Dynamic Structures in Bubbling Gas - Solid Fluidised Beds

The Local Granular Rheology

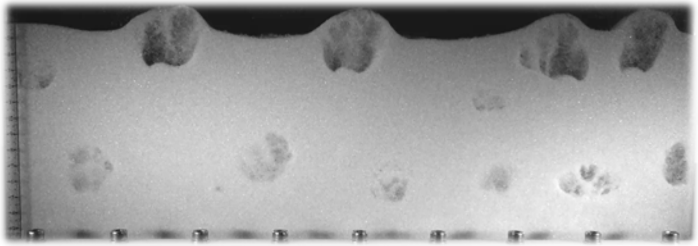
Dr. V. Francia, Mr. K. Wu, Prof M-O Coppens

University College London, Chemical Engineering.
CNIE. Centre for Nature Inspired Engineering.

a) Structured Fluidization - A Nature Inspired Approach

Dynamic granular structures

Response to a periodic perturbation in the surrounding flow. Wide spatial and temporal scales e.g. tides & waves, gusts & eddies



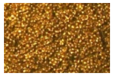
Pulsed fluidization

$$U_o/Umf = A + B \cdot (1 + \sin(2\pi \cdot f \cdot t))$$

1. Potential to control, design and scale-up fluidized beds
2. Help to understand the fundamental granular flow physics
3. A powerful tool to validate computational models

Quasi-2D fluidized bed

Glass beads, zinc, steel, polystyrene



Bronze distributor plate

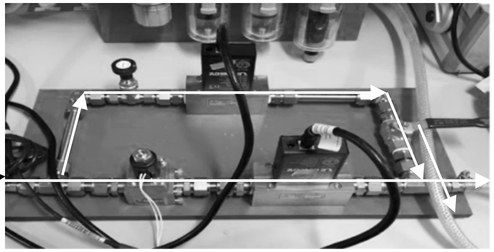
Fusilli

T - 15 mm
W - 450 mm
H - 800 mm

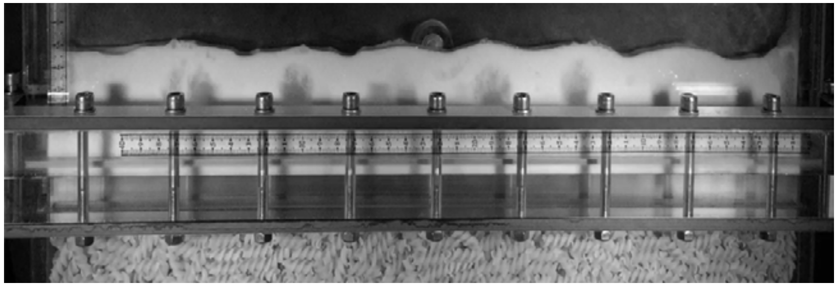
Filtered ambient air

2 parallel lines

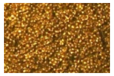
Needle Valve – Constant
Solenoid Valve – Oscillating



$$U_o/Umf = A + B \cdot (1 + \sin(2\pi \cdot f \cdot t))$$



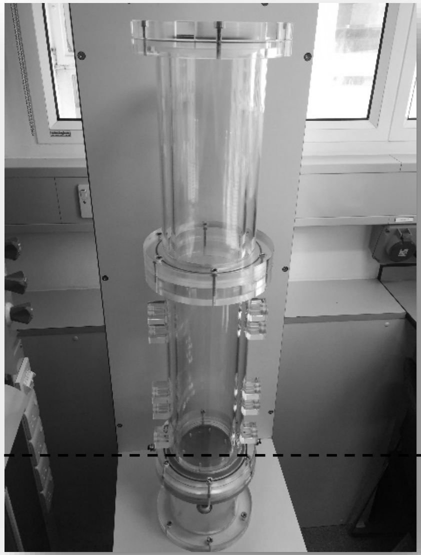
Glass beads, zinc, steel, polystyrene



Bronze distributor plate

Fusilli

3D fluidized bed

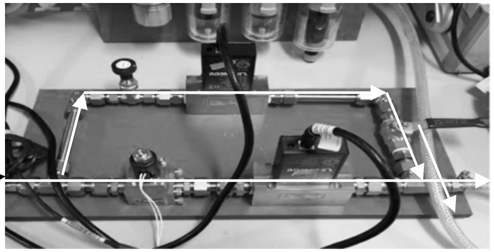


D - 140 mm
H - 800 mm

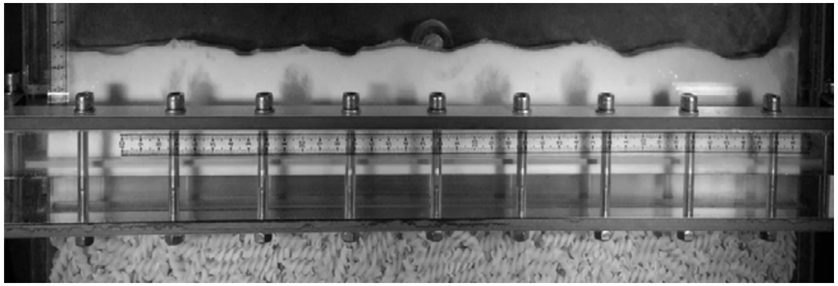
Filtered ambient air

2 parallel lines

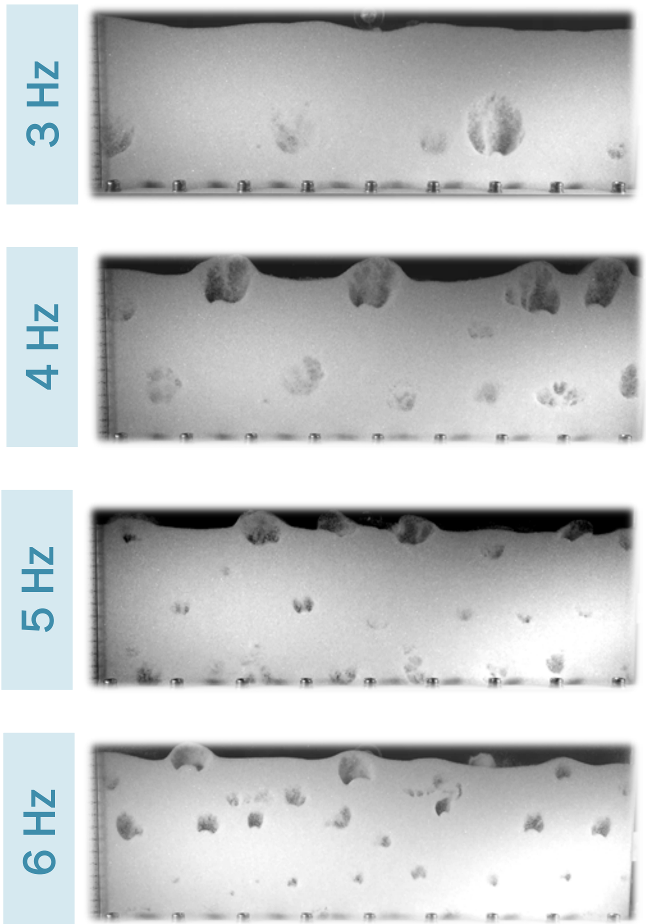
Needle Valve – Constant
Solenoid Valve – Oscillating



$$U_o/Umf = A + B \cdot (1 + \sin(2\pi \cdot f \cdot t))$$



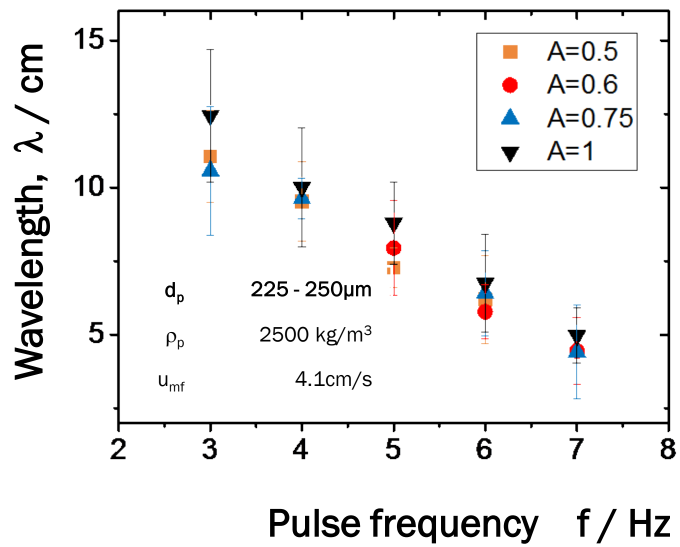
b1- Controlling the bubble dynamics - Arrangement



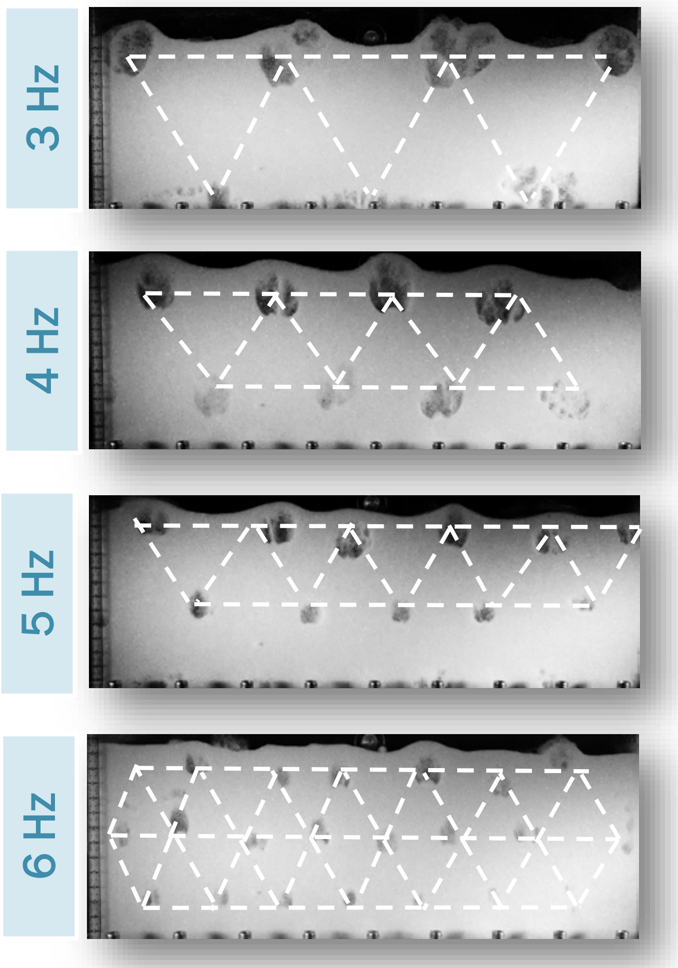
Screening

… size reduces with increasing frequency because the excess gas reduced in every pulse.

$$U_o/Umf = 3 + A \cdot sin(2\pi f\ t).$$



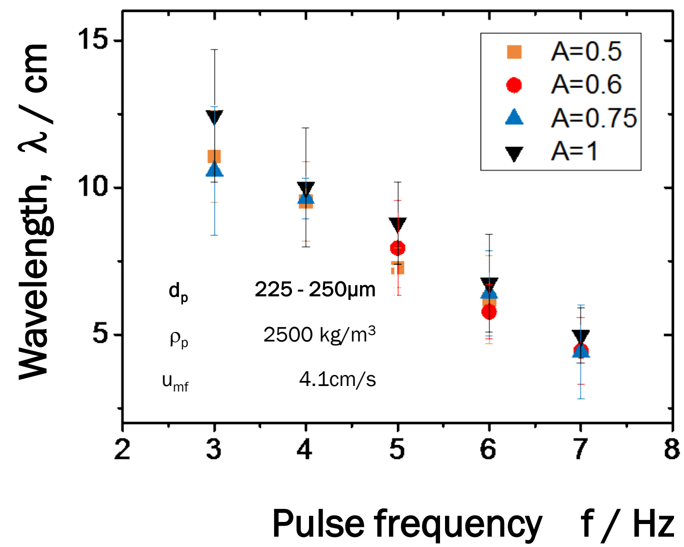
b1- Controlling the bubble dynamics - Arrangement



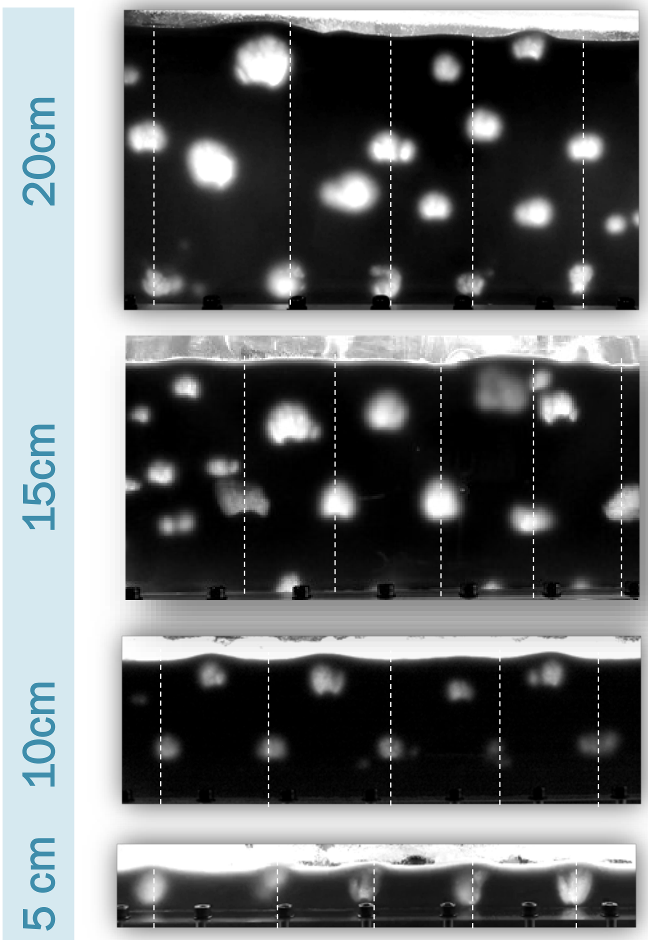
Screening

Size distribution becomes narrower because all nucleate and arrange in a particular manner…

$$U_o/Umf = 3 + A \cdot sin(2\pi f\ t).$$

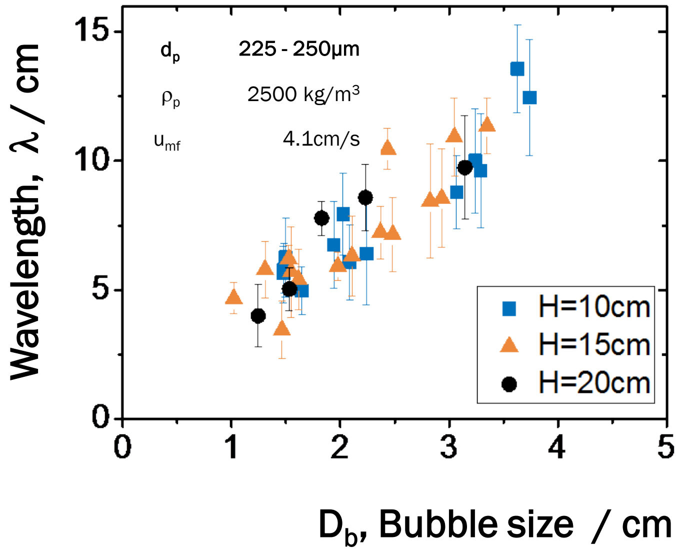


b1- Controlling the bubble dynamics - Size



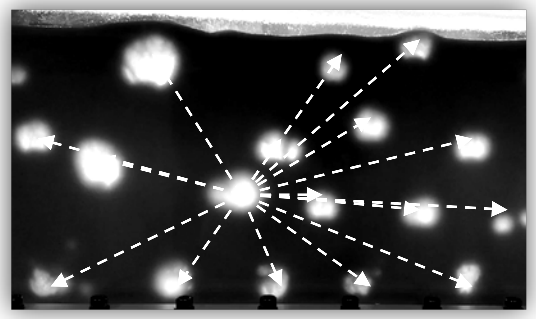
Screening

Size follows the wavelength of the perturbation to accommodate excess gas into more bubbles



b1- Controlling the bubble dynamics - Quality

D_b = 1.55 cm

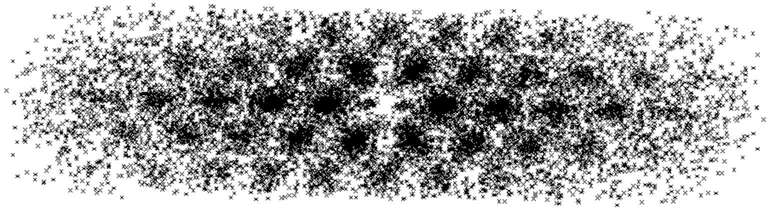


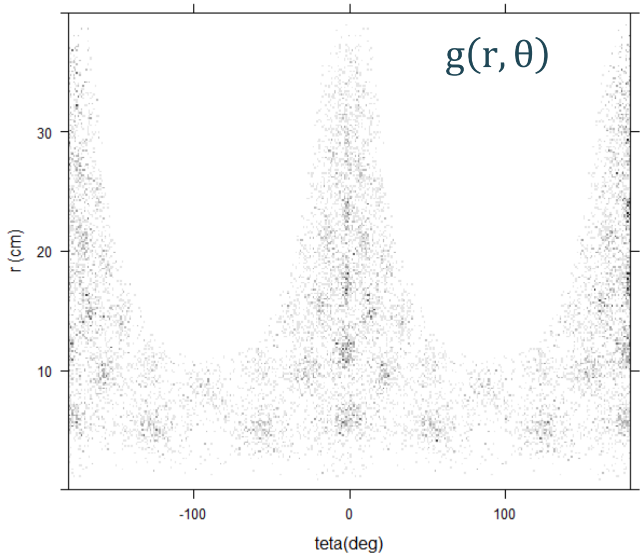
Looking at the **cross correlation** of the bubble positions from a Langrangian frame of reference.

We can use 2D probability density fields to quantify the strength of the local bubble arrangement.

$$P=\int_0^{\infty}\int_0^{2\pi} g(r,\theta)\,d\theta\,dr = 1$$

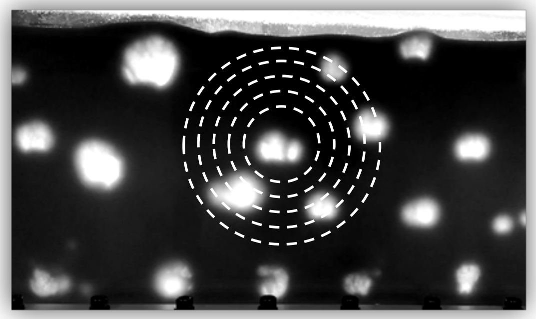
Quantification





b1- Controlling the bubble dynamics - RDF

D_b = 1.55 cm

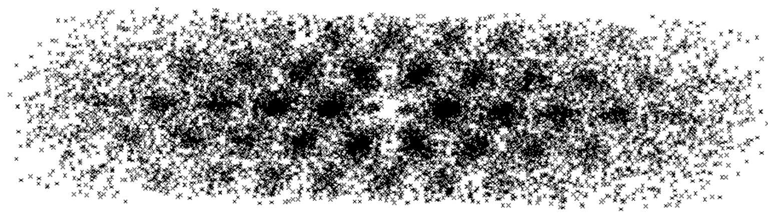


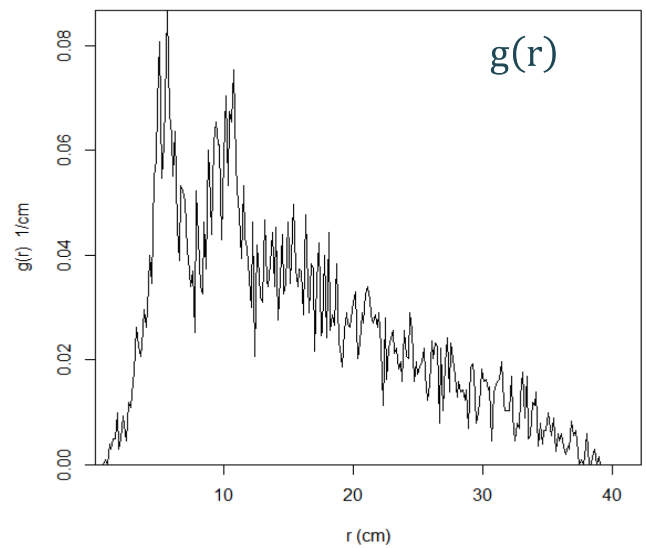
Looking at the **cross correlation** of the bubble positions from a Langrangian frame of reference.

1D probability density fields set the **most probable local distances** for neighbouring bubbles.

$$g(r)=\int_0^{2\pi} g(r,\theta)d\theta$$

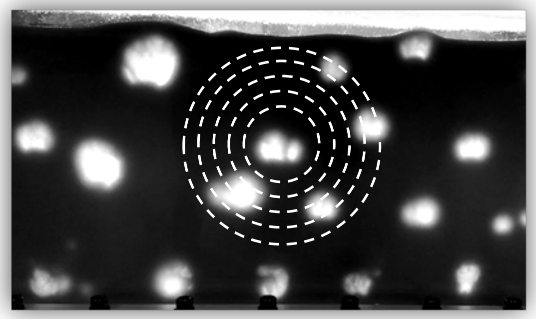
Quantification





b1- Controlling the bubble dynamics - 1st Generation

D_b = 1.55 cm

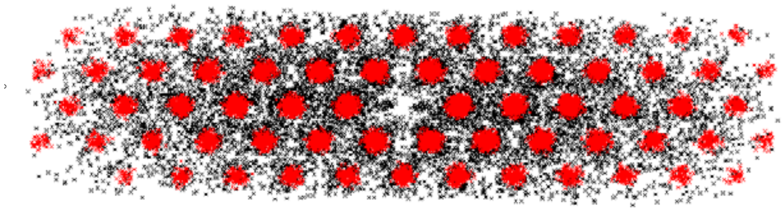


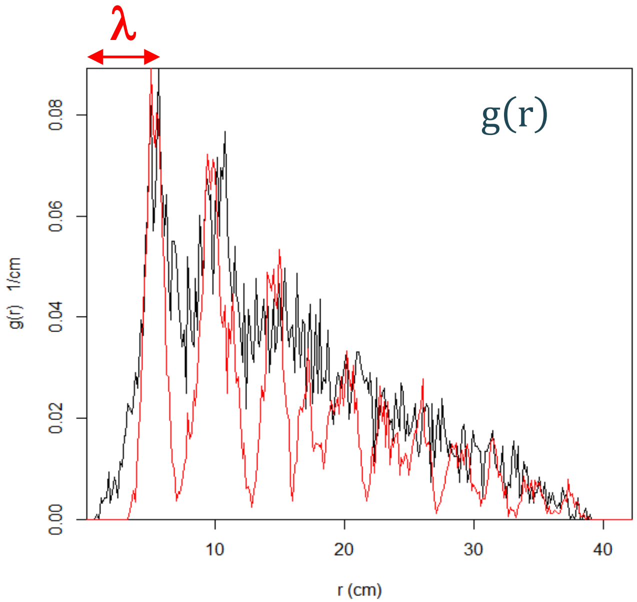
Looking at the **cross correlation** of the bubble positions from a Langrangian frame of reference.

1D probability density fields set the **most probable local distances** for neighbouring bubbles.

$$g(r)=\int_0^{2\pi} g(r,\theta)d\theta$$

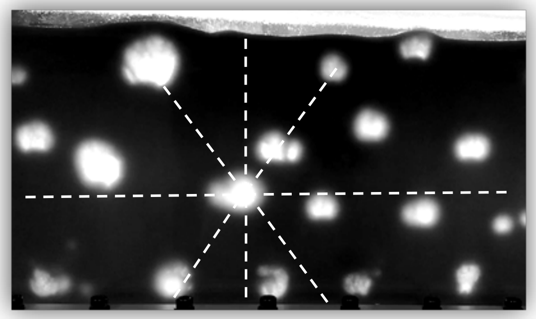
Quantification





b1- Controlling the bubble dynamics - ADF

D_b = 1.55 cm

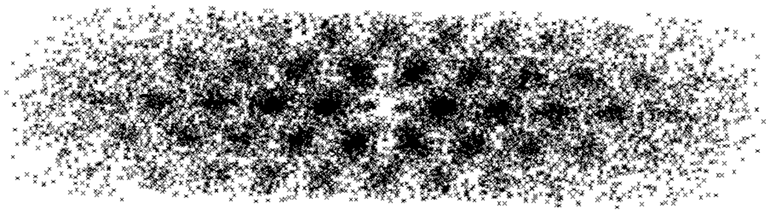


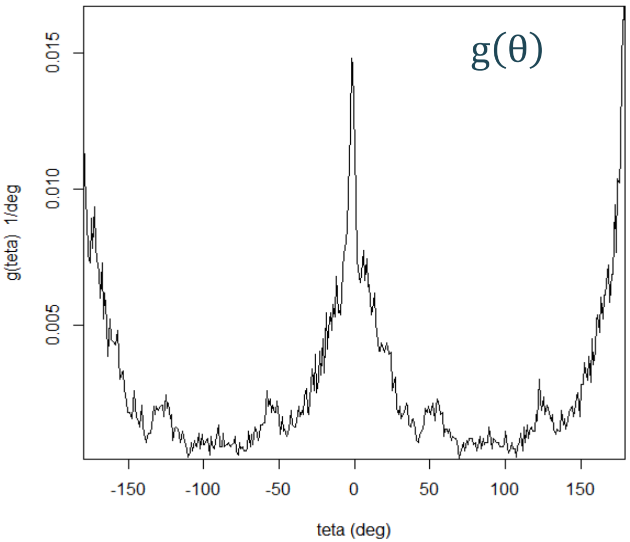
Looking at the **cross correlation** of the bubble positions from a Langrangian frame of reference.

1D probability density fields set the **most probable local angles** for neighbouring bubbles.

$$g(\theta)=\int_0^\infty g(r,\theta)dr$$

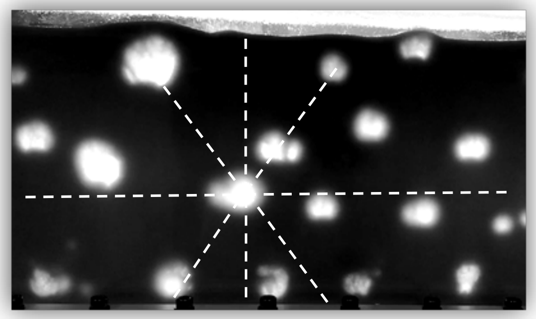
Quantification





b1- Controlling the bubble dynamics - 1st Generation

D_b = 1.55 cm

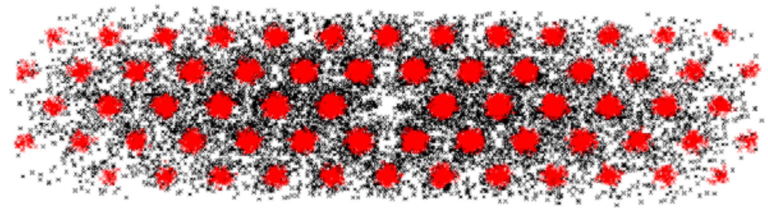


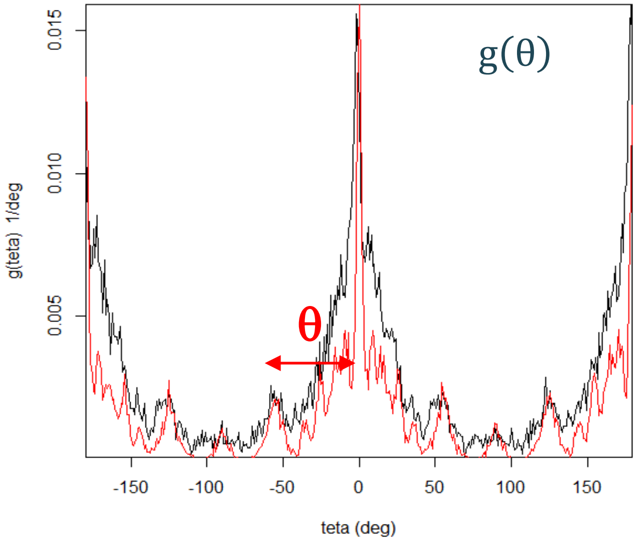
Looking at the **cross correlation** of the bubble positions from a Langrangian frame of reference.

1D probability density fields set the **most probable local angles** for neighbouring bubbles.

$$g(\theta)=\int_0^\infty g(r,\theta)dr$$

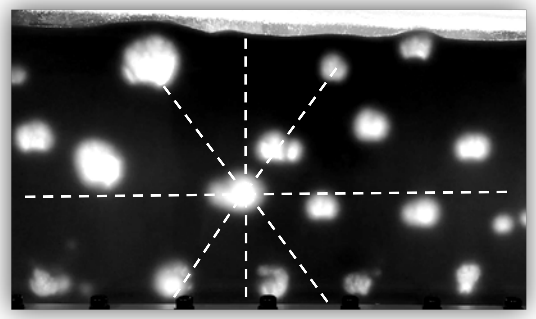
Quantification





b1- Controlling the bubble dynamics - Optimization

D_b = 1.55 cm



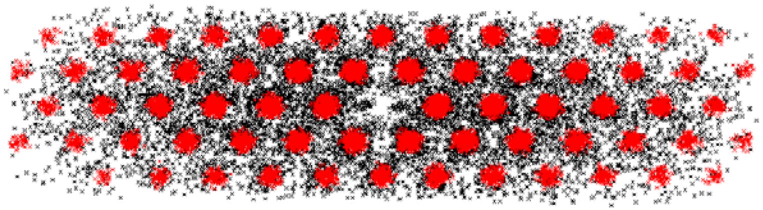
Need to move to a quantitative study of pattern formation. Measurement of local order in the arrangement of the bubbles.

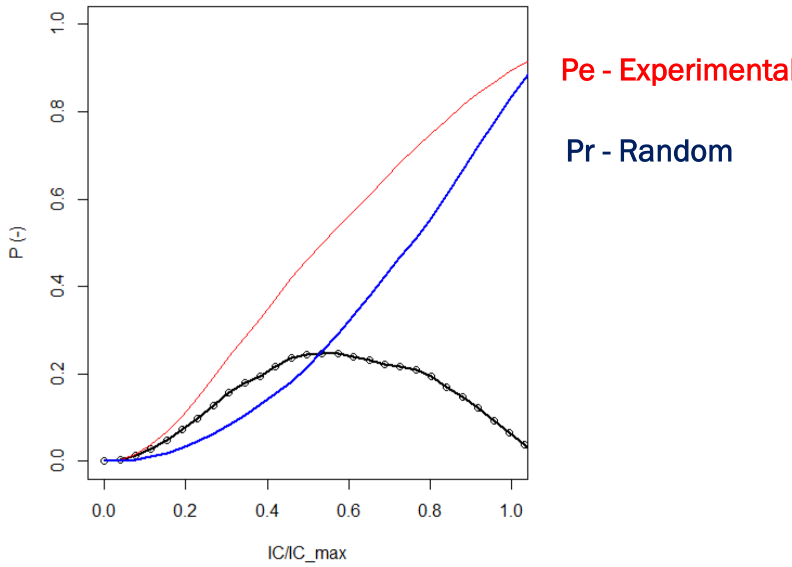
Variance associated to a triangular tessellation of given variability vs that of random placement.

I = 0 Random Placement

I = 1 Triangular tessellation

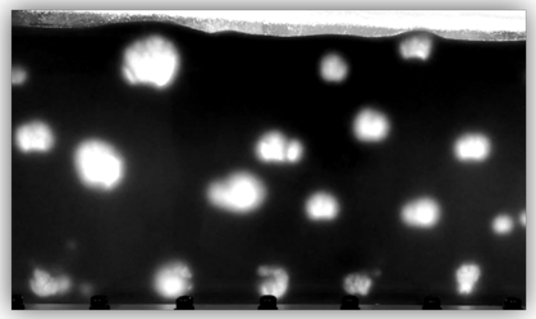
Quantification



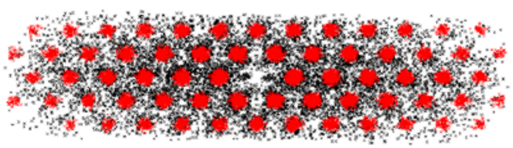


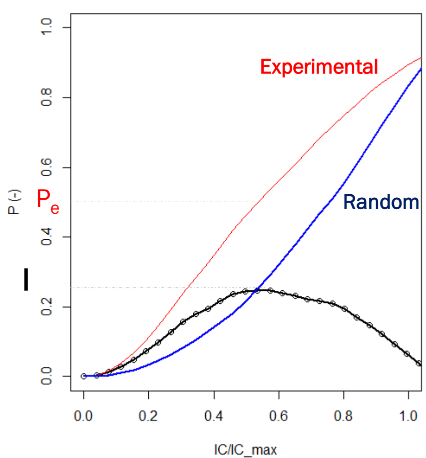
b1- Controlling the bubble dynamics - Optimization

D_b = 1.55 cm

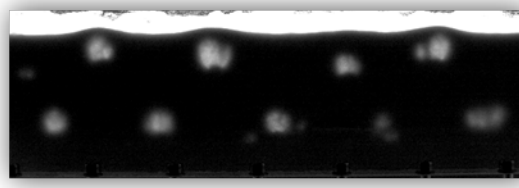


P_e = 42 % I_1 = 0.25

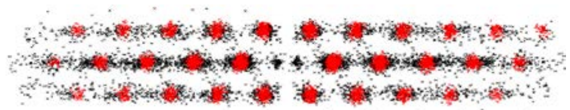


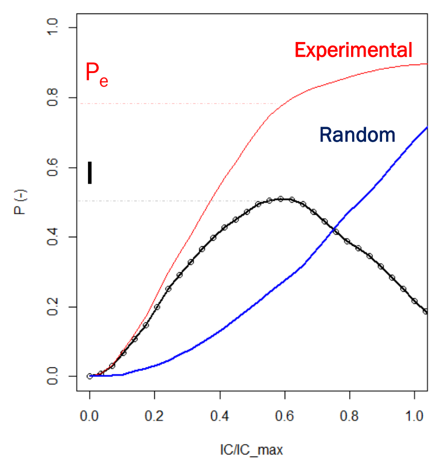


D_b = 1.21 cm



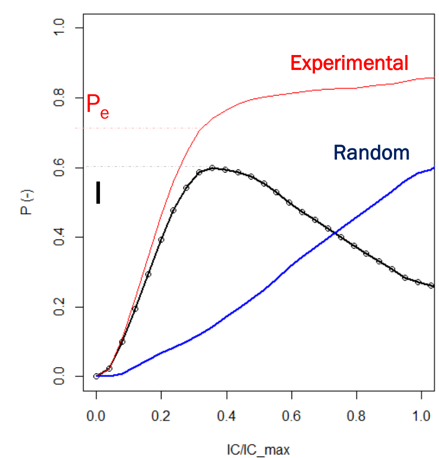
P_e = 77 % I_1 = 0.51





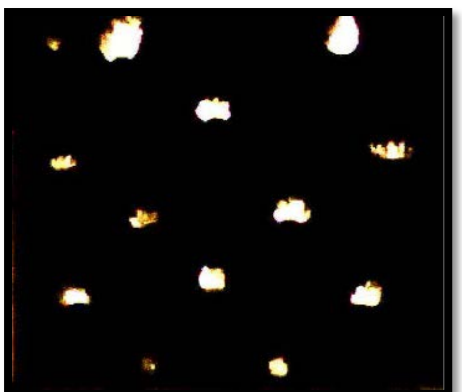
D_b = 1.42 cm

$P_{e,7}$ = 74 % I_1 = 0.61



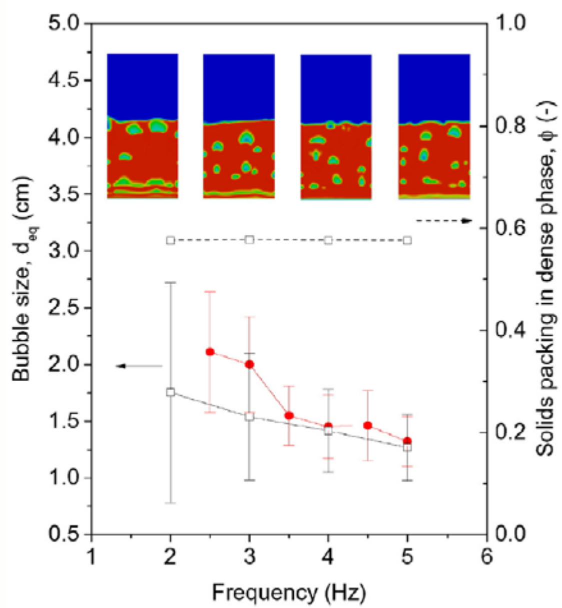
b2- Performance of Kinetic Models

Experimental

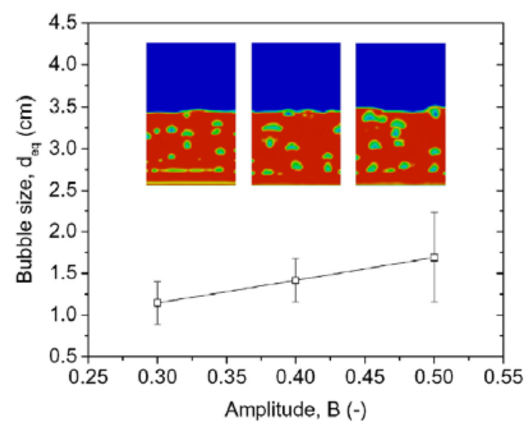


High 2D beds - Gidaspow – Shaeffer - Lun

- A classical kinetic formulation can predict well average bubble characteristics while failing to capture the bubble dynamics.



$$u_0/u_{mf} = A + B\sin(2\pi ft)$$

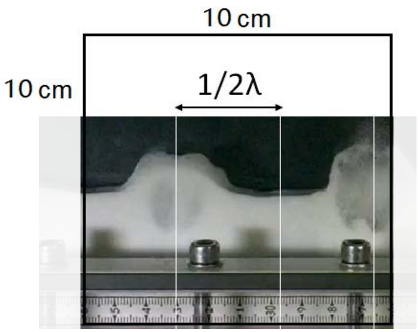


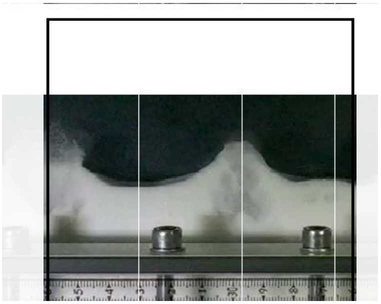
Wu et al. *Powder Tech.* 295, 35–42 (2016)

b2- Nucleation – TFM vs CFD/DEM

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$

Experimental



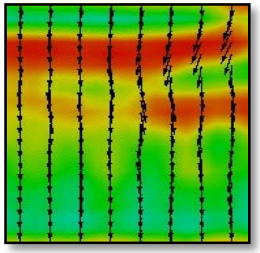


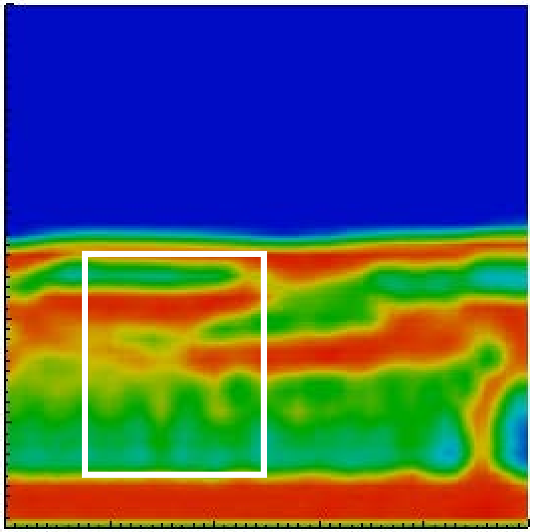
$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - **CFD / DEM**

- A dynamic pattern stabilises after a few pulsation cycles.
- Solving the granular rheology, even at the resolution of DEM allows capturing the alternation of the bubble nucleation sites.



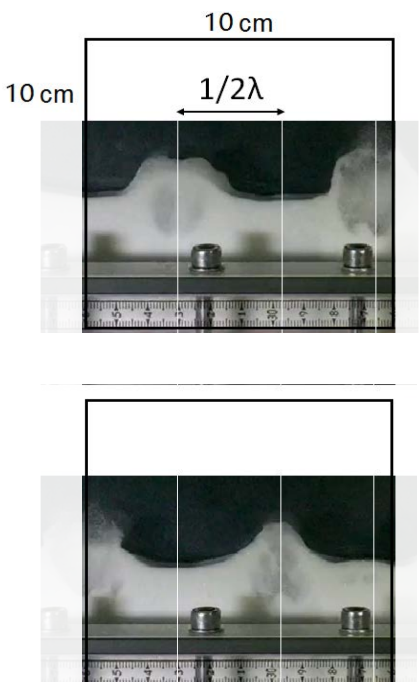


Wu et al. *Chem Eng Journal,* In Press (2017)

b2- Nucleation – TFM vs CFD/DEM

$$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\ t)$$

Experimental

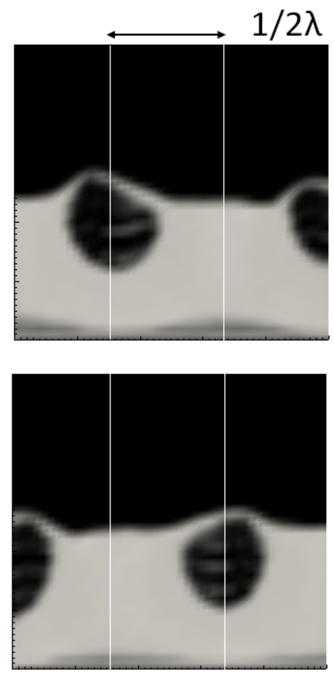


D_b = 2.5 ± 0.2 cm

λ = 6.5 ± 0.6 cm

Low 2D beds - TFM vs CFD / DEM

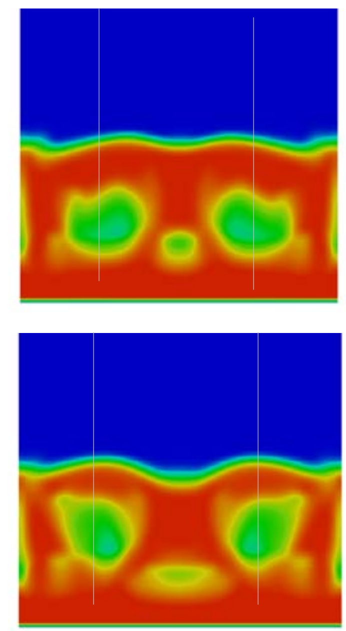
CFD / DEM



D_b = 2.2 ± 0.5 cm

λ = 6.4 ± 0.2 cm

TFM



D_b = 2.2 ± 1.0 cm

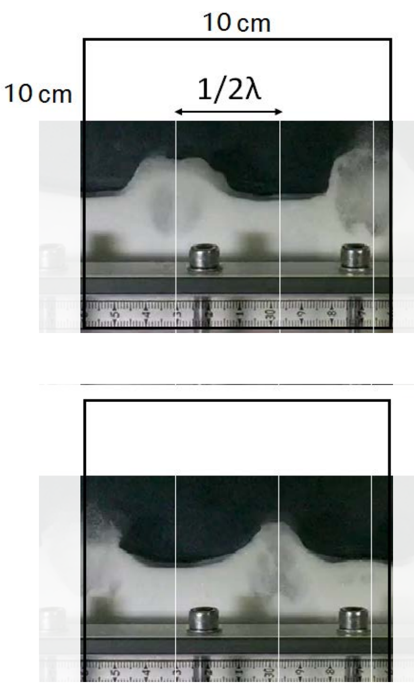
λ = 6.2 ± 0.3 cm

Wu et al. *Chem Eng Journal,* In Press (2017)

b2- Nucleation – TFM vs CFD/DEM

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$

Experimental

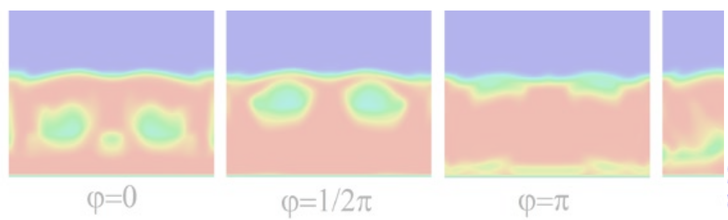


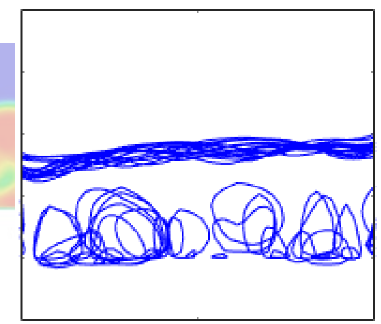
$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

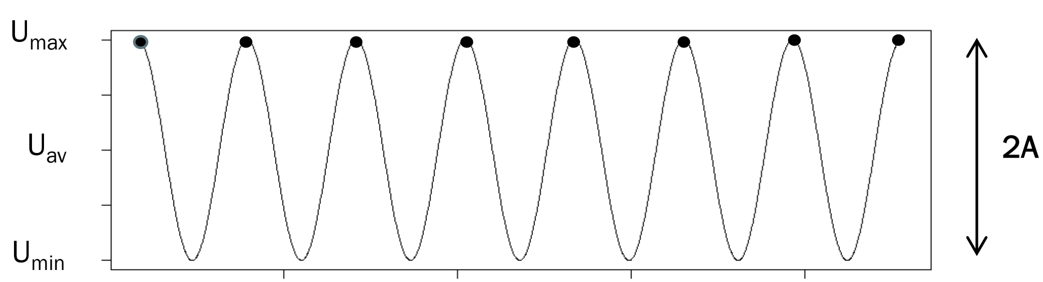
Low 2D beds - TFM vs CFD / DEM

- Instable. There are instances of a consistent nucleation and size, but the arrangement does not propagate spatially (big bed) or in time (through numerous pulsation cycles).





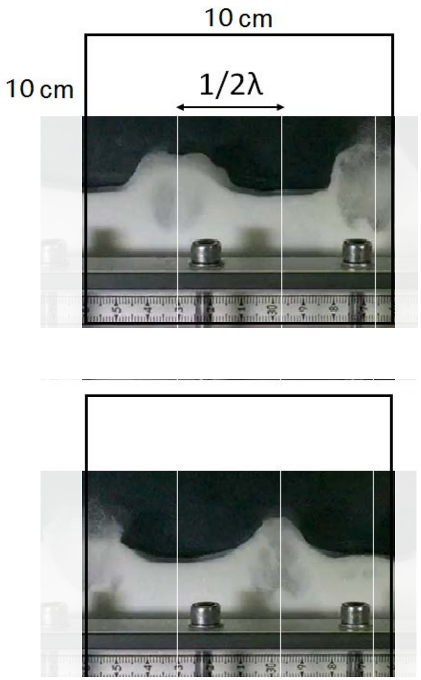
$U_{gas} = U_{min} + A(1 + \sin\phi)$



b2- Nucleation – TFM vs CFD/DEM

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\ t)$

Experimental

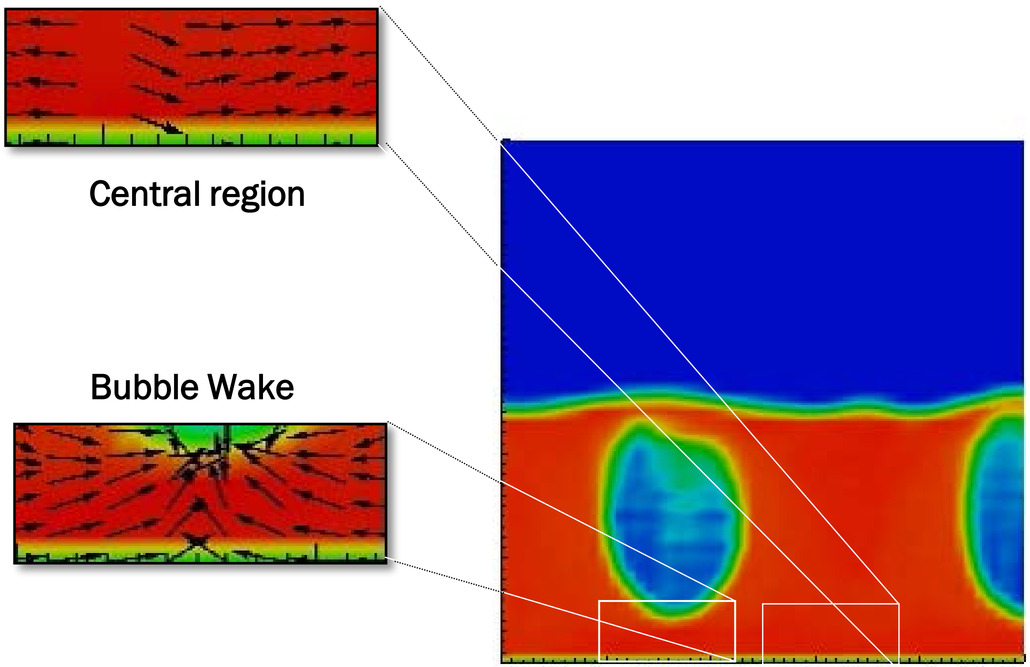


$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - CFD / DEM

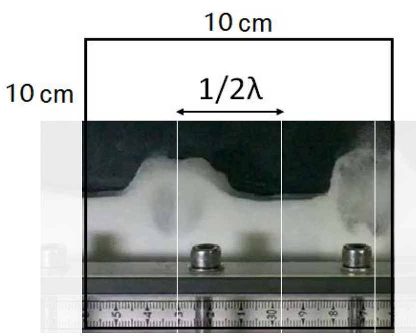
- Two areas of interest at the generation of the next bubble

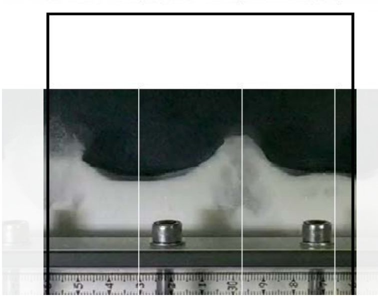


b2- Nucleation – TFM vs CFD/DEM

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\ t)$

Experimental



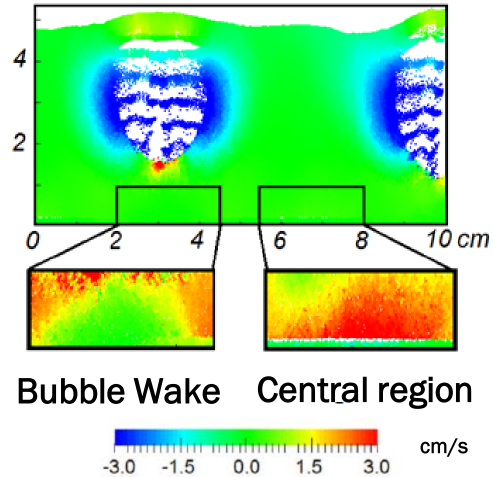


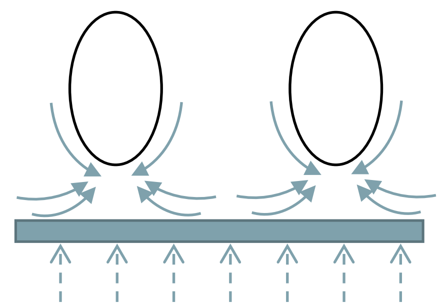
$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - CFD / DEM

Solid axial velocity, $V_{S,Z}$



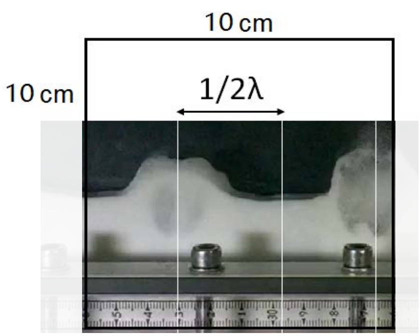


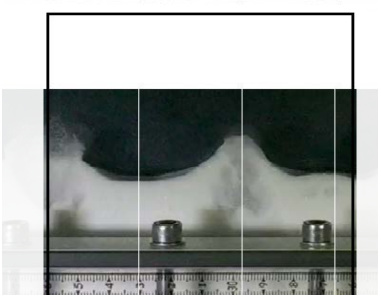
1. Accumulation in the wake immobilises the solids near the distributor,
2. A compressive stress counters the increasing drag force when the air flow rises in the next pulsation cycle.
3. The stress in the distributor dPs/dy caused by the wakes follow the oscillation of the gas flow cutting across 2 orders of magnitude

b2- Nucleation – TFM vs CFD/DEM

$$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$$

Experimental



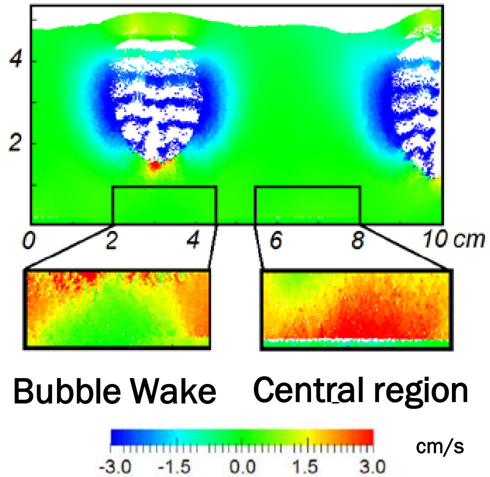


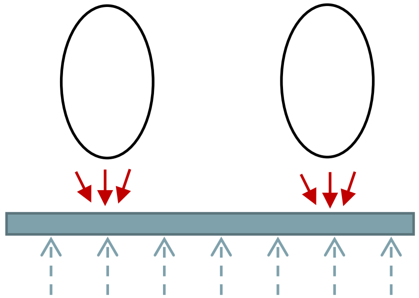
$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - CFD / DEM

Solid axial velocity, $V_{S,Z}$



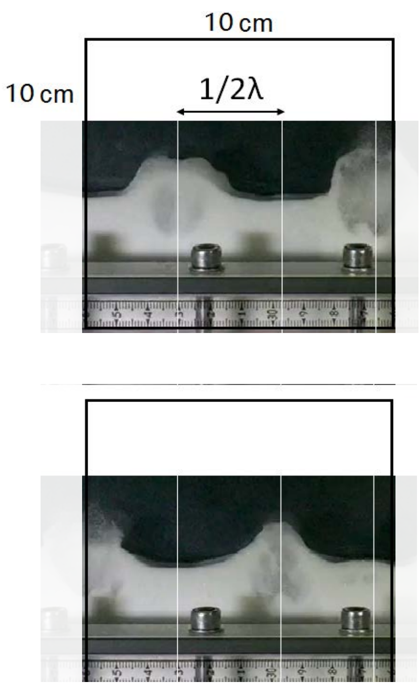


1. Accumulation in the wake immobilises the solids near the distributor,
2. A compressive stress counters the increasing drag force when the air flow rises in the next pulsation cycle.
3. The stress in the distributor dPs/dy caused by the wakes follow the oscillation of the gas flow cutting across 2 orders of magnitude

b2- Nucleation – TFM vs CFD/DEM

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\ t)$

Experimental

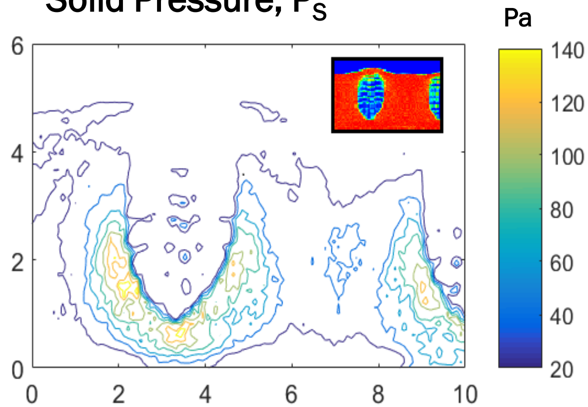


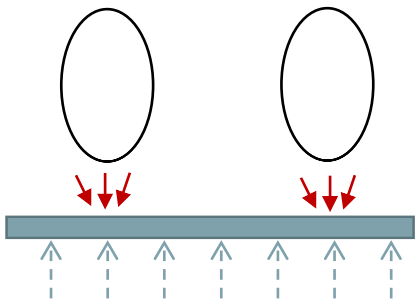
$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - CFD / DEM

Solid Pressure, P_S



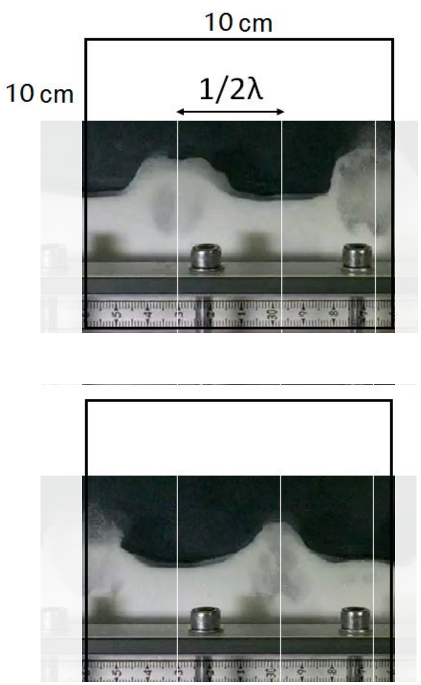


1. Accumulation in the wake immobilises the solids near the distributor,
2. A compressive stress counters the increasing drag force when the air flow rises in the next pulsation cycle.
3. The stress in the distributor dPs/dy caused by the wakes follow the oscillation of the gas flow cutting across 2 orders of magnitude

b2- Nucleation – TFM vs CFD/DEM

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$

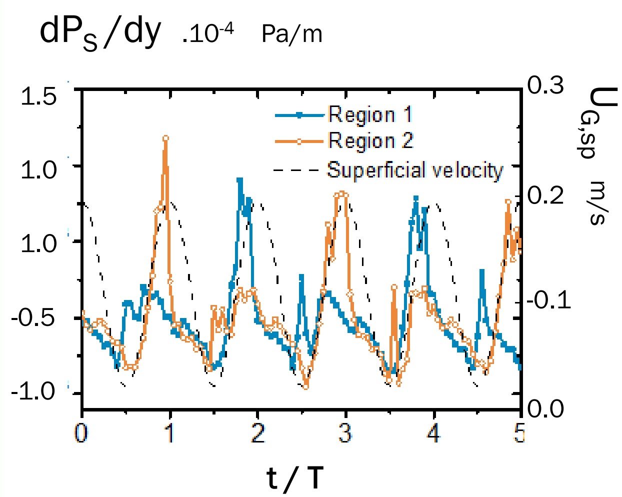
Experimental

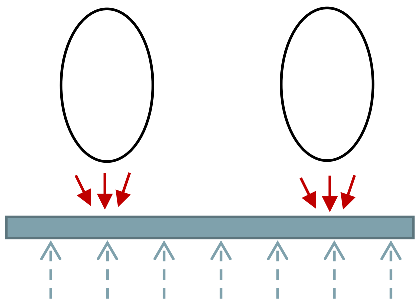


$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - CFD / DEM



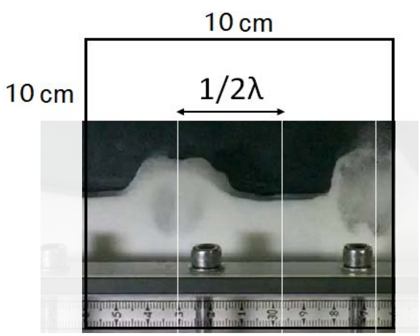


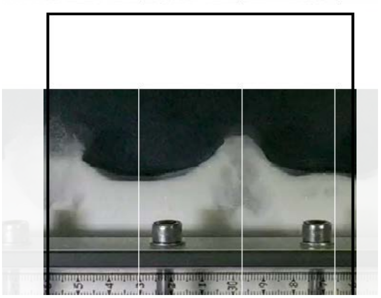
1. Accumulation in the wake immobilises the solids near the distributor,
2. A compressive stress counters the increasing drag force when the air flow rises in the next pulsation cycle.
3. The stress in the distributor dPs/dy caused by the wakes follow the oscillation of the gas flow cutting across 2 orders of magnitude

b2- CFD/DEM - 2D Beds

$$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$$

Experimental



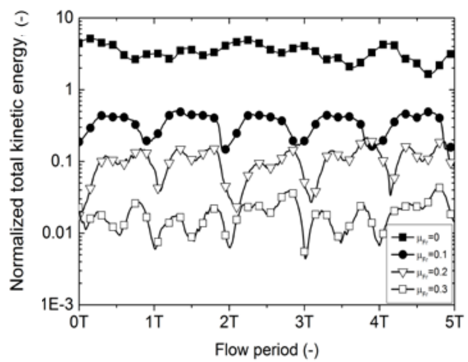


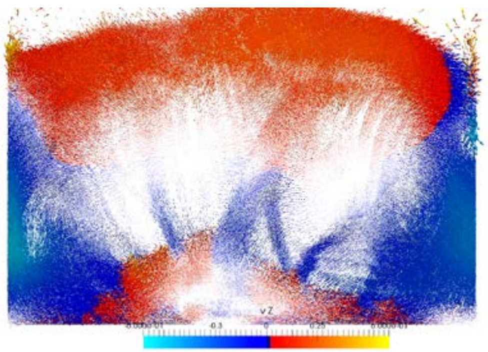
$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - **CFD / DEM**

1. As friction increases, energy dissipated rises…
2. Only after a given point the compressive stress is enough to prevent lateral flow in the wake all the way to the distributor
3. Particle-particle friction is key to the bubble-bubble wavelength



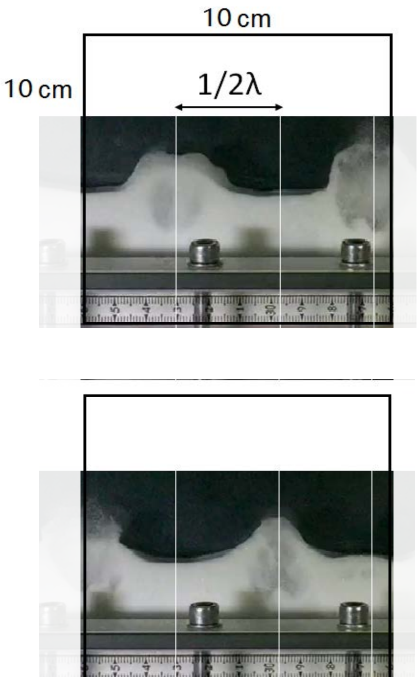


$\mu_{p\text{-}p} = 0$

b2- CFD/DEM - 2D Beds

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$

Experimental

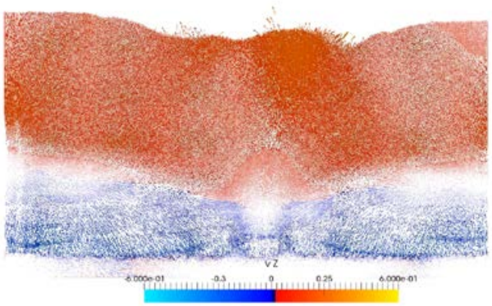


$D_b = 2.5 \pm 0.2$ cm

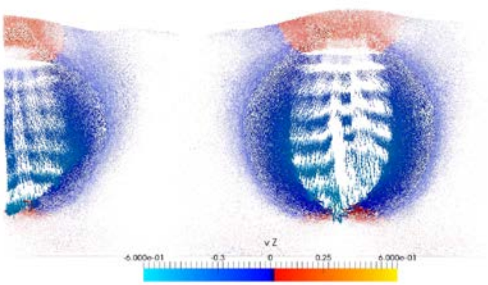
$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - CFD / DEM

1. As friction increases, energy dissipated rises...
2. Only after a given point the compressive stress is enough to prevent lateral flow in the wake all the way to the distributor
3. Particle-particle friction is key to the bubble-bubble wavelength



$\mu_{p\text{-}p} = 0.10$

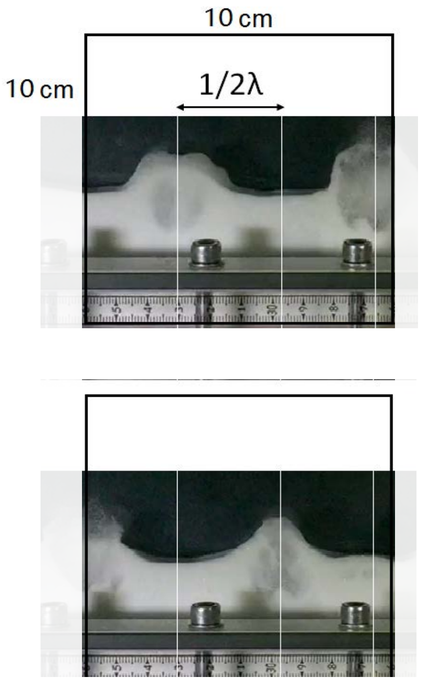


$\mu_{p\text{-}p} = 0.20$

b2- CFD/DEM - 2D Beds

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\ t)$

Experimental

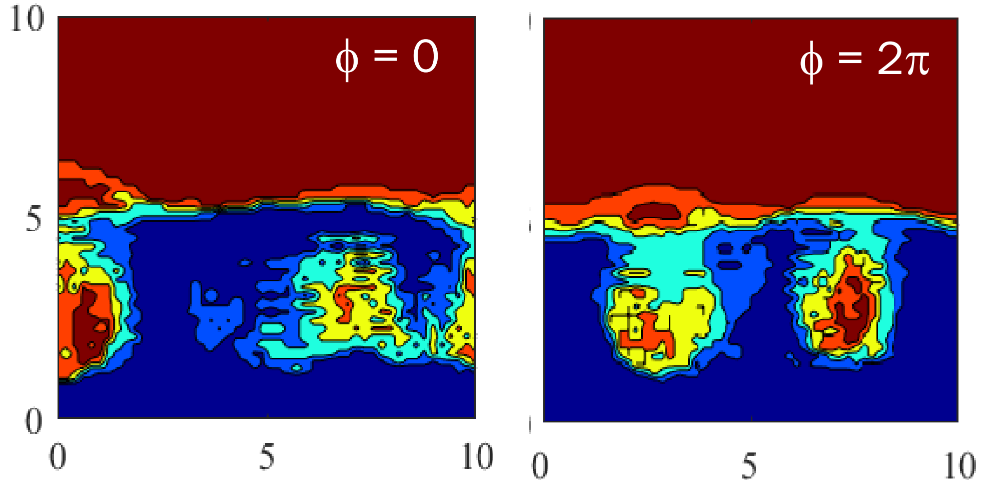


$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

3. Circulation between both bubbles becomes correlated…
4. Nucleation becomes more stable and a pattern emerges

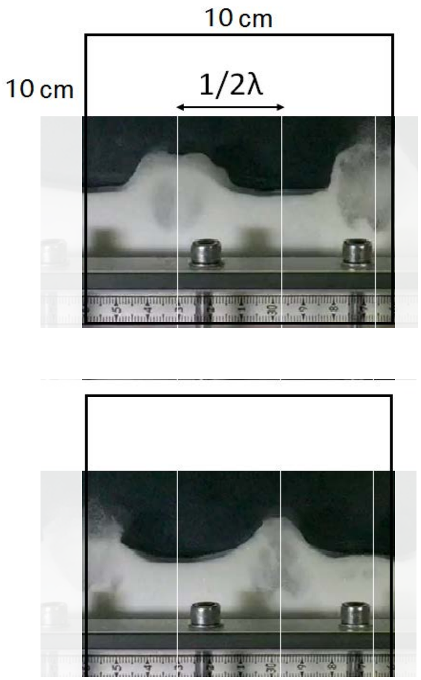
Bubble probability density contour



$\mu_{p\text{-}p} = 0.10$

b2- CFD/DEM - 2D Beds

Experimental



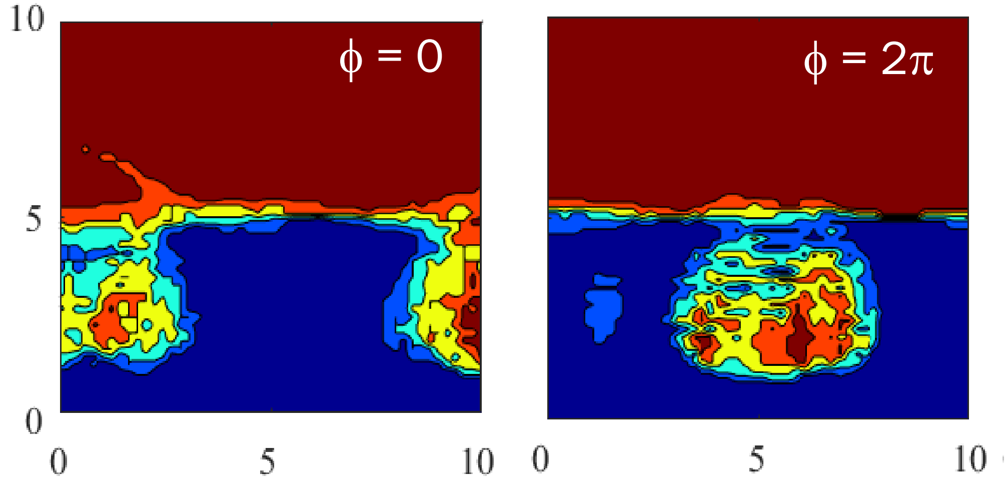
D_b = 2.5 ± 0.2 cm

λ = 6.5 ± 0.6 cm

$$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$$

3. Circulation between both bubbles becomes correlated…
4. Nucleation becomes more stable and a pattern emerges

Bubble probability density contour

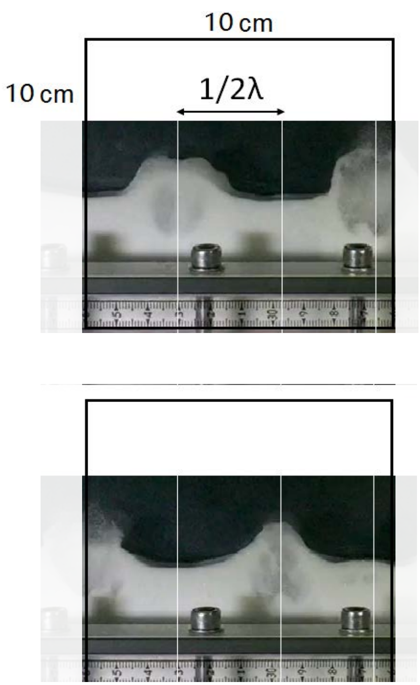


$\mu_{p\text{-}p}$ = 0.20

b2- CFD/DEM - 2D Beds

$$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$$

Experimental

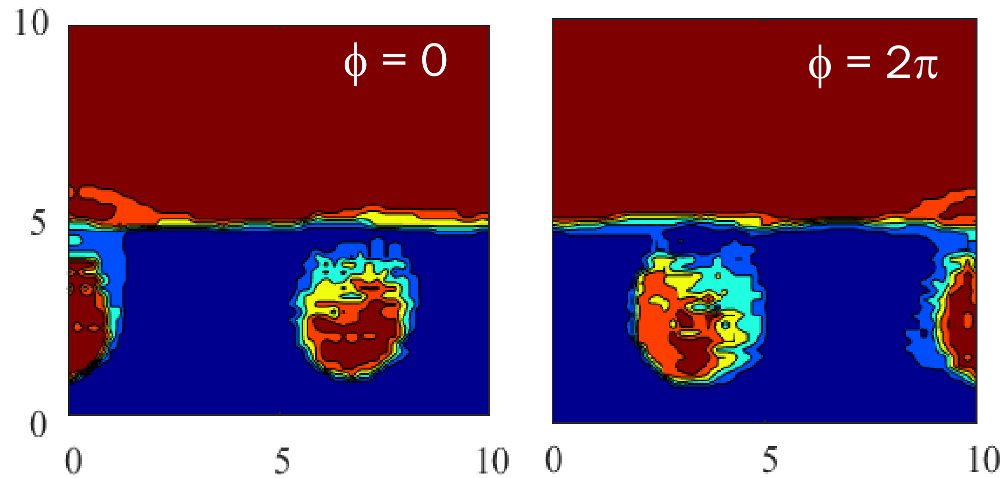


$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

3. Circulation between both bubbles becomes correlated…
4. Nucleation becomes more stable and a pattern emerges

Bubble probability density contour

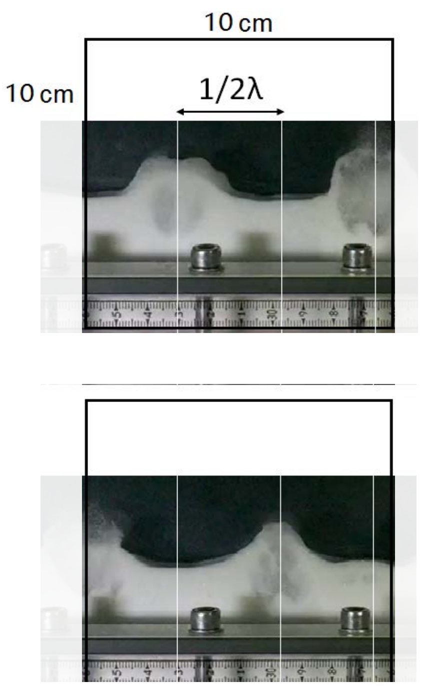


$\mu_{p\text{-}p} = 0.30$

b2- CFD/DEM - 2D Beds

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$

Experimental

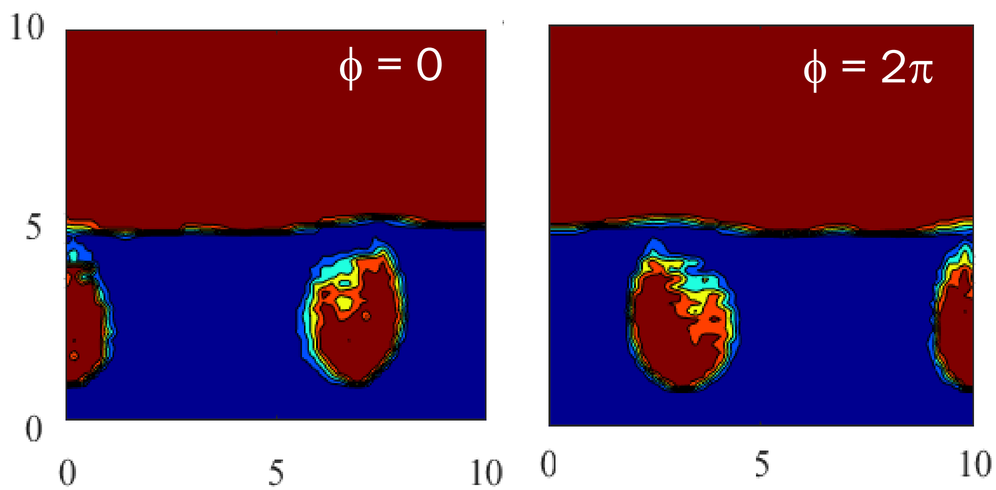


$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

3. Circulation between both bubbles becomes correlated...
4. Nucleation becomes more stable and a pattern emerges

Bubble probability density contour

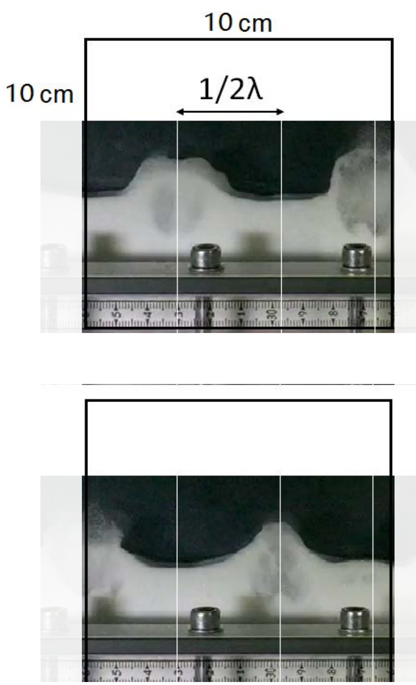


$\mu_{p\text{-}p} = 0.35$

b2- CFD/DEM - 2D Beds

$$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$$

Experimental

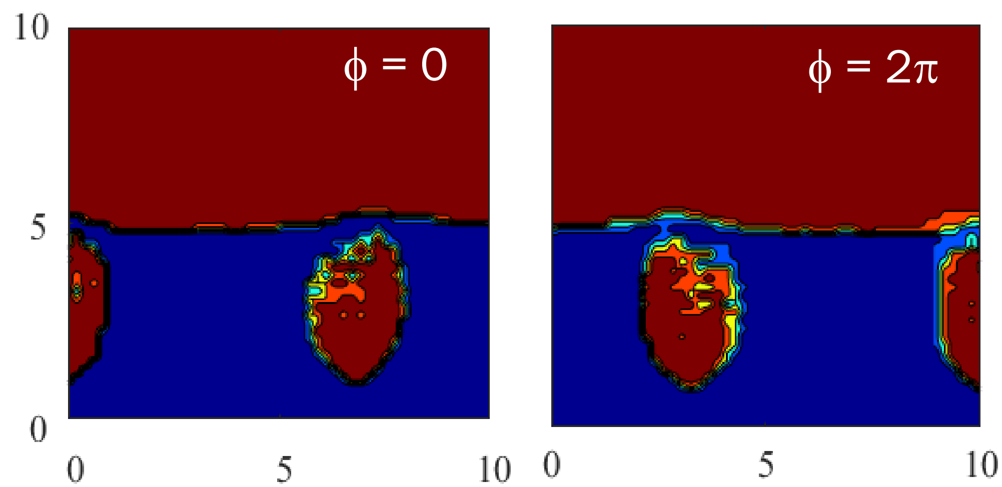


$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

3. Circulation between both bubbles becomes correlated…
4. Nucleation becomes more stable and a pattern emerges

Bubble probability density contour



$\mu_{p\text{-}p} = 0.40$

Take away

- ❖ Dynamic rearrangement of bubbles occurs experimentally leading to a predictable bubble structure. Wavelength is strongly correlated with the bubble size suggesting a local force balance is behind the arrangement mechanism.

- ❖ TFM - classical implementations correctly predict average properties but fail to capture the bubble dynamics under pulsed conditions.

- ❖ CFD/DEM - reproduces the observed bubble dynamics The analysis suggests that a compressive force in the bubble wake originates the triangular tessellation

- ❖ The compressive force results from shearing the granular bed in areas of a high solid fraction, and thus is highly sensitive to particle-particle frictional contacts, which are seen to play a key role in the stabilization of the tessellation.

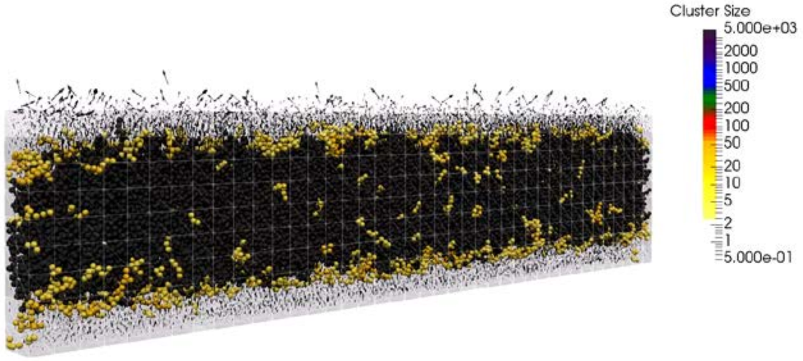
Now - Clustering – Capability development

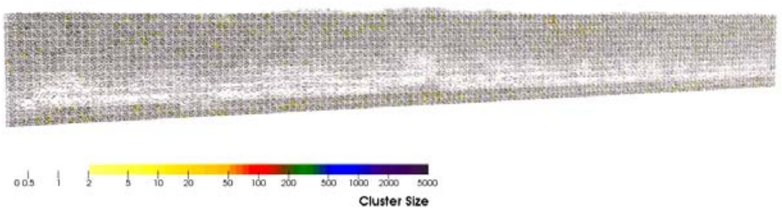
Migrating to MFIX

MFIX – clustering dynamics

- Identify locked regions.
- Quantify compressive and rotational forces in the plastic regime.
- Find key pivot points in the wake of a rising bubble than 1- ensure nucleation and 2- prevent lateral transport.
- Relate to size and inlet properties

1. Recognition of particle clusters.
2. Implementation within parallelized framework.
3. Tracking clusters properties.
4. Map to the Eulerian grid.
5. Energy housekeeping.





Now - Kinetic Approach - Chialvo & Sundaresan

Migrating to MFIX

Modified Garzo & Dufty KTGF

- RDF to identify a dynamic jamming.
- e_{eff} to account for frictional losses.
- Rheological model based in an inertial number to bridge into the plastic regime.

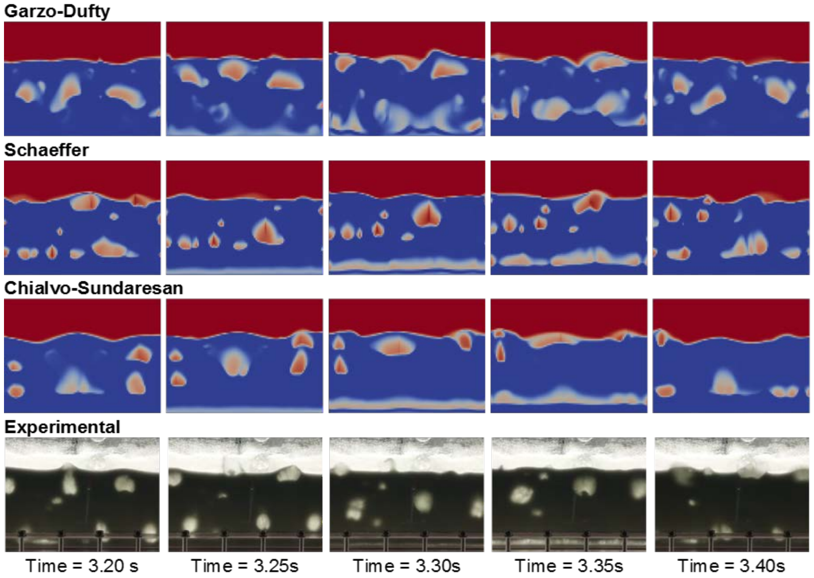
$$\tau = \eta_s \chi_s P_s + \tau_{GD}\ \delta\tau$$

$$\chi_s = 1 - \frac{1}{(I_0/I')^{1.5} + 1} \qquad I' = \gamma d \varepsilon_s \sqrt{p/\rho_s}$$

1. Extend from 2D to 3D
2. Bingham - Papanastasiou
3. Unstable nearby τ_s and ε_c with SIMPLE loop
4. Corrected boundary conditions TBD

Van Dijk M.

[1] Chialvo S, Sundaresan S. Physics of Fluids 25, 070603 (2013)
[2] Jop, P., Forterre, Y. & Pouliquen, O. A *Nature* **441**, 727-730 (2006)
[3] da Cruz, F., Emam, S., Prochnow, M., Roux, J.-N. & Chevoir, F. *Phy Rev E* **72** (2005)
[4] Mitsoulis, E. *Rheology Rev*, 135-178 (2007)



UCL

EPSRC
Engineering and Physical Sciences Research Council

CfNIE
Centre for Nature Inspired Engineering

PSRI
Particulate Solid Research, Inc.

TU Delft

TU/e
Technische Universiteit Eindhoven
University of Technology

Mr. Kaiqiao Wu

Mr. Mark Van Dijk

Dr .Victor Francia

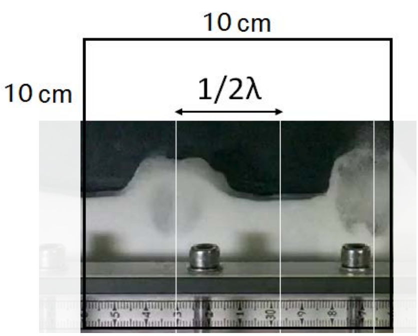
Dr. Lilian de Martin

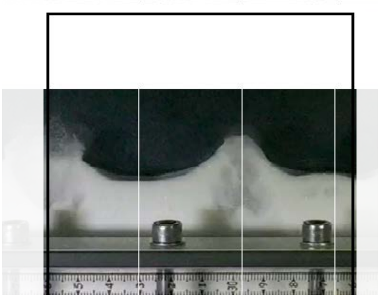
Prof. Marc-Olivier Coppens

b2- Nucleation – TFM vs CFD/DEM

$U_o/Umf = 2.64 + 2.14 \cdot \sin(2\pi f\, t)$

Experimental

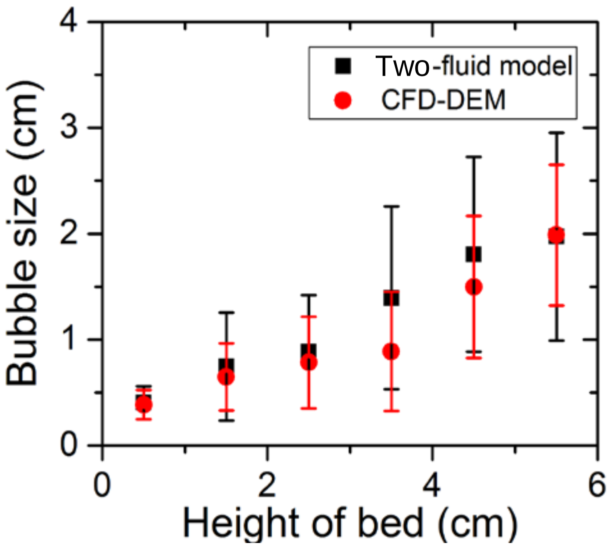




$D_b = 2.5 \pm 0.2$ cm

$\lambda = 6.5 \pm 0.6$ cm

Low 2D beds - TFM vs CFD / DEM



- In small beds, a kinetic formulation can indeed predict average bubble size throughout the nucleation process,

a) **Structured Fluidisation**

b) **Dynamic bubble flows**

b1- Experimental studies.

I. Pulsating flow.

II. Stability analysis.

b2- Numerical studies.

I. Kinetic frames.

II. CFD/DEM.

III. Now - Migration to MFIX.

c) **Future Steps**

a) Structured Fluidization - A Nature Inspired Approach

Predictive ability

Introducing new degrees of freedom at a design stage will enable reducing the instability of gas-solid coupled flow fields.

Acting interaction forces

Particle-particle:

Spatial e.g. electric fields.

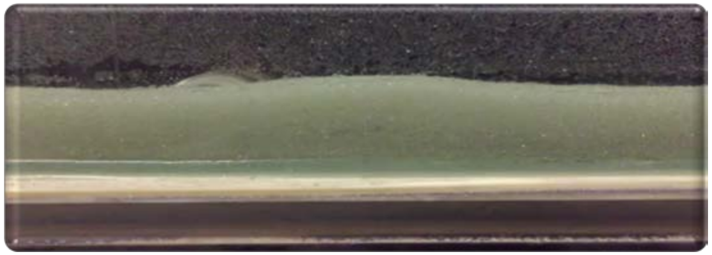
Fluid-particle:

Spatial e.g. fractal injectors

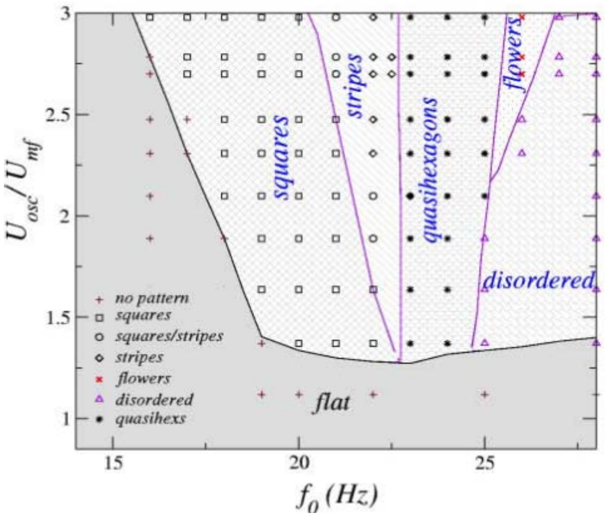
Tempo-spatial e.g. pulsation

3D shallow experimental patterns

2cm height shallow quasi-2D bed



- Pattern also forms in a shallow bed (pulse frequency of 10 Hz ~2cm)



Phase diagram

Irregularity

f ~ 10Hz

Squares pattern

f ~ 12Hz

Concentric pattern

f ~ 15Hz

Stripes pattern

f ~ 19Hz

Spiral pattern

Driving frequency

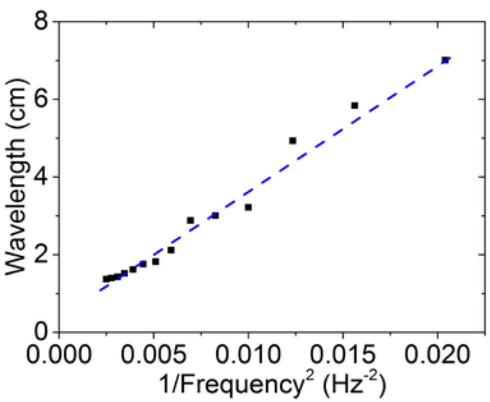
- 3mm high 238um Ballotini in a 14cm diameter bed

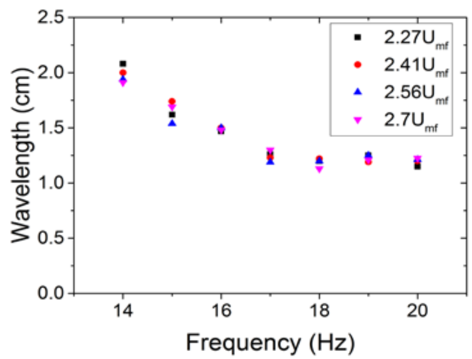
Phy.Rev.Let 90.13 (2003).

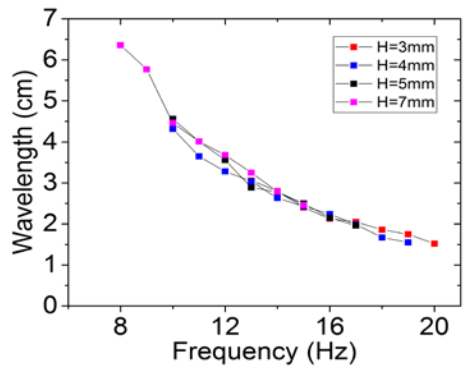
Characteristic wavelength and onset of pattern

Parameter	wavelength	Onset of pattern
Bed height	No	Yes
Amplitude	No	Yes
Particle diameter	Yes	Yes
Pulsating frequency	Yes, dominating	Yes
Pulsating offset	Yes, but very slightly	Yes

e.g.,







Faraday waves

- The onset of pattern is similar to the surface waves in liquid systems