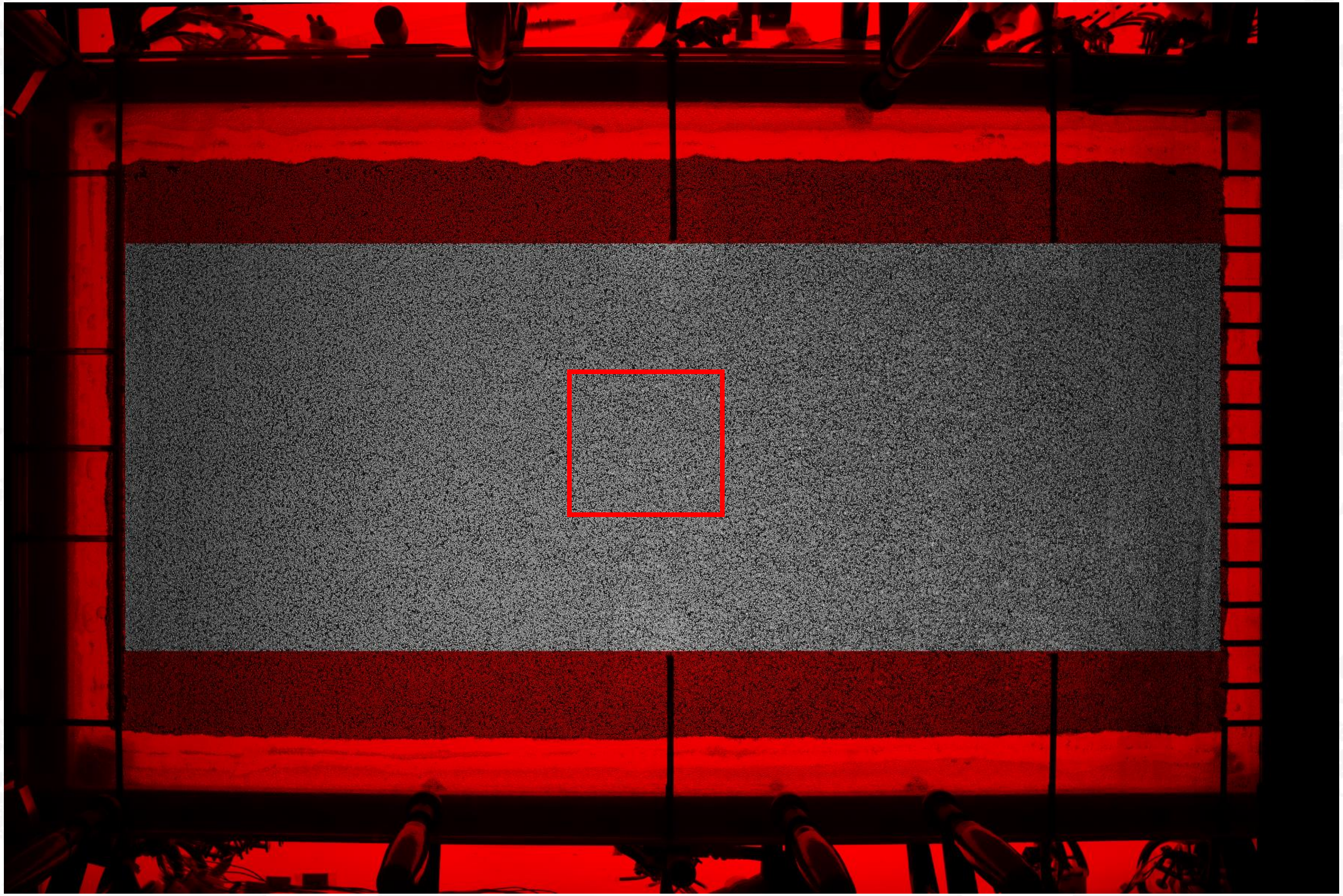
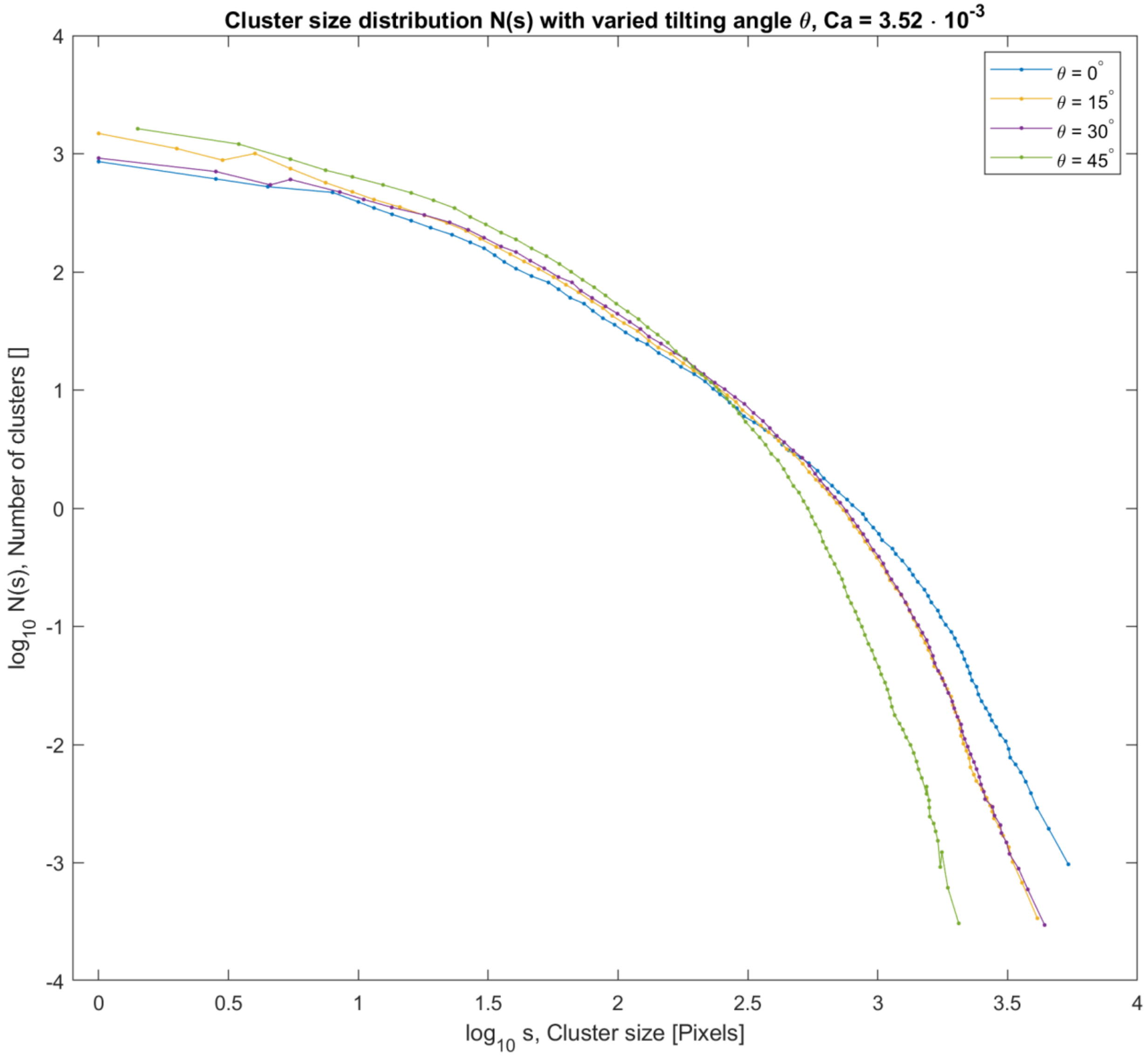


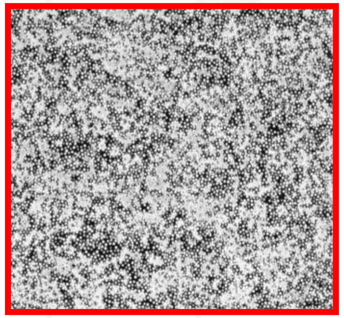
Image processing



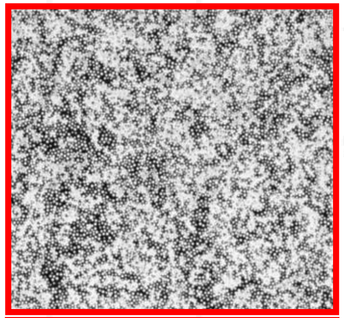
Impact of gravity on cluster size distribution



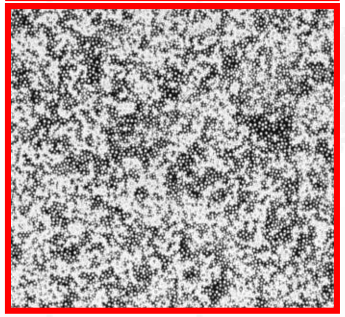
Ca = 3.52e-3



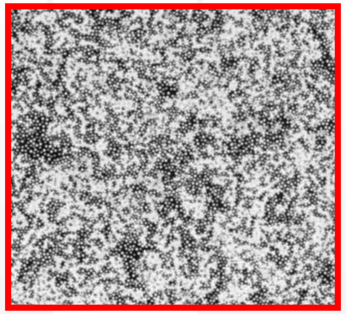
θ = 45°



θ = 30°

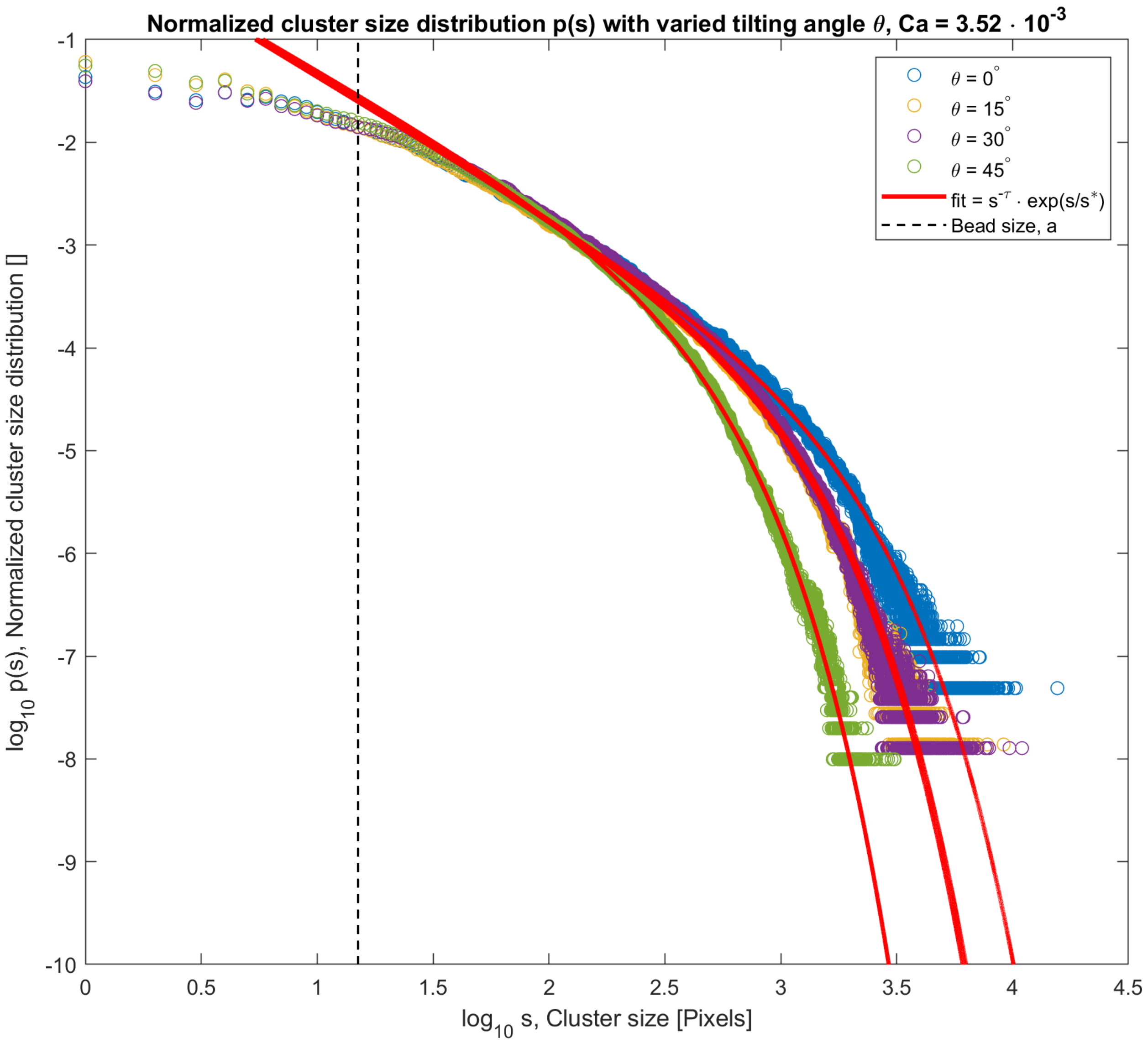


θ = 15°



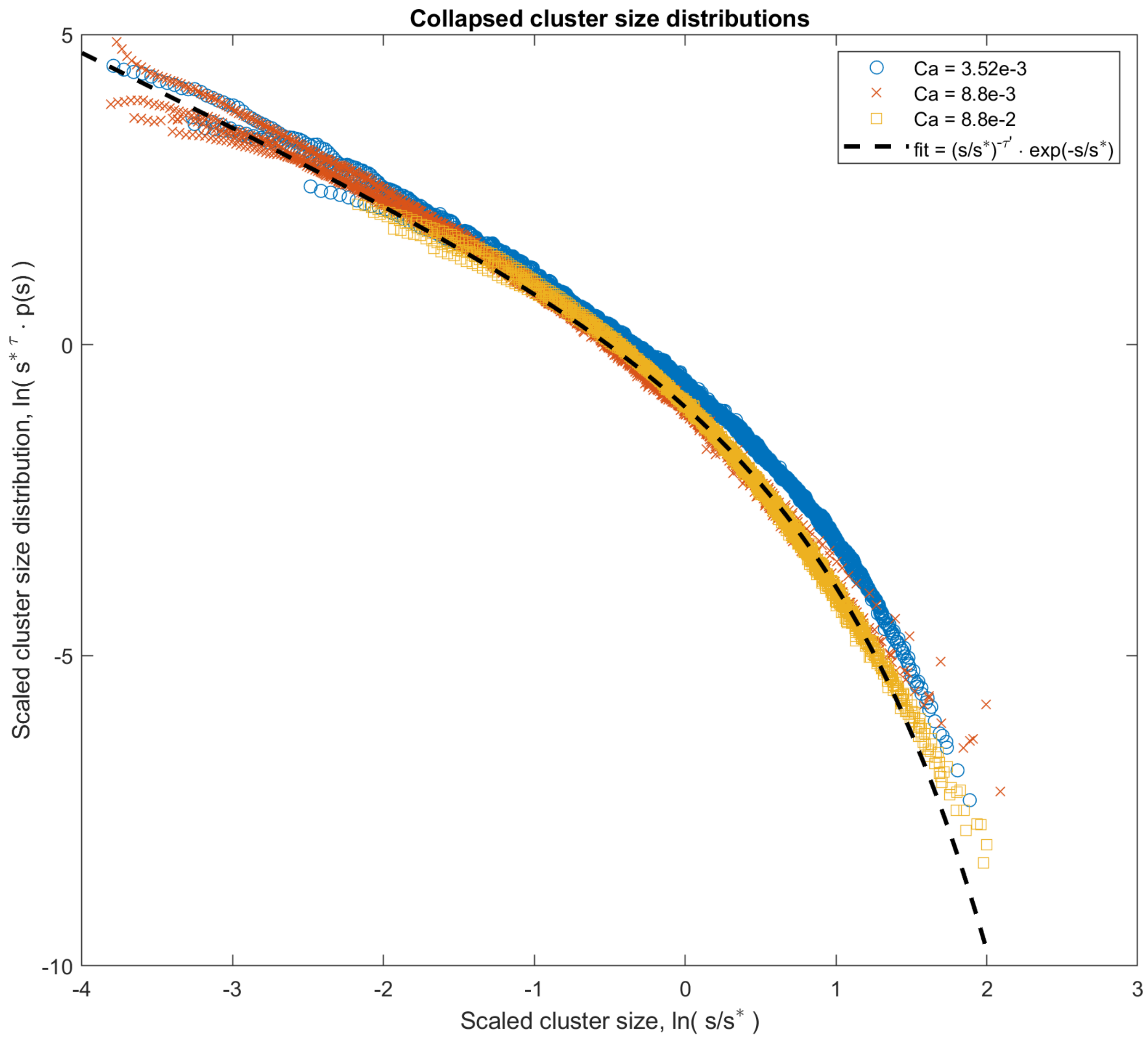
θ = 0°

Impact of gravity on cluster size distribution



$$p(s) \propto s^{-\tau} \exp(-s/s^{*})$$

Impact of gravity on cluster size distribution



$$p(s) \propto s^{-\tau} \exp(-s/s^*)$$

How is this changing with tilting angle and Ca?

○ $\tau = 1.17 \pm 0.04$

× $\tau = 1.24 \pm 0.04$

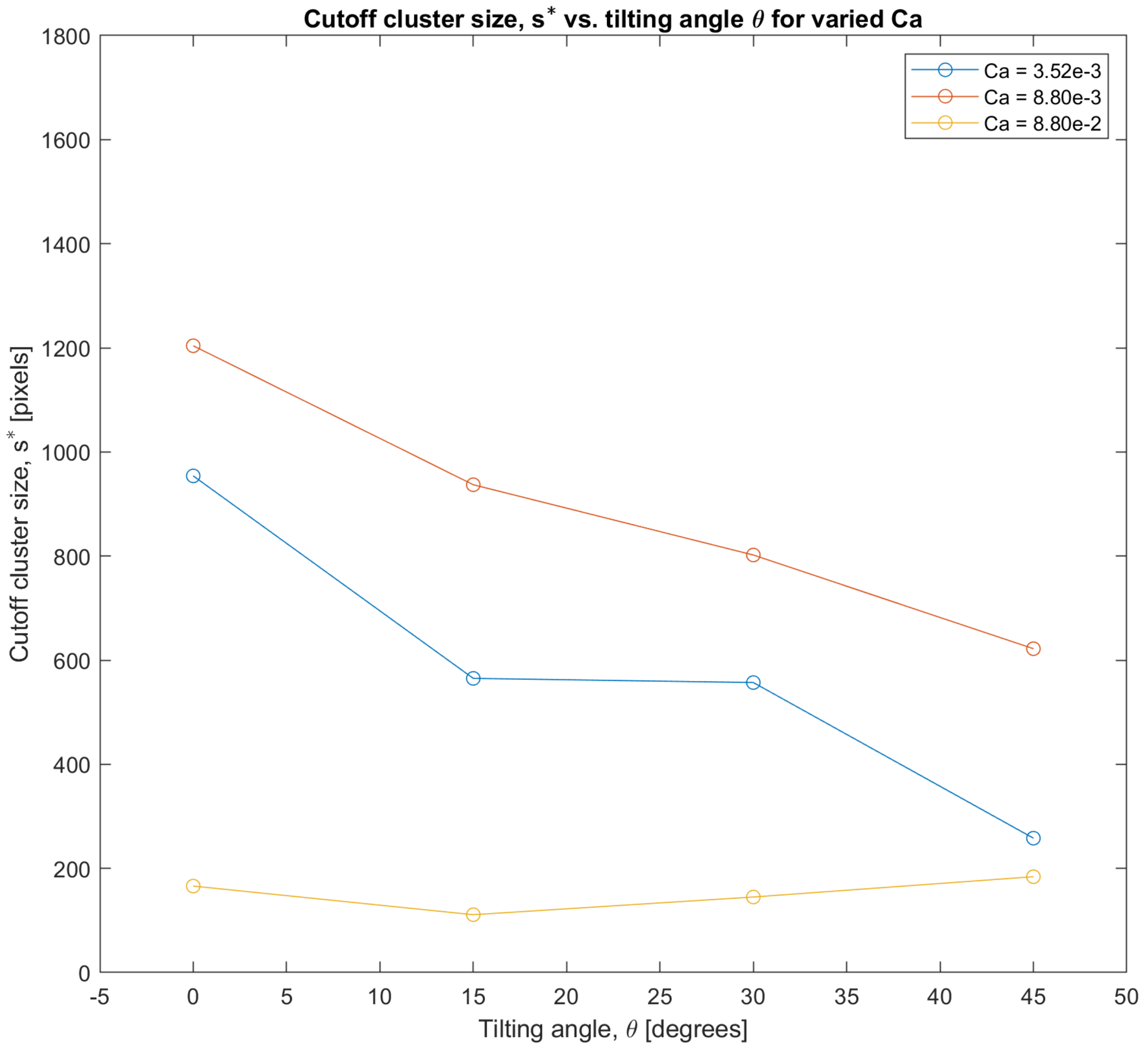
□ $\tau = 1.13 \pm 0.03$

$\tau' = 1.18 \pm 0.06$

$\tau = 2.0 \pm 0.2$

Tallakstad et al. PRE **80**, 036308 (2009)

Impact of gravity on cluster size distribution

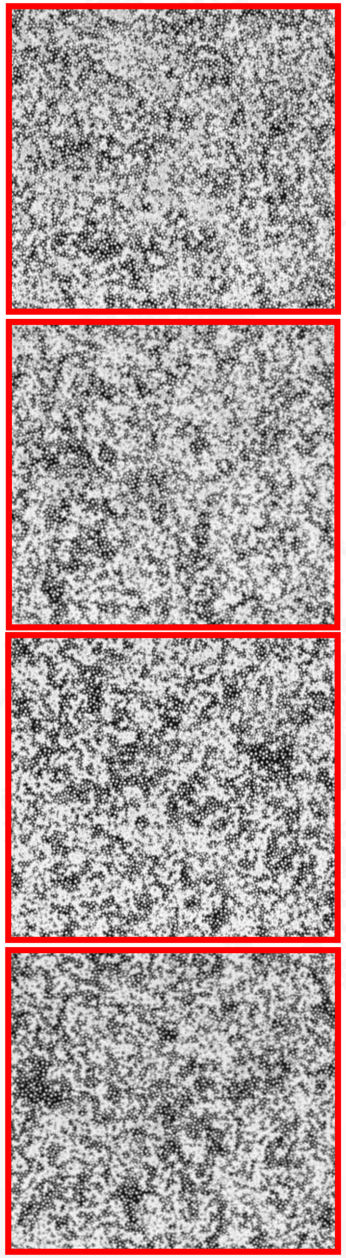


1. s* in the fast experiment more or less constant
2. Do not see $s^* \propto \mathrm{Ca}^{-\zeta}$

Reproducible?

Impact of gravity on air cluster size

Ca = 3.52e-3



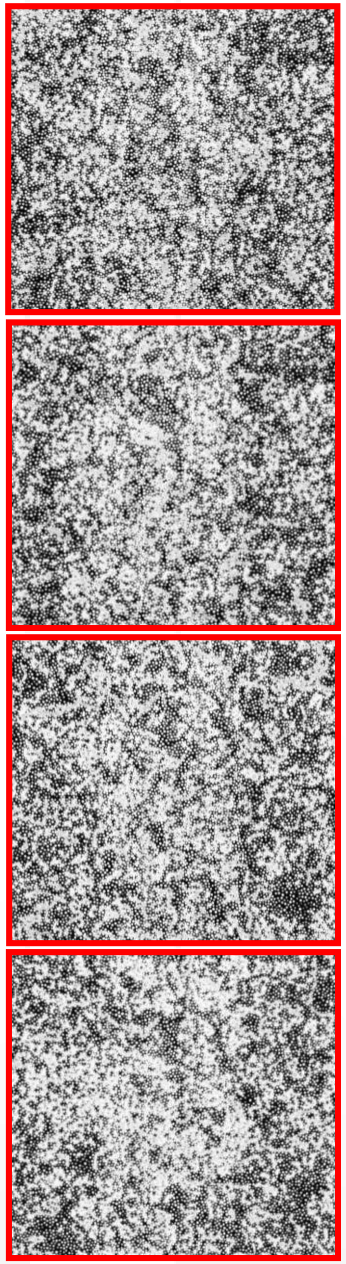
θ = 45°

θ = 30°

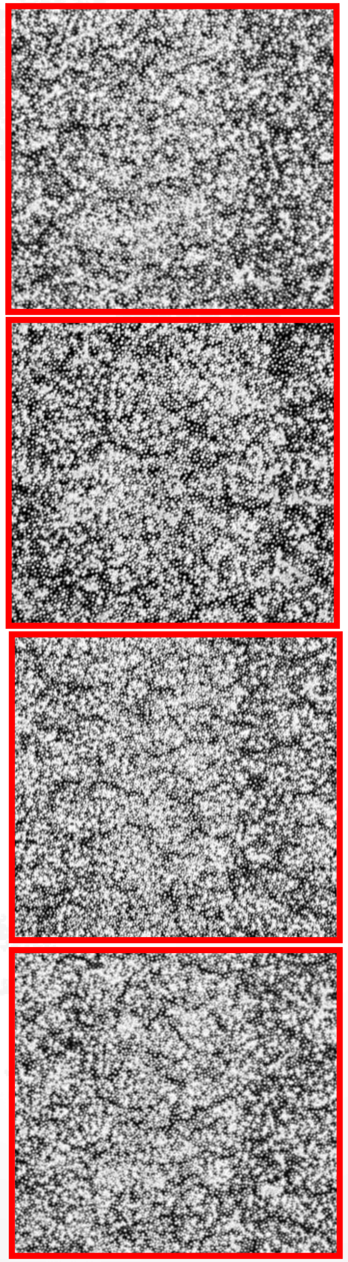
θ = 15°

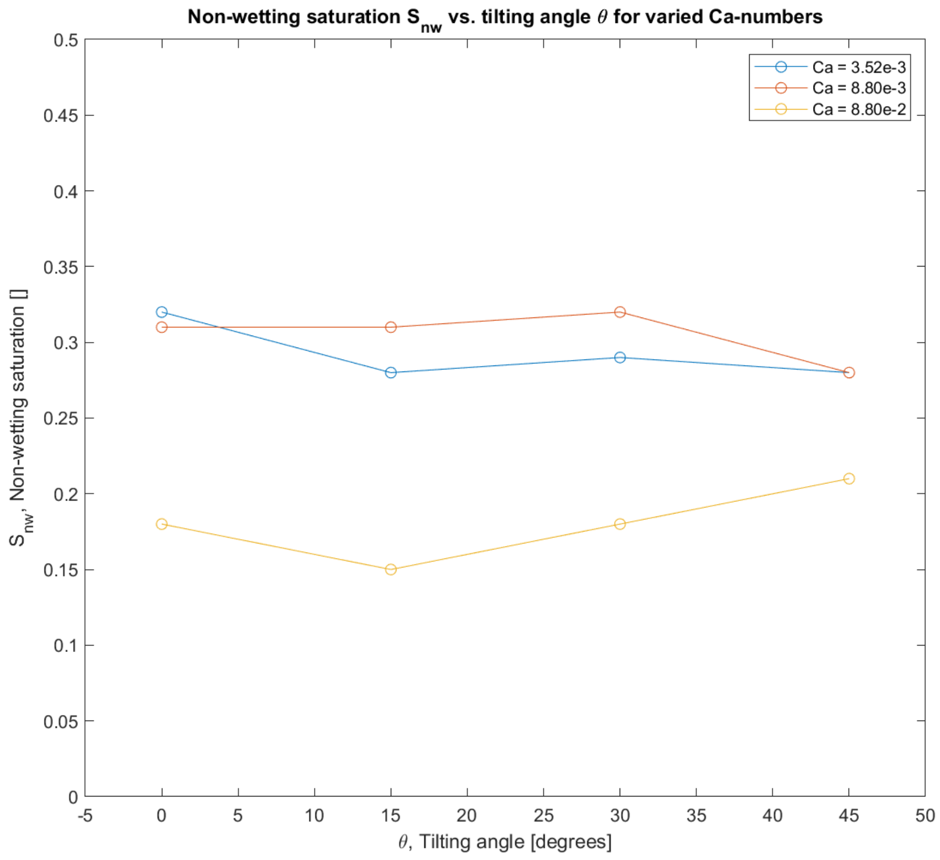
θ = 0°

Ca = 8.80e-3



Ca = 8.80e-2





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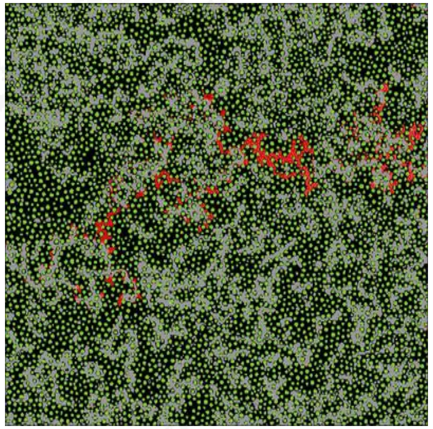
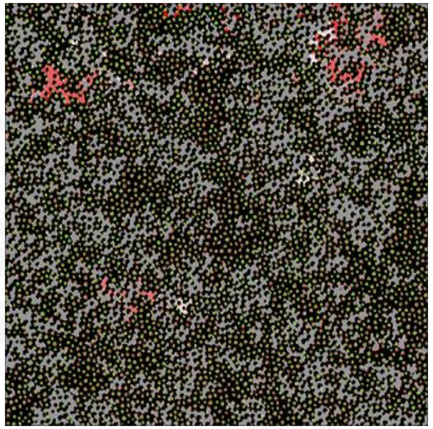
Cluster mobility

θ = 0°

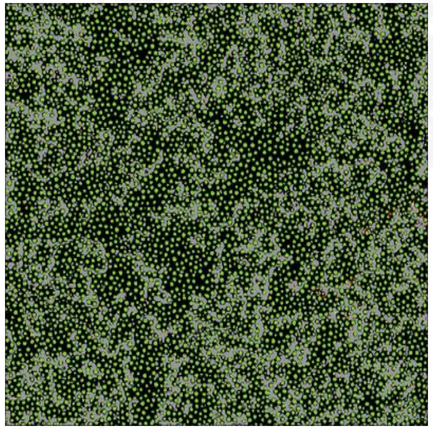
Ca = 3.52e-3
Gray:
Immobile
> 30 min



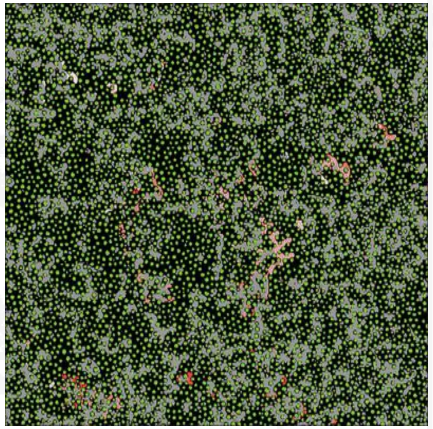
Ca = 8.80e-3
Gray:
Immobile
> 30 min



Ca = 8.80e-2
Gray:
Immobile
> 4.5 min



θ = 30°



θ = 15°

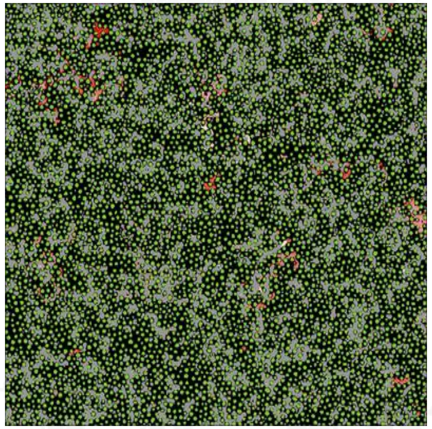
Top and middle rows: 1 s in video = 20 min in real time
Bottom row: 1 s in video = 3 min in real time

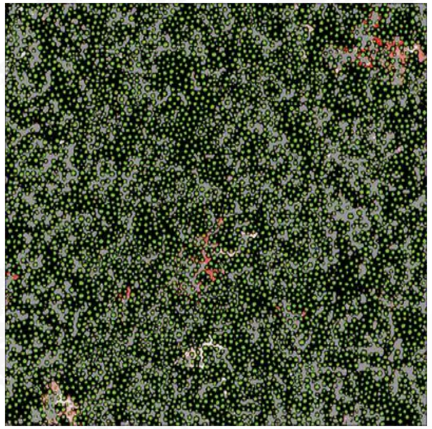
$$I^* \frac{\Delta P}{L} = \Delta P_c = P_d - P_i$$

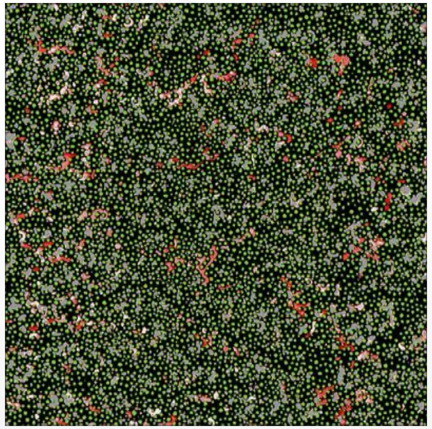
Mobile clusters decrease in size when Ca and tilting angle increases

Amount of mobile clusters increase when Ca and tilting angle increases

θ = 45°







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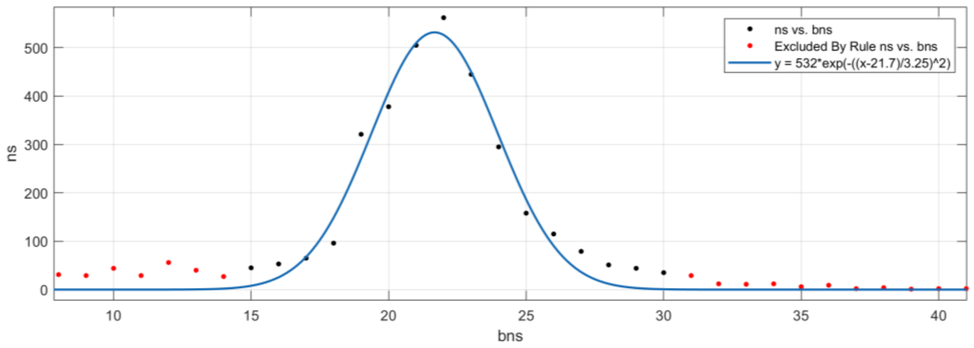
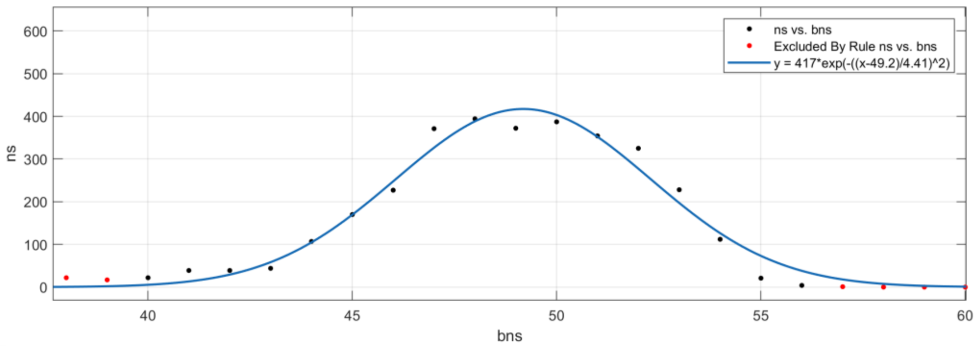
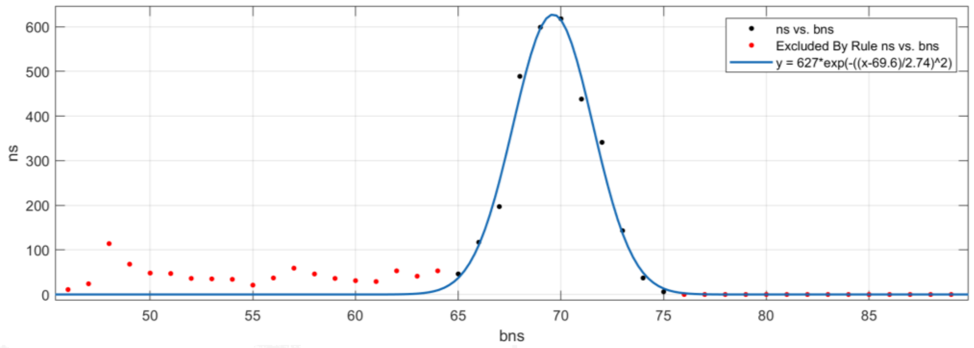
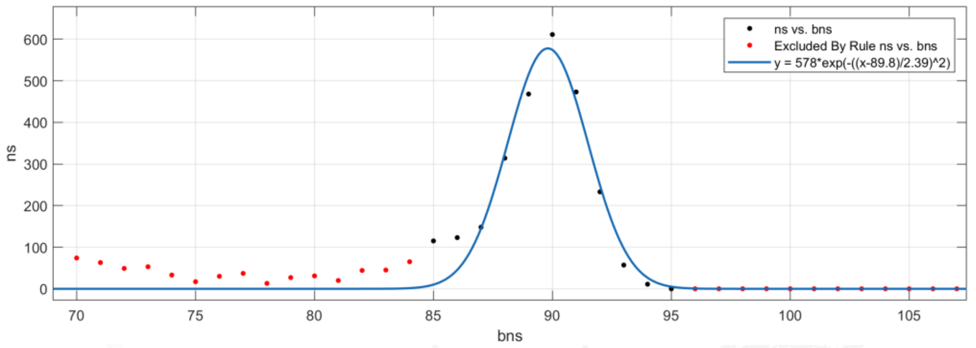
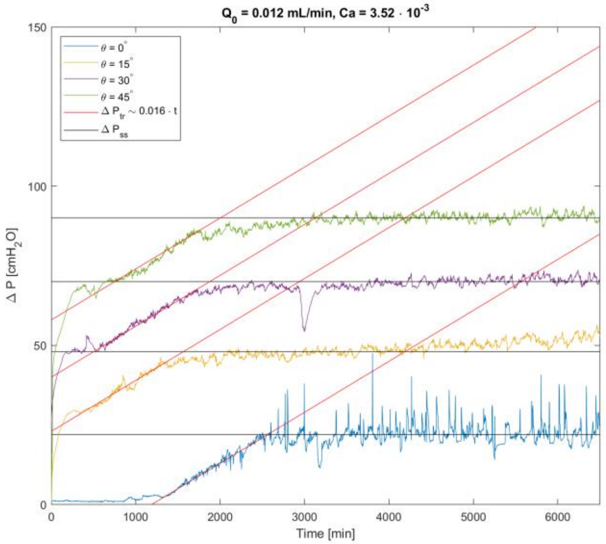
Finding the steady-state pressure drop



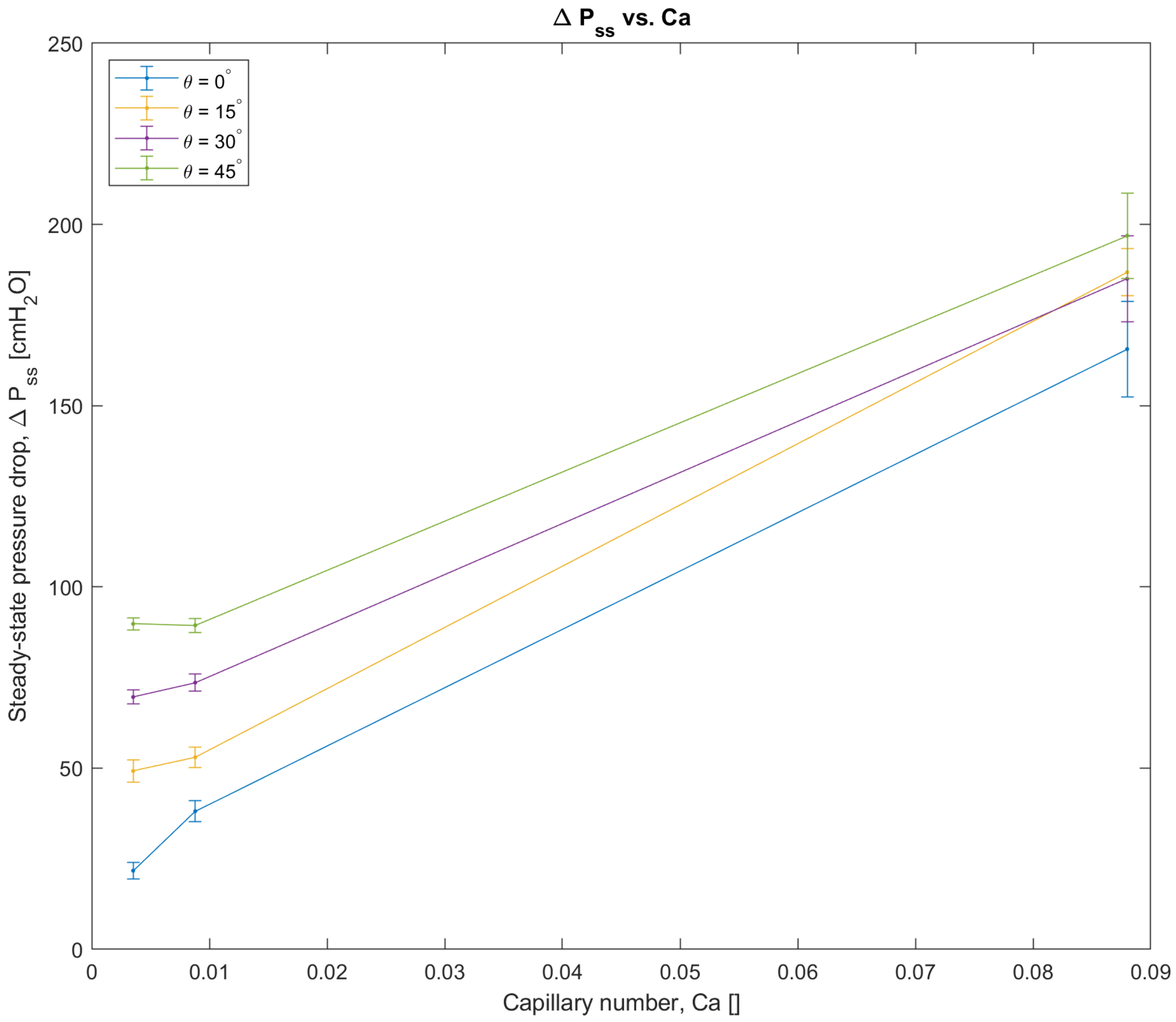




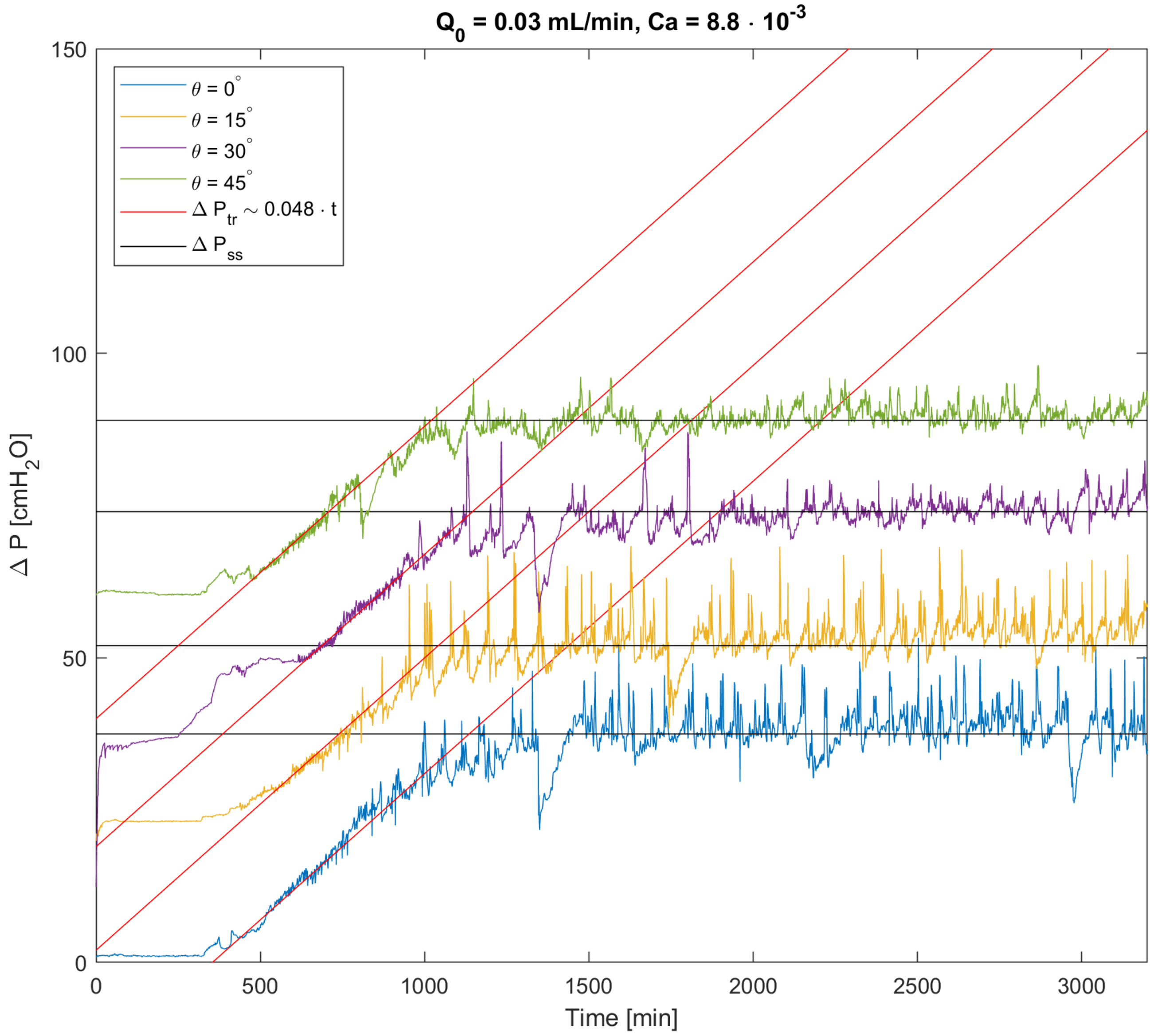




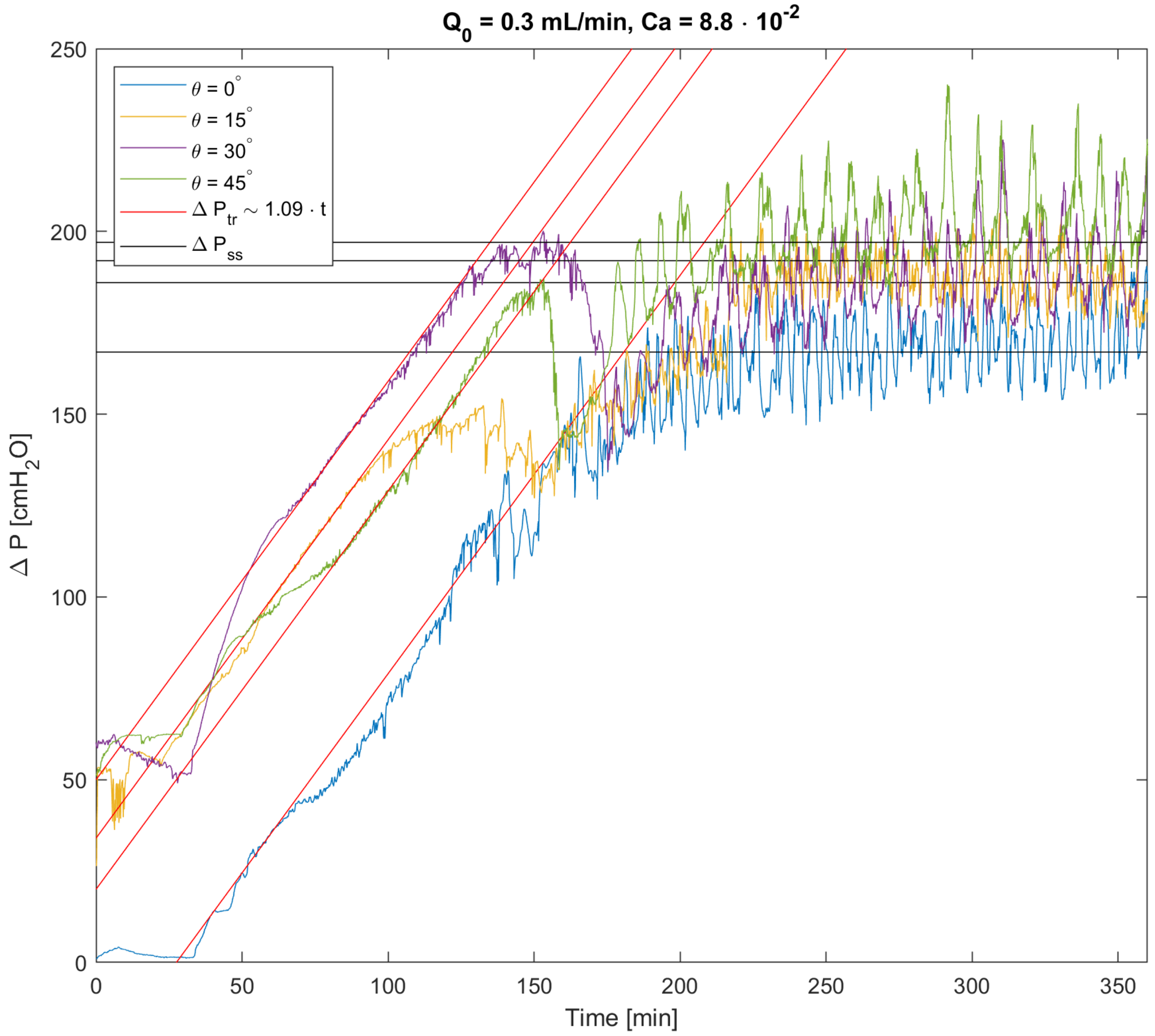
Impact of gravity on the Pressure drop



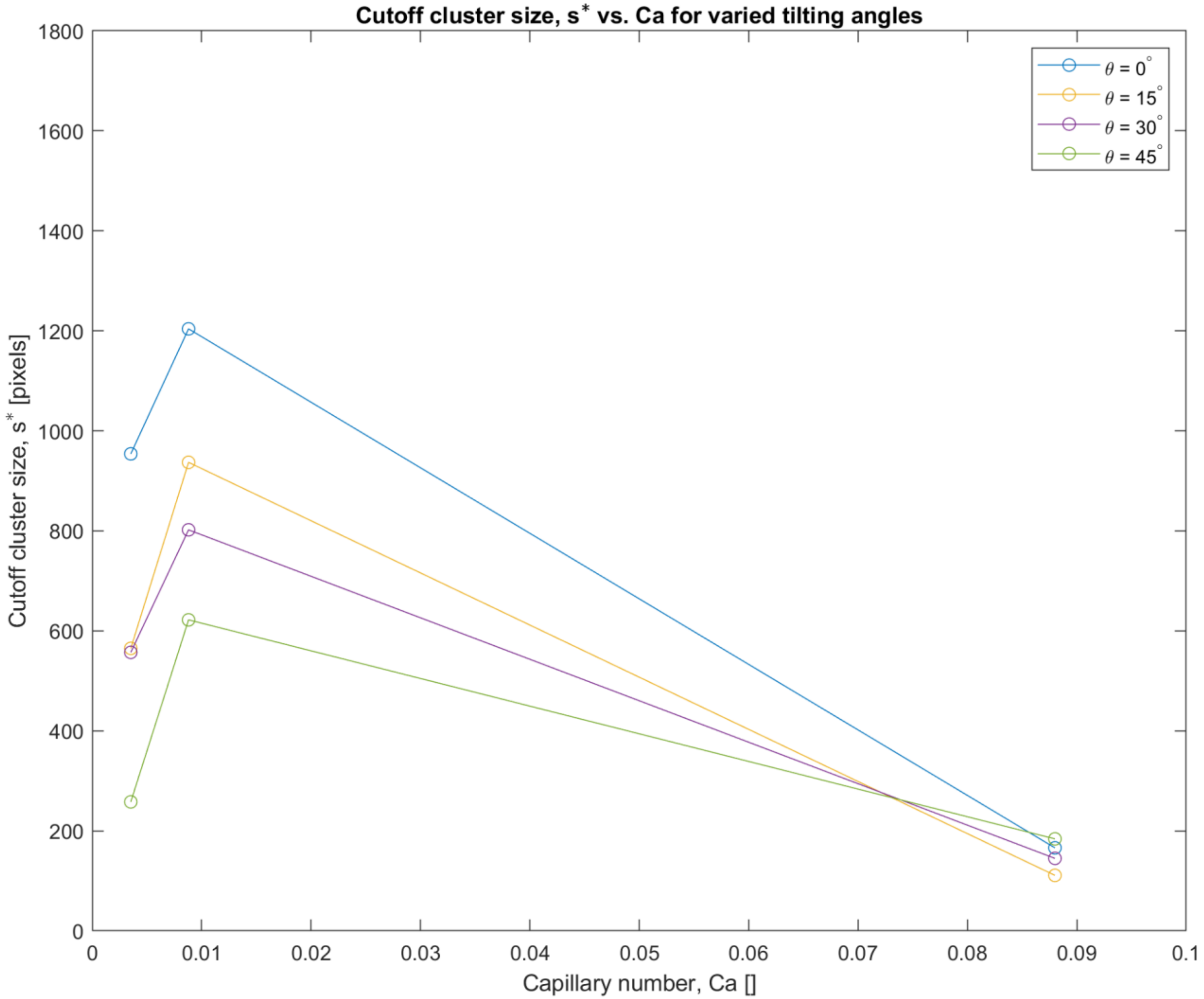
Pressure drop across cell – time evolution



Pressure drop across cell – time evolution



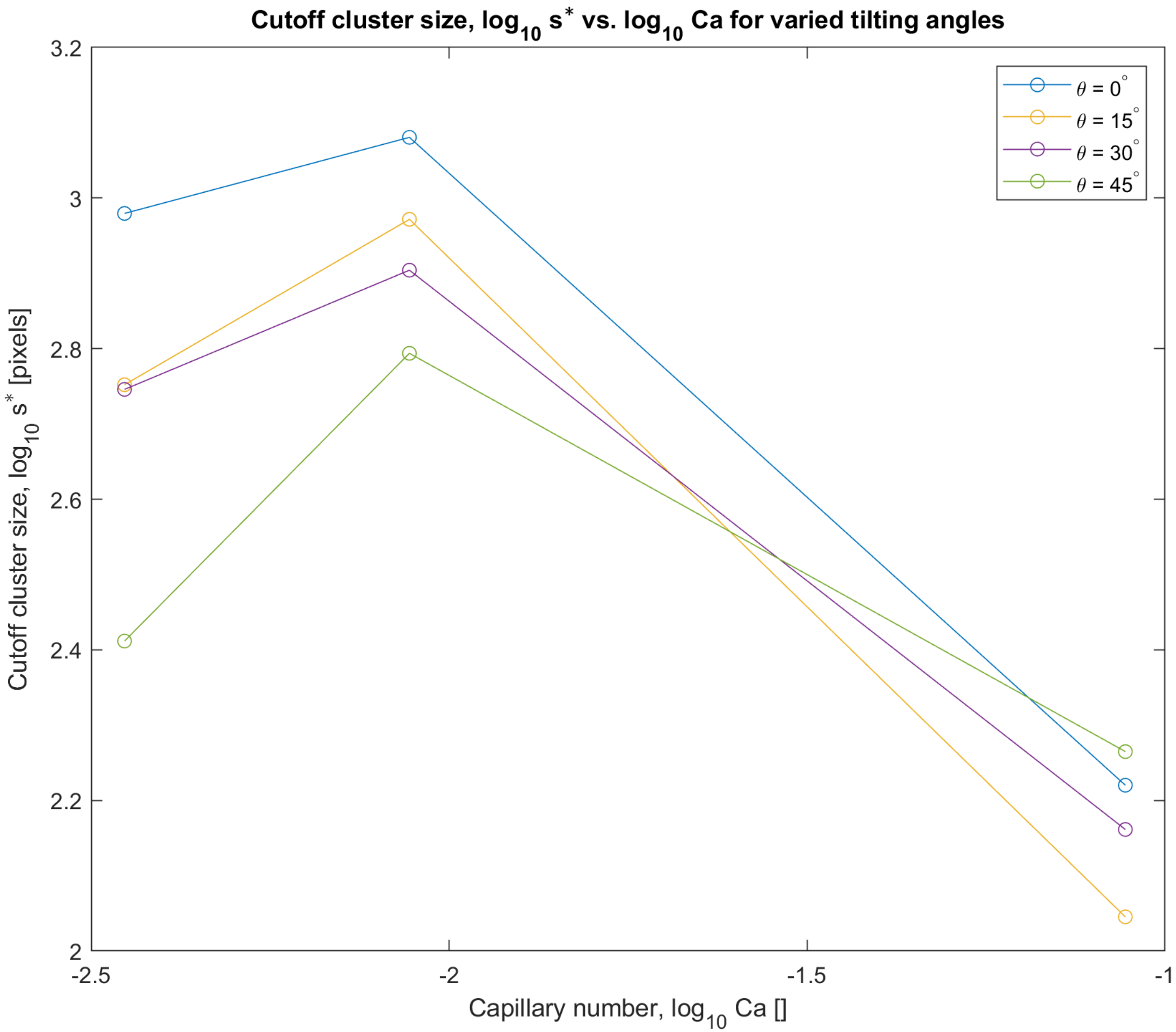
Impact of gravity on cluster size distribution



Why not? $s^* \propto \mathrm{Ca}^{-\zeta}$

Reproducible?

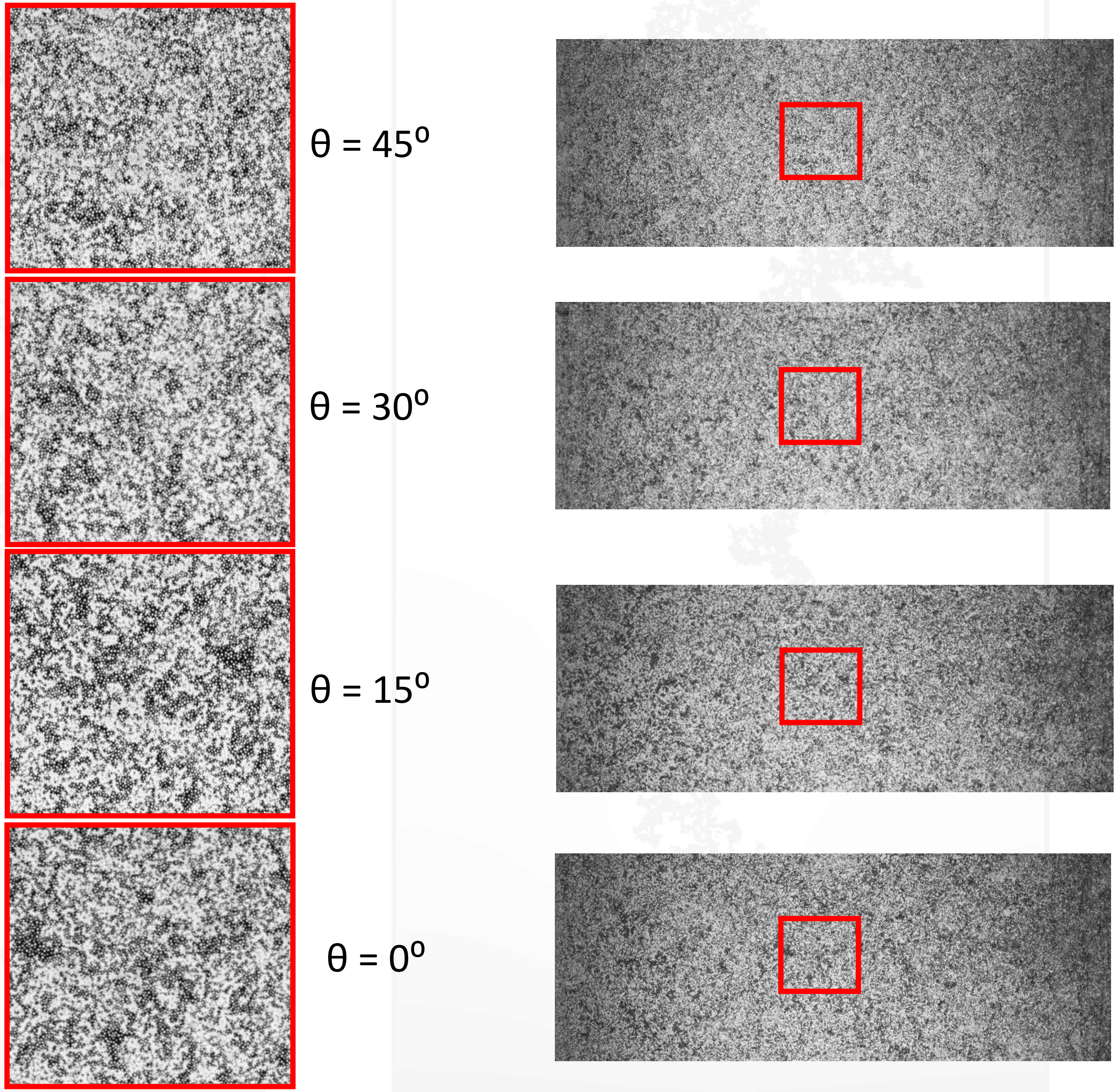
Impact of gravity on cluster size distribution



Why not? $s^* \propto \mathrm{Ca}^{-\zeta}$

Reproducible?

Impact of gravity on air cluster size



Ca = 3.52e-3

PoreLab
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Ca – pressure theory

(1) $$\mathrm{Ca} = \frac{\mu_w Q_w a^2}{\gamma \kappa_0 A}$$

(2) $$|\nabla P|\, l^* = \Delta P_L \frac{l^*}{L} = \bar{P}_t$$

(3) $$V_{dis} = L A_{dis} = L a^2 \frac{W}{l^*} = \frac{aV}{l^*}$$

Since the overall interface area between the wetting and nonwetting phase is fluctuating around a constant value in steady-state, changes in the potential energy stored in the interfaces do not contribute to the average dissipation, and we are justified in writing

$$Q_{tot} \Delta P_L = D_f = -\int_{V_{dis}} dV u |\nabla P| = \frac{\mu_w}{\kappa_0} \int_{V_{dis}} dV u^2 \;, \tag{4}$$

where we have applied Darcy's law locally, in the dissipative part of the wetting fluid. Taking the local Darcy velocity $u = (Q_w/A)(V/V_{dis})$ as a constant, and using Eqs. (3), (1) and (2) respectively we obtain

$$\Delta P_L = \frac{8\gamma V l^*}{15 a^3 A} \mathrm{Ca} \quad \Rightarrow \quad |\nabla P|^2 = \frac{8\gamma \bar{P}_t}{15 a^3} \mathrm{Ca} \;, \tag{5}$$

i.e. $|\nabla P| \propto \sqrt{\mathrm{Ca}}$, consistent with the exponent β in