Ballistic Aggregation In Flow

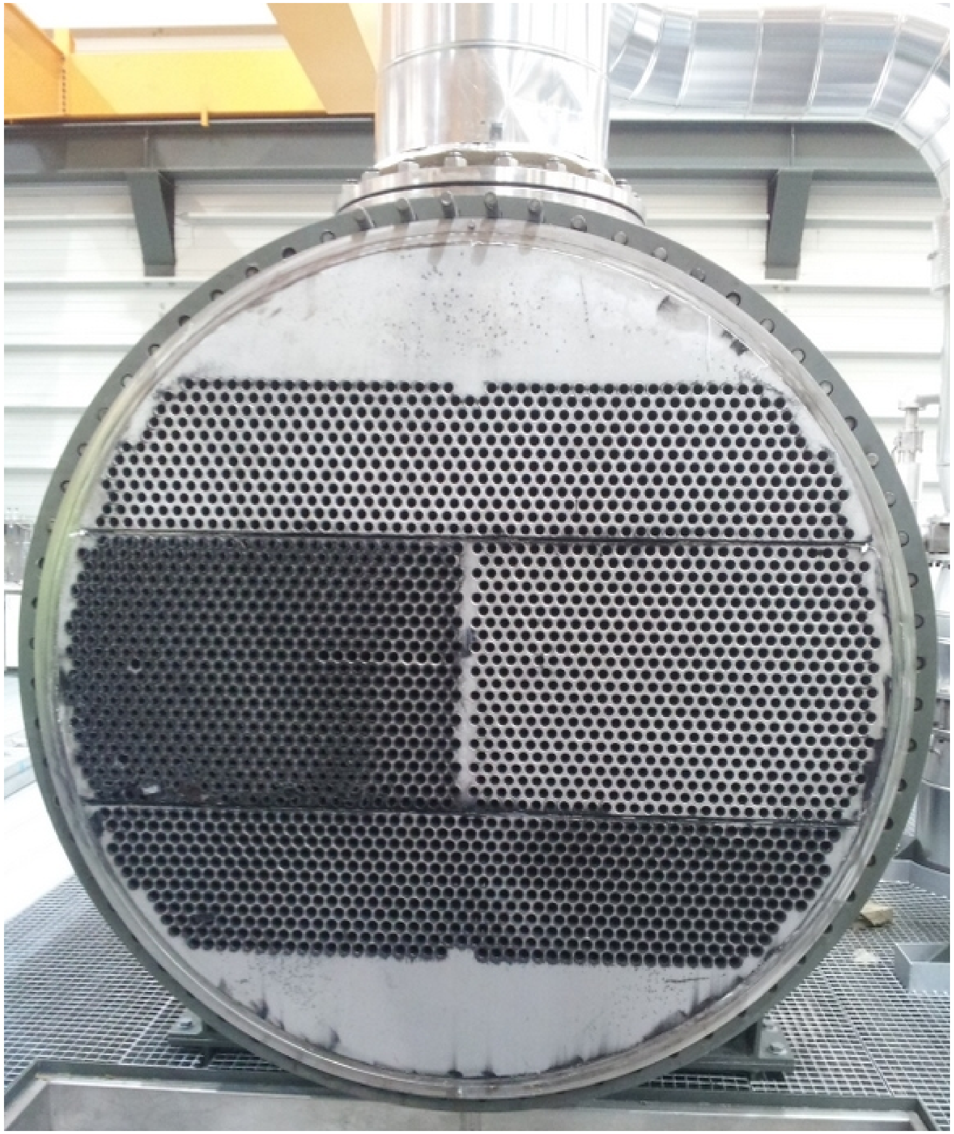
Christopher Hawkins

Luiza Angheluta, Bjørn Jamtveit
Physics of Geological Processes,
Department of Physics, University of Oslo, Norway

Daniela B. Meier, Liane Benning
School of Earth and Environment
University of Leeds


Hellisheiði Power Plant, Iceland

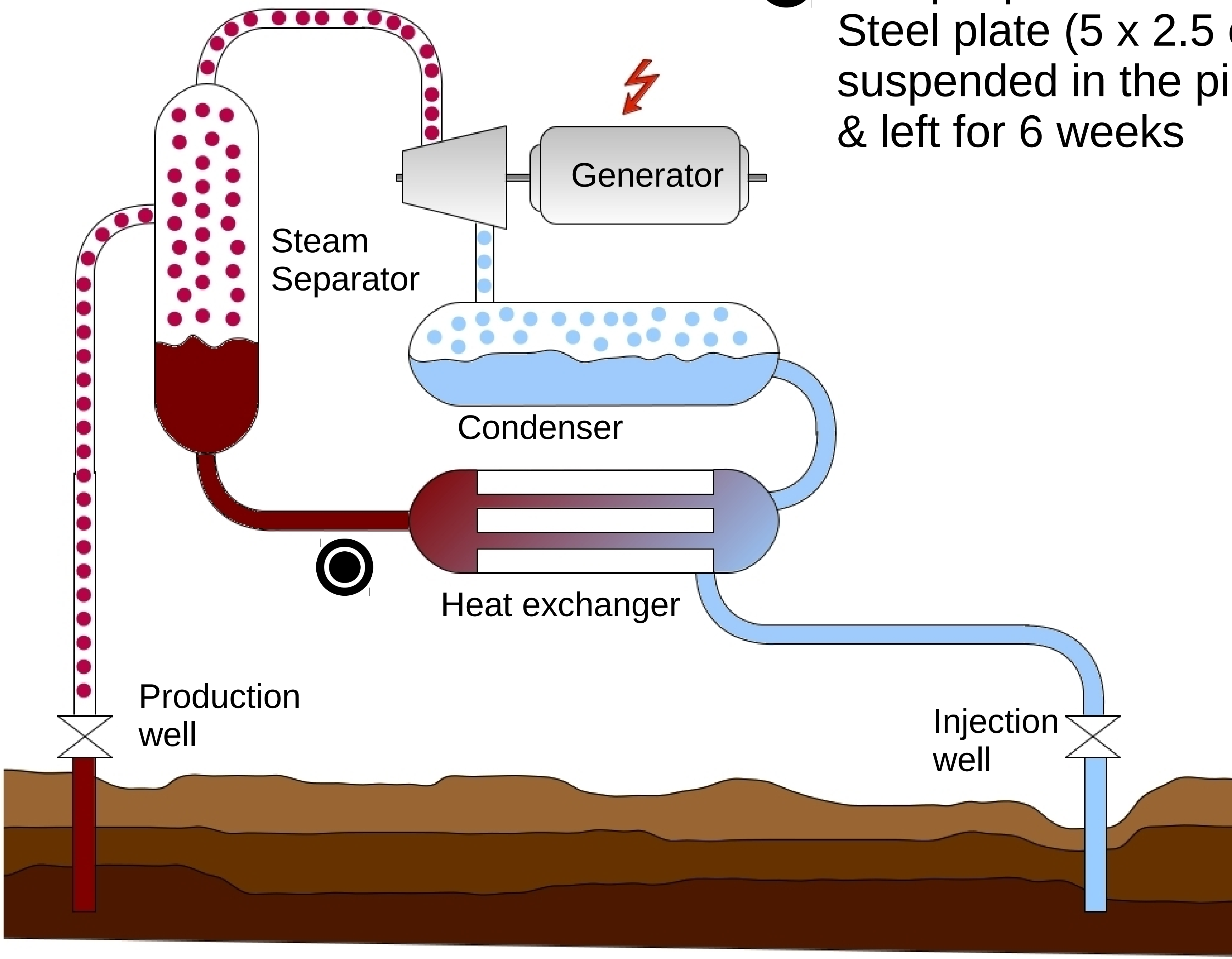
Hellisheiði Power Plant

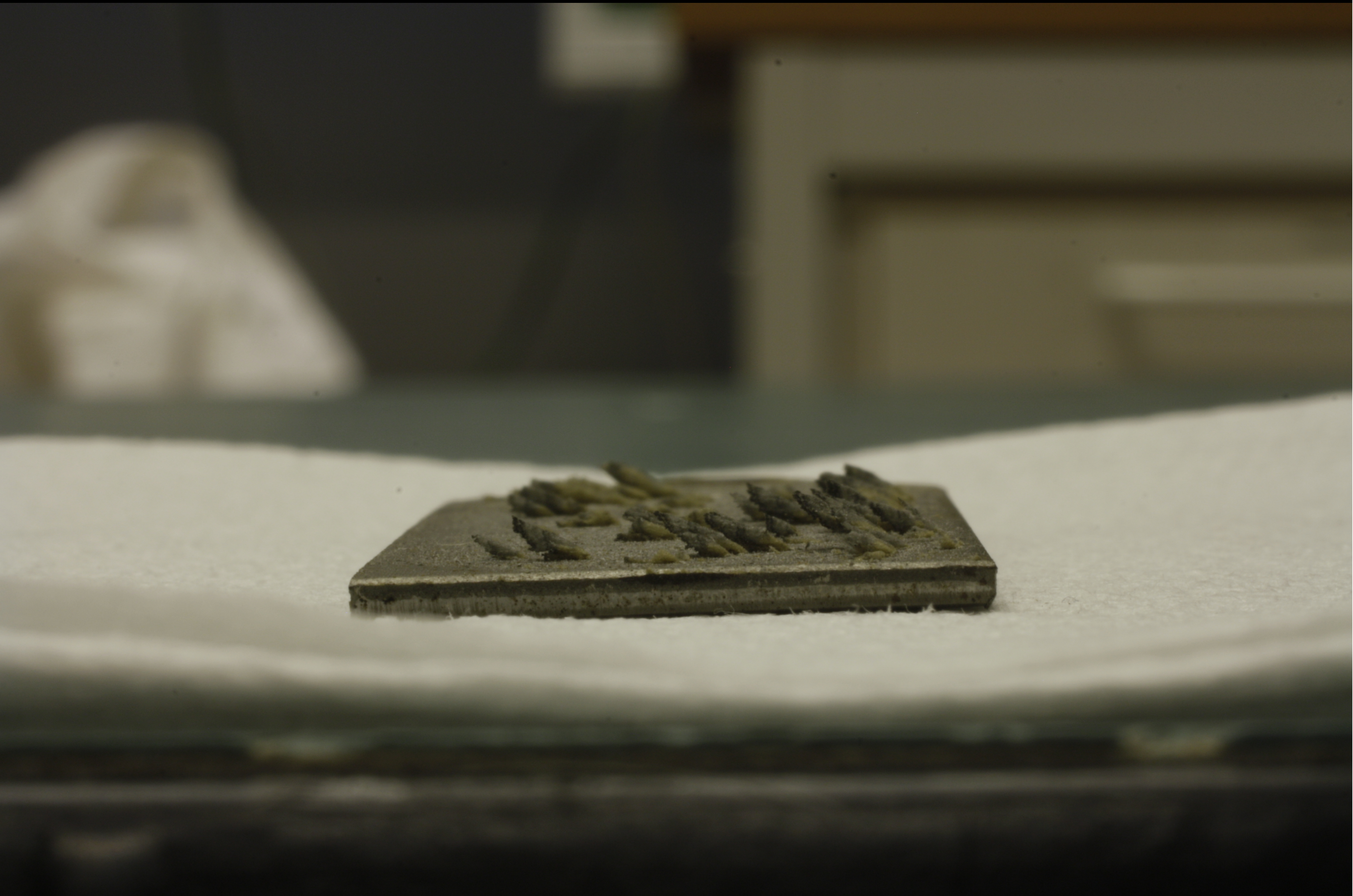


- Third largest geothermal power station in the world
- Pumps geothermal fluid at 300°C from depth of 3km
- Produces 303 MW electricity
- Fluid rich in silica ~1500 ppm
- Silica scaling occurs in pipes

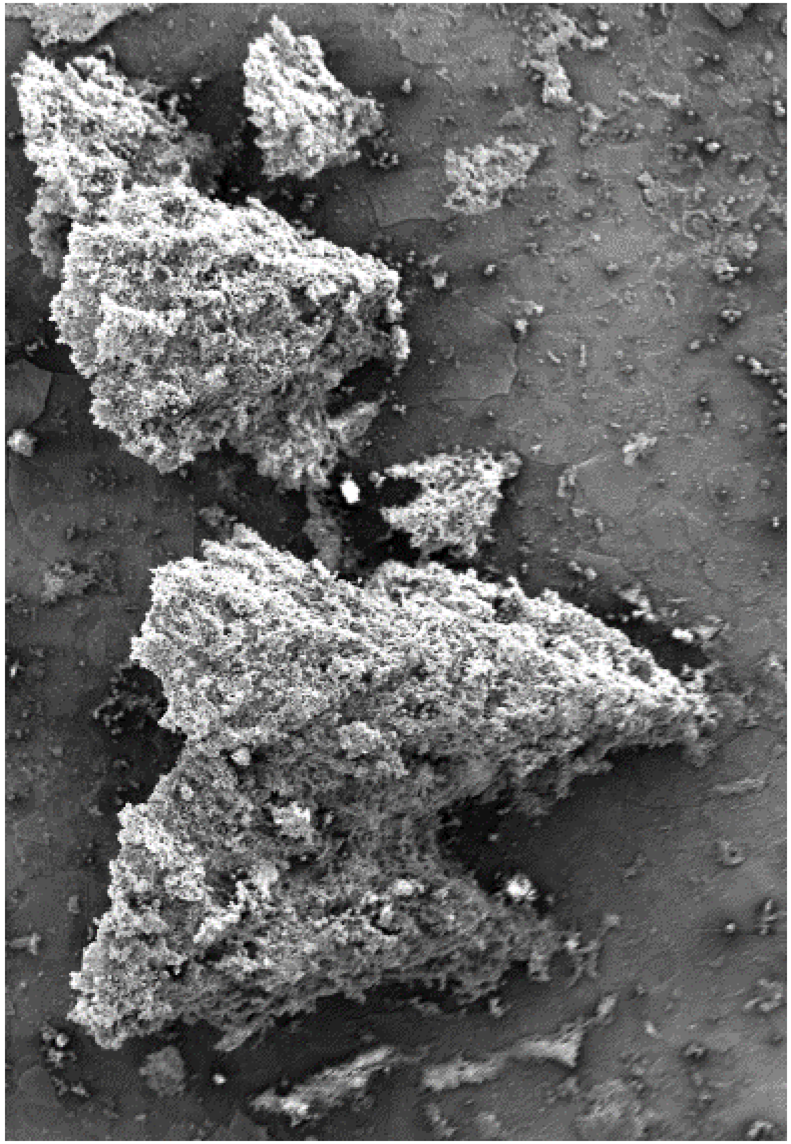
Plant schematic

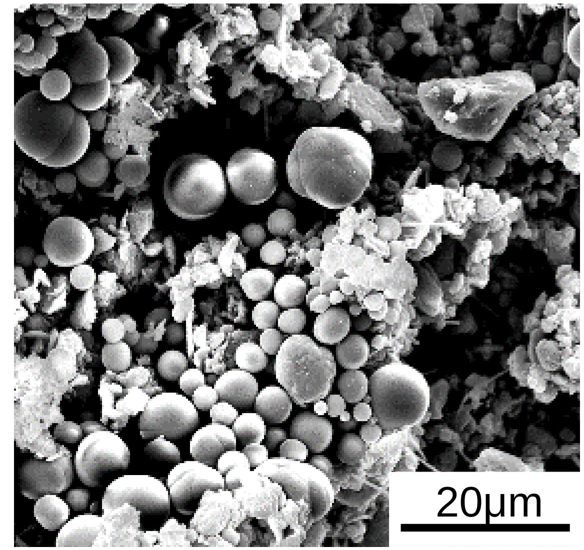
Sample point
Steel plate (5 x 2.5 cm)
suspended in the pipe
& left for 6 weeks

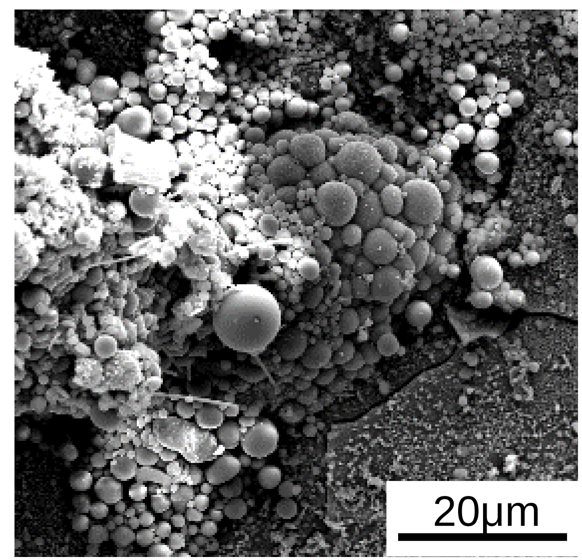




Closer look at the samples



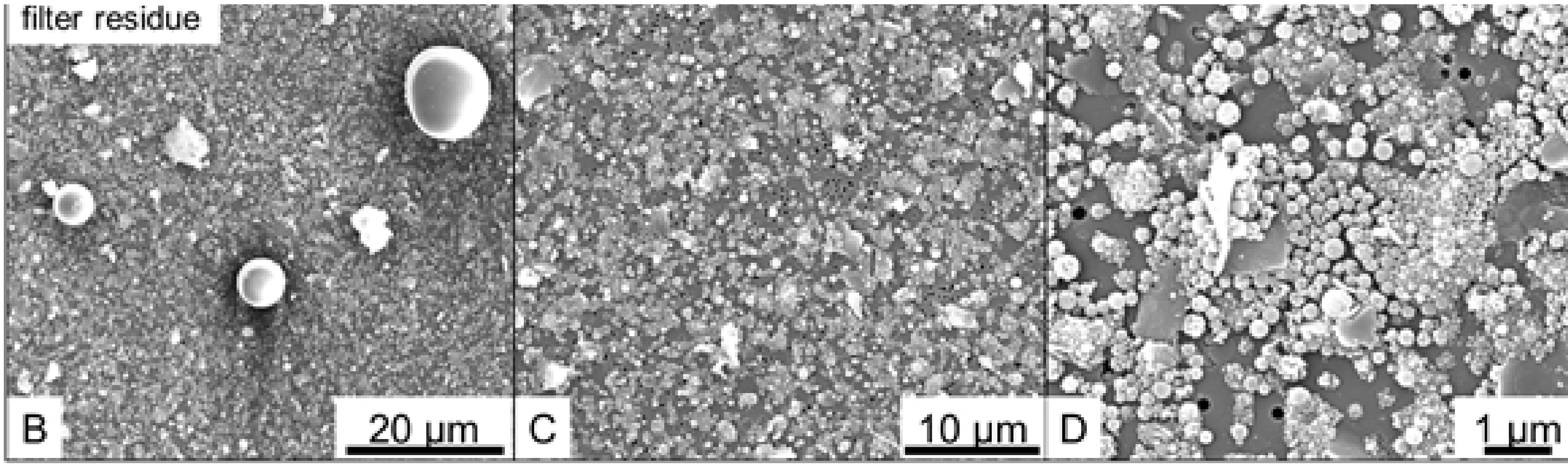




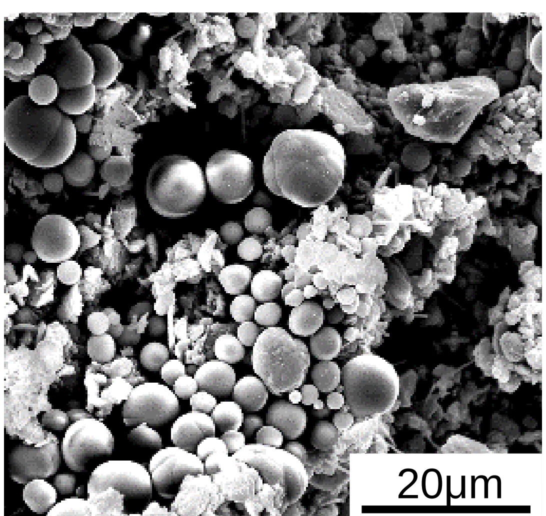
- Fan-like structure made of Silica spheres
- Precipitate in the bulk > Ballistic aggregation

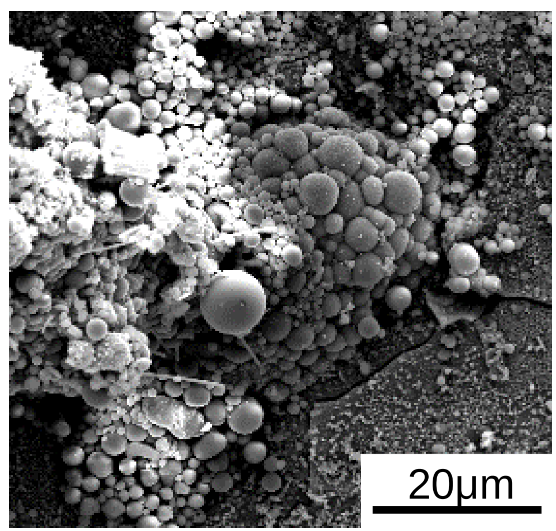
Bulk particles vs Structure particles

Bulk – Some large particles, mostly small



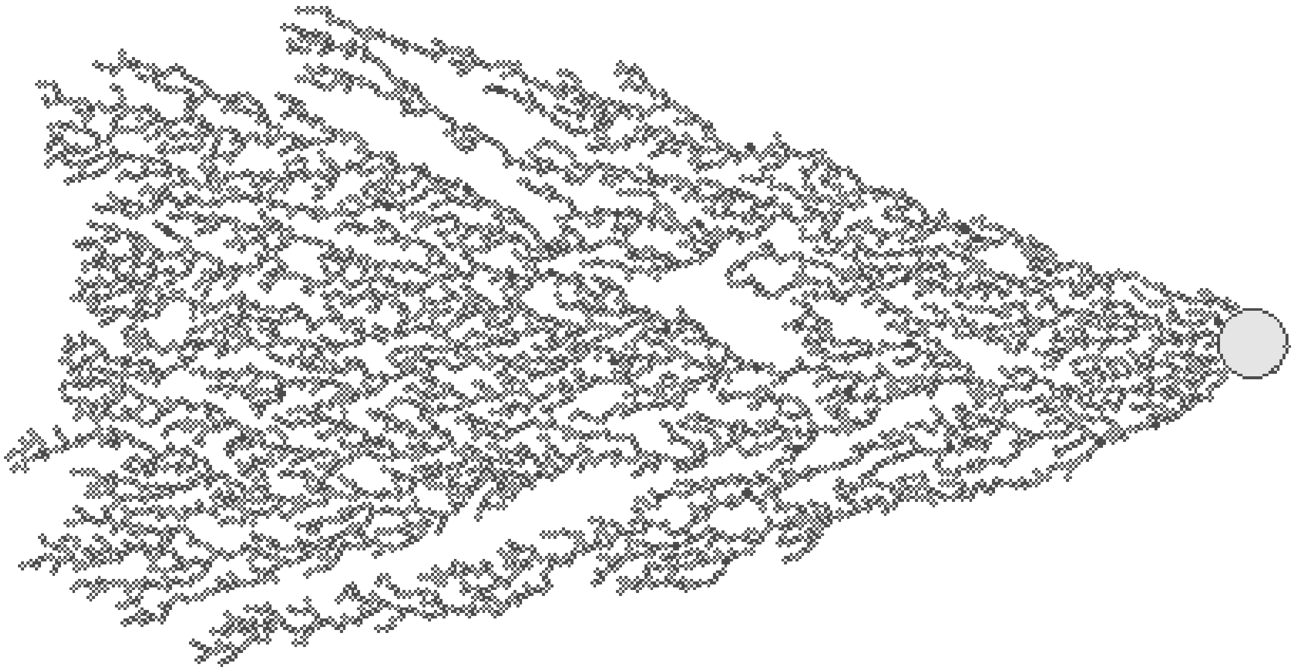
Structure – Mostly large particles





Large particles preferentially deposited

Fan-like structures



Single nucleation site – particles move in one direction

Particle forces

$$m\frac{d\boldsymbol{v}}{dt} = (\rho - \rho_f)\frac{4\pi}{3}R^3\boldsymbol{g} - 6\pi\eta R\,(\boldsymbol{v} - \boldsymbol{u})$$

Gravity & Buoyancy Drag

Assume: State plus a deviation due to the growing structure

Particle Velocity: $\boldsymbol{v} = \boldsymbol{v}_0 + \boldsymbol{v}'$ Fluid Velocity: $\boldsymbol{u} = \boldsymbol{u}_0 + \boldsymbol{u}'$

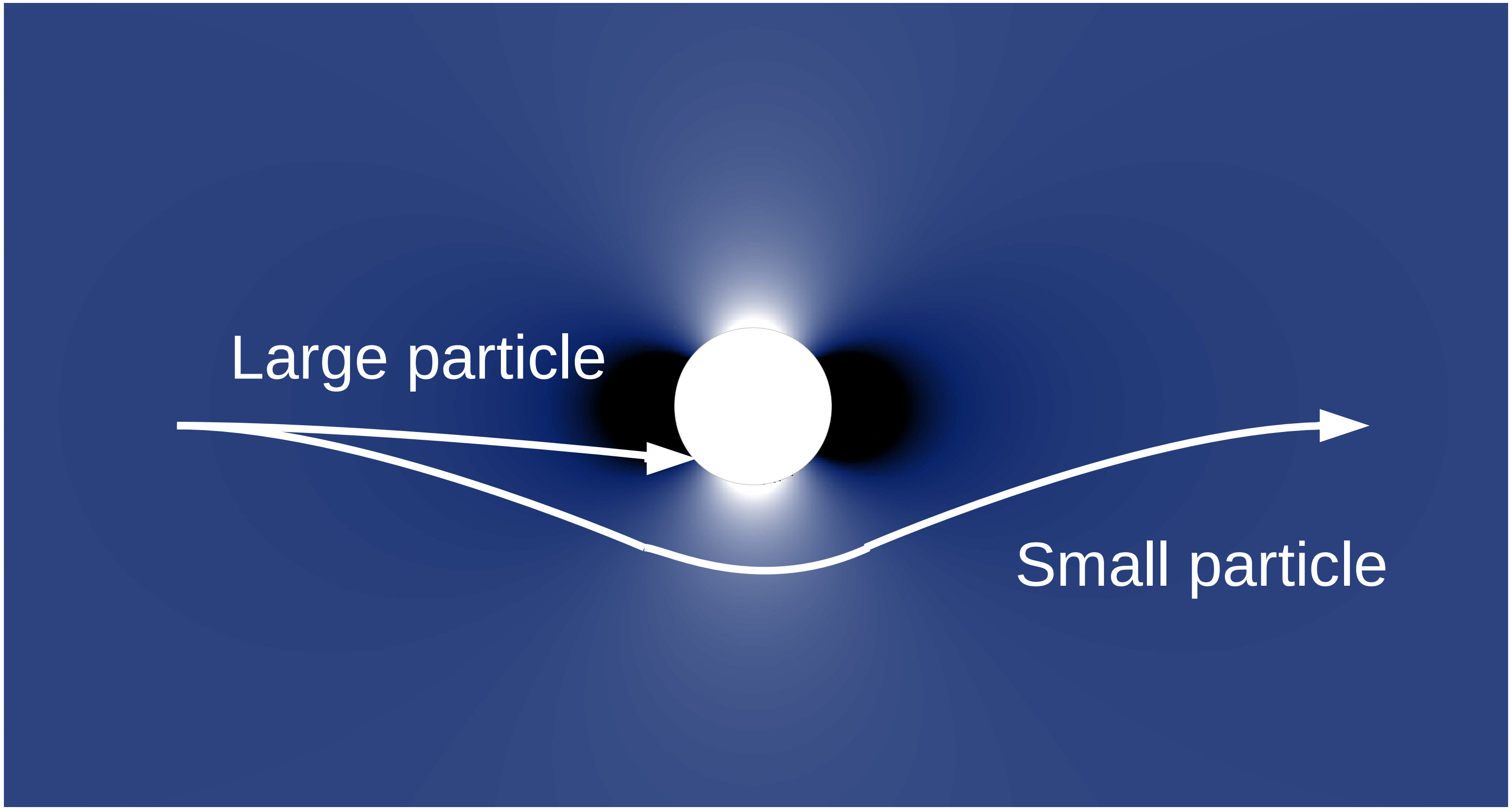
$2(\rho - \rho_f)R^2 g/(9\eta)$ Steady state falling velocity

$$\frac{d\boldsymbol{v}'}{dt} = -\frac{9\eta}{\rho R^2}\,(\boldsymbol{v}' - \boldsymbol{u}')$$ Deviation due to growing structure

Larger heavier particles will fall faster and be less affected by the flow

Particle forces

Larger heavier particles are less affected by the flow



Larger heavier particles will be more likely to aggregate

Model

Fluid flow -
Navier-Stokes equations solved using Lattice Boltzmann

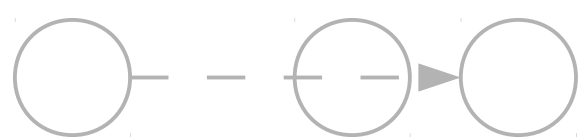
$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\mu\nabla^2\mathbf{u}+f$$

Particle Collisions -
Classical physics + prescribed aggregation probability

$$\begin{aligned} m_1\boldsymbol{v}_1' &= m_1\boldsymbol{v}_1-\boldsymbol{\Delta p}, \\ m_2\boldsymbol{v}_2' &= m_2\boldsymbol{v}_2+\boldsymbol{\Delta p}, \end{aligned} \qquad \boldsymbol{\Delta p}=\frac{m_1 m_2}{m_1+m_2}(1+e)\left(\boldsymbol{v}_{12}\cdot\boldsymbol{n}\right)\boldsymbol{n},$$

Stop particles moving trough one another

$$\Delta t_{max}=R_{min}/v_{max}$$



Separation of scales

In the real system the particles are very small compared to the bulk flow

- Size of pipe = 1m
- Flow velocity = 1m/s
- Smallest particles < 1μm

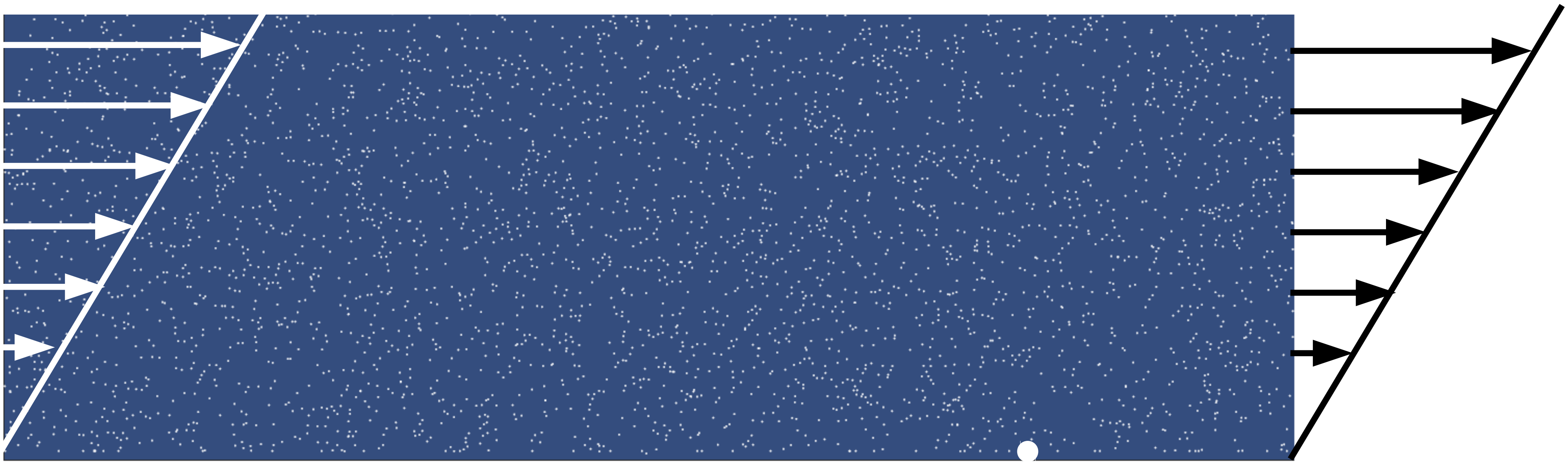
Simulation scales

- Time step must be less than $\Delta t_{max} = R_{min}/v_{max}$
- Spacial step small enough to resolve growing structure

We don't have to computing power for this

BUT: We are only interested in the near wall region

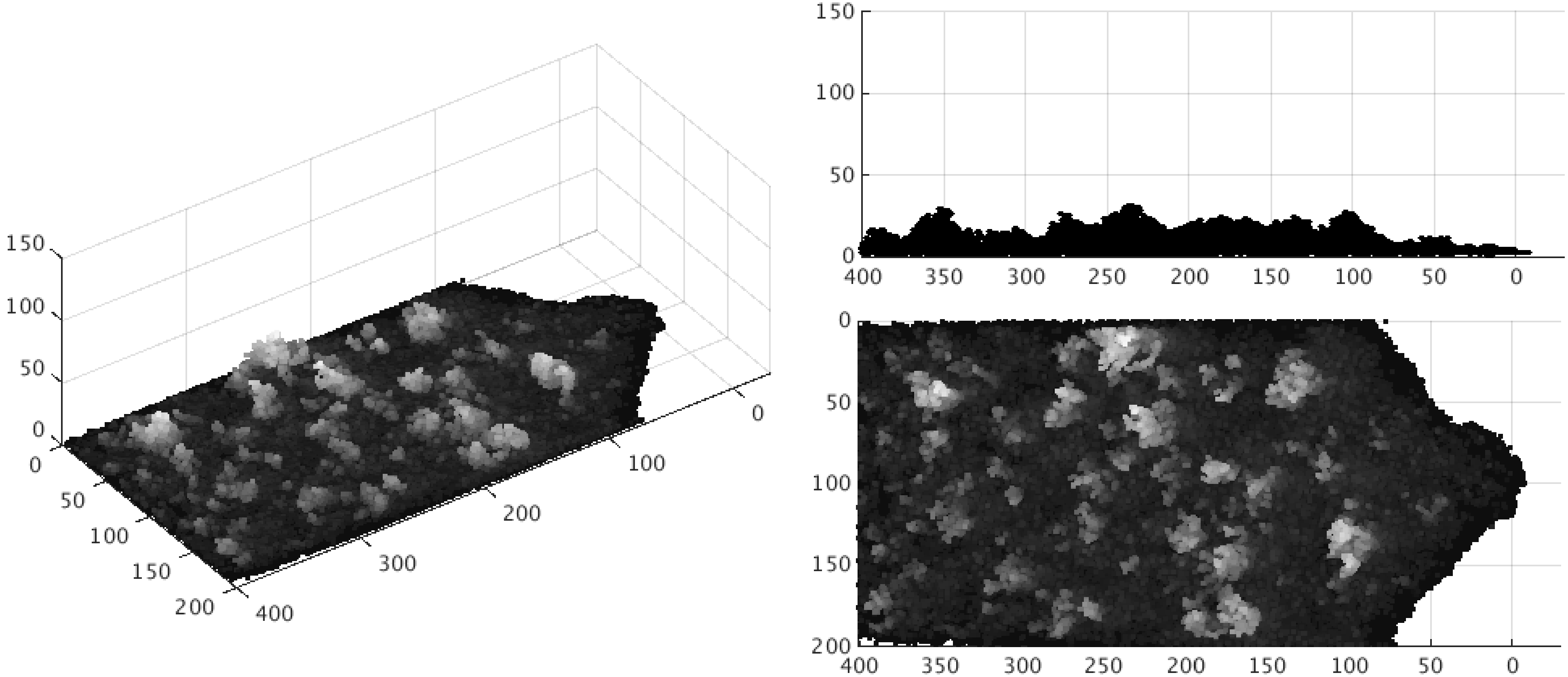
Setup



Conditions intended to match near wall flow in a large pipe system

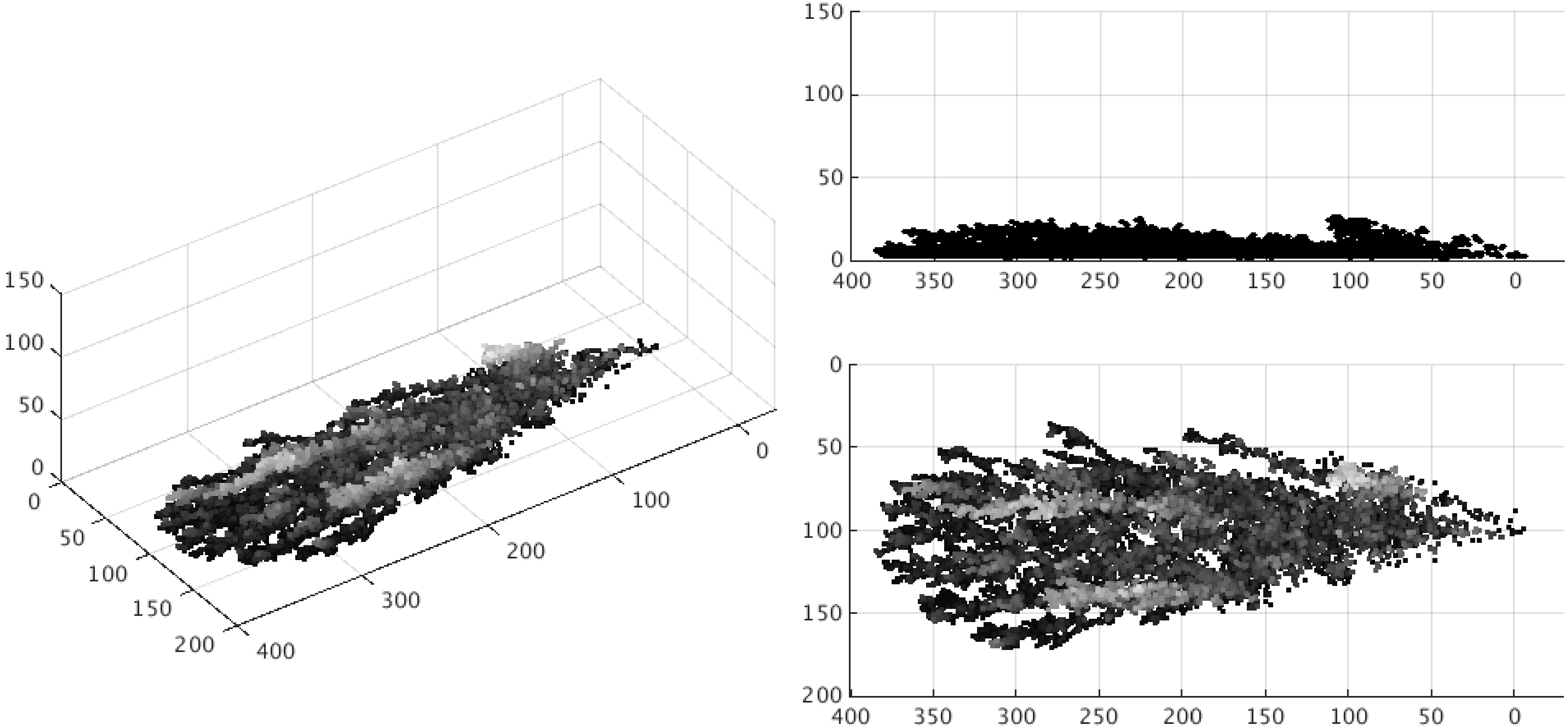
- Solid boundary on bottom
- Shear flow
- Single nucleation site
- Re = 100

Heavy particles, G=0.1



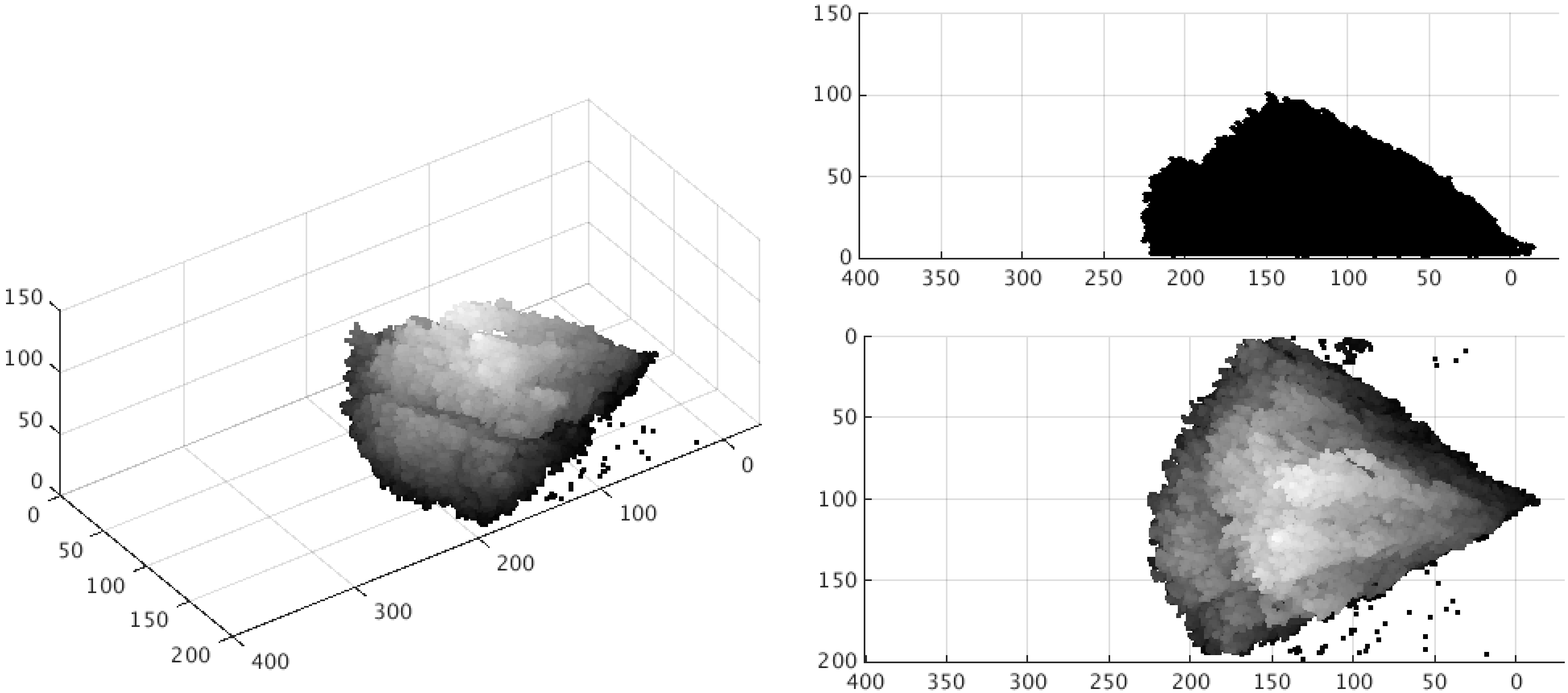
- Particles fall steeply causing a thin layer to form on the bottom plate
- Further falling particles aggregate across this thin layer

Light particles, G=0.001



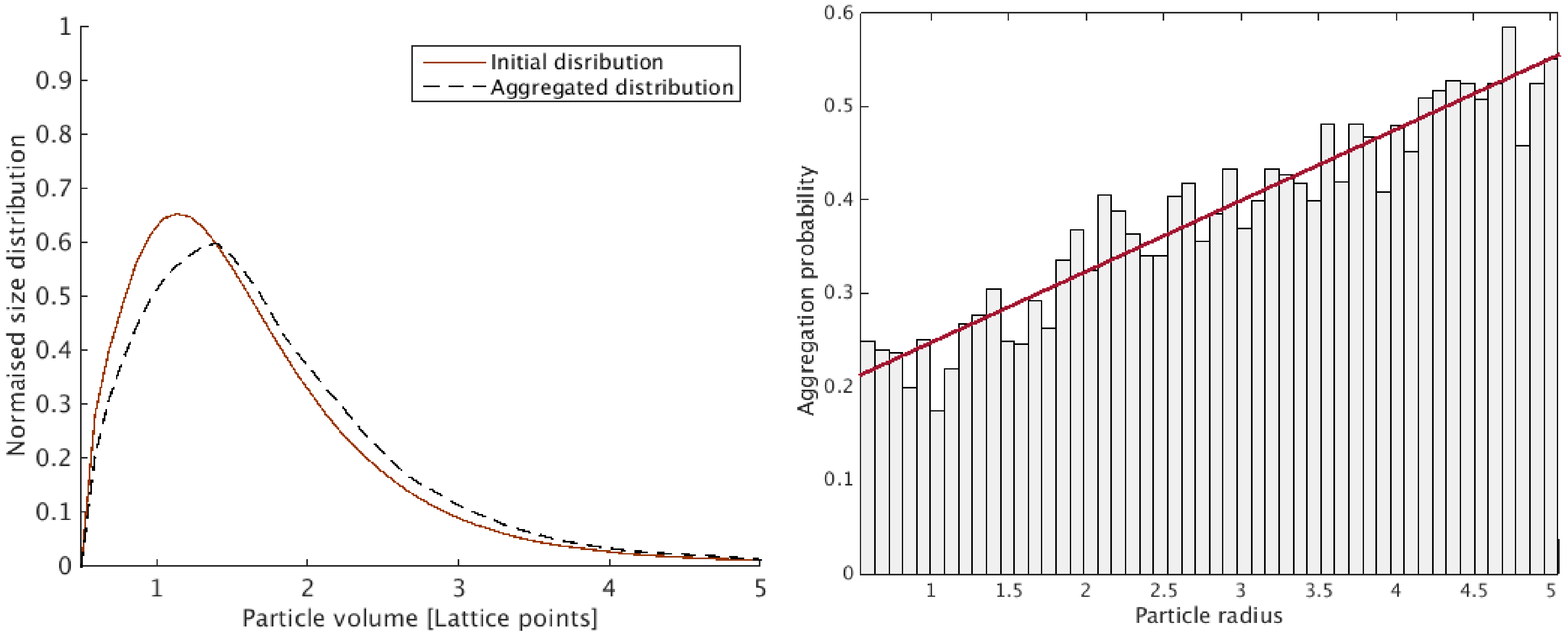
- Particles strongly diverted by flow away from solid structures
- Flow at bottom plate is stagnant hence particles settle here

Mid weight particles, G=0.01



- A balance of forces causes cone-like structures to form
- Structures very similar to those observed

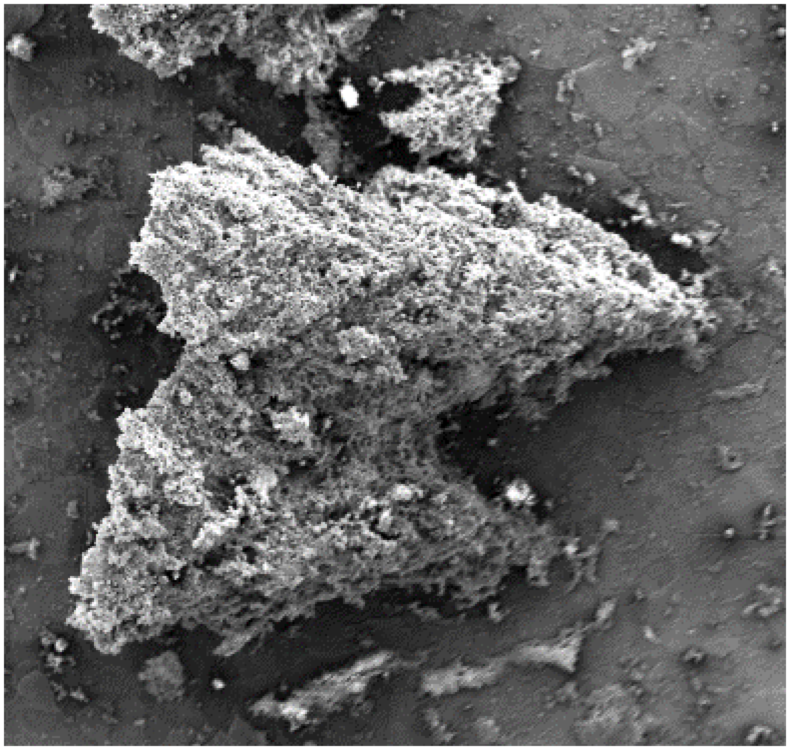
Polydisperse particle system



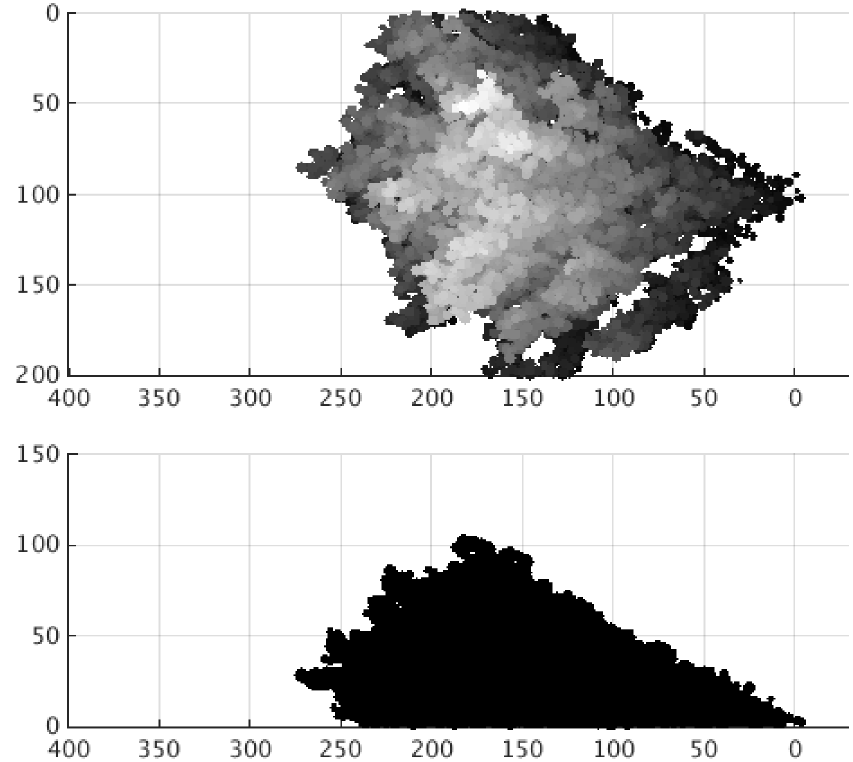
- Start with a lognormal distribution of particle sizes
- Probability of aggregation increases with particle size

Polydisperse particle system

Samples



Simulation



- Ballistic aggregation in flow causes the growth of fan-like structures
- Large particles more likely to aggregate than smaller ones due to divertive effects of flow

The End