Drying of cohesive particles in vibrated fluidized beds

Modeling hydrodynamics under mechanical vibration

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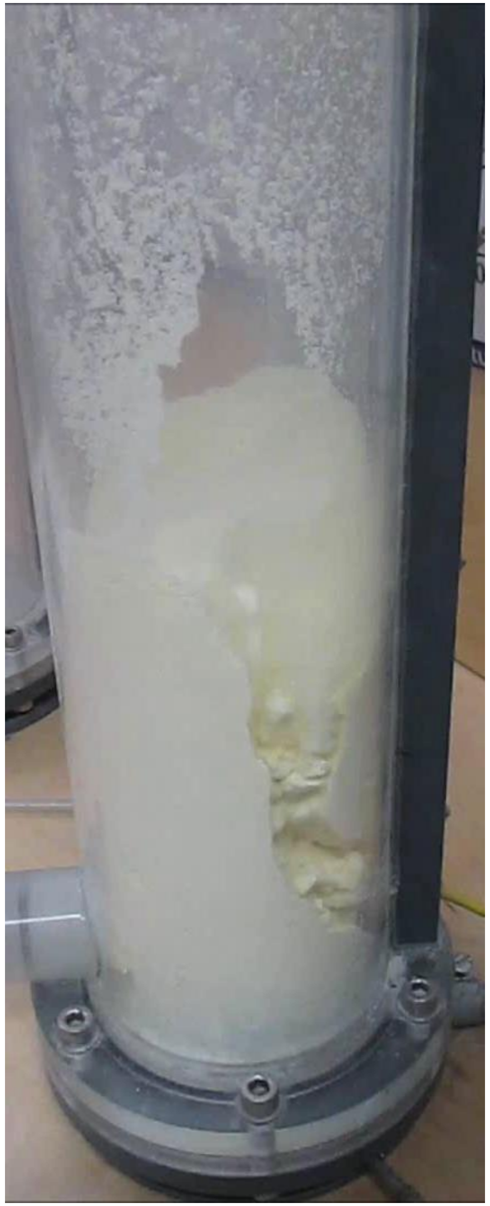
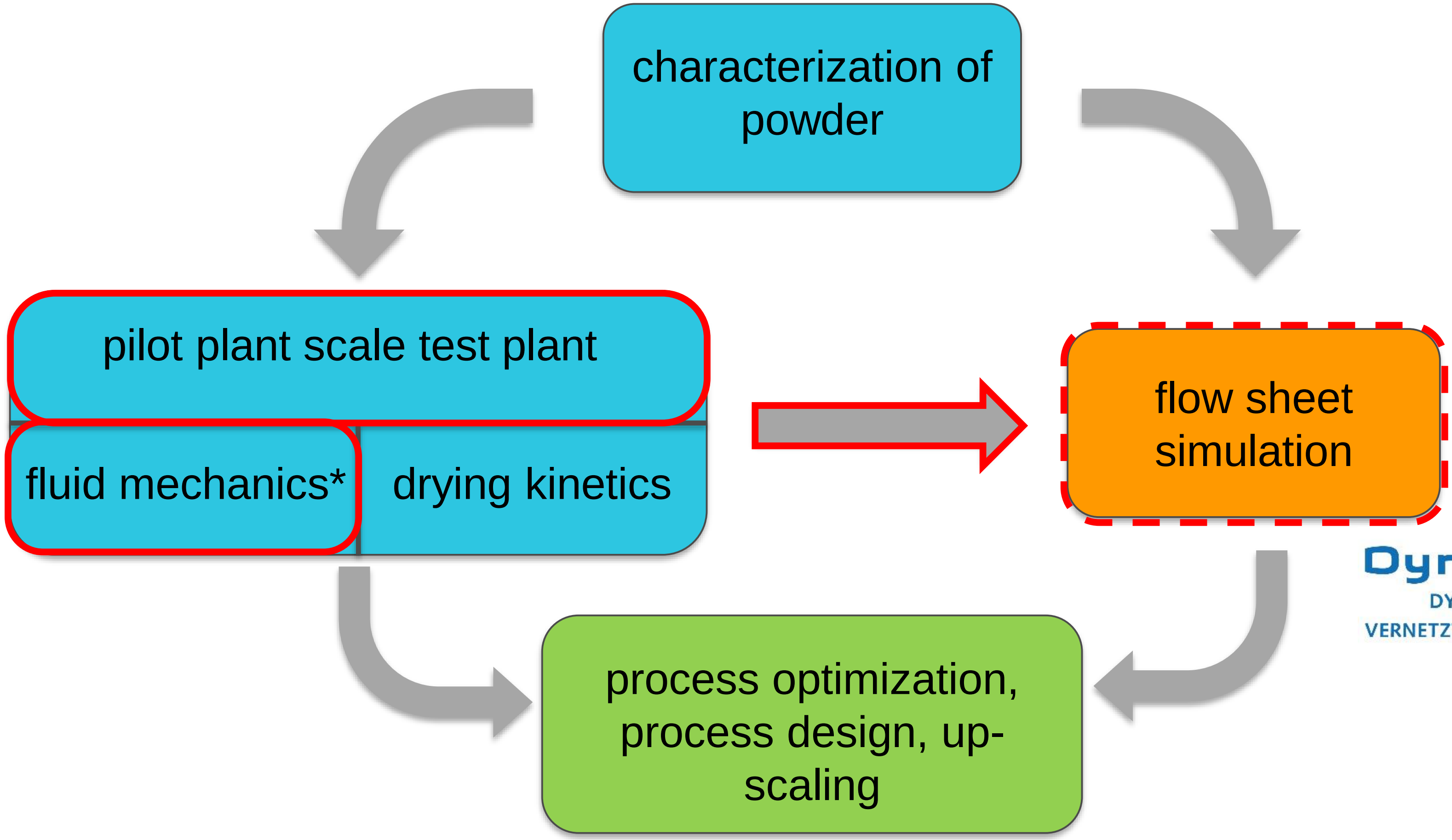


Cohesive powders gain importance:

nano-particles, pharmaceutical and food powders

Vibration enhances fluidization of cohesive powders:

- vibrated fluidized bed (VFB) research only in lab-scale
- scarce research on VFB drying of milk powder



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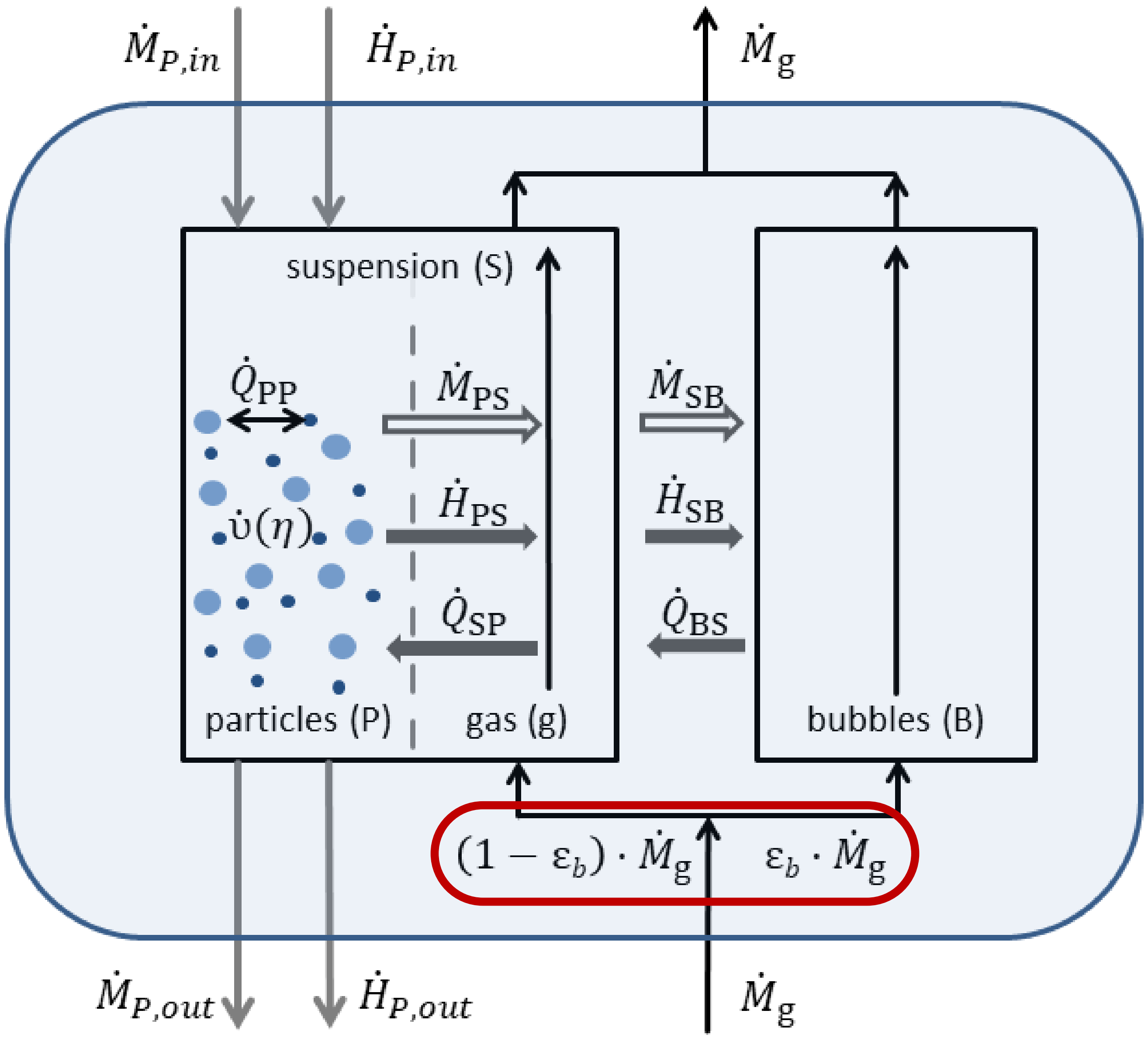
* Lehmann et al., Fluidization characteristics of cohesive powders in vibrated fluidized bed drying at low vibration frequencies, Powder Technology, accepted

Basis: Alaathar [1,2]

- steady state model of continuous fluidized bed dryers
- for Geldart B particles
- distributed parameters: T, d_p, x, τ
- drying kinetics model [3 - 5]
- fluid mechanics model [6]
- key parameter: bubble volume fraction ε_b

Required adjustments:

- dynamic model
- cohesive powders
- influence of vibration



[1] Alaathar et al., Powder Technology 238, (2013)
[2] Alaathar, PhD Thesis, TUHH, (2017)
[3] Groenewold and Tsotsas, Drying Technology, 15 (1997)
[4] Burgschweiger et al., Can. Journ. of Chem. Engin., 77 (1999)
[5] Burgschweiger and Tsotsas, Chem. Engin. Science, 57 (2002)
[6] Werther and Wein, AIChE Symp., 90 (1994)

Material:

Whole milk powder		
ρ_s	[kg/m³]	866.4±73.5
d_{32}	[µm]	101.7±1.3

Investigated process parameters:

- gas flow rate
- vibration intensity Λ

$$\Lambda = \frac{a_{vibration}}{g} = \frac{(2\pi f)^2 \cdot A_{vib}}{g}$$

Whole milk powder:
x = 4 wt.-%; m = 12.5 kg; u = 0.3 m/s; Λ = 0.58

Analysis of fluid mechanics via:

- Δp measurement
- visual observation (high speed camera)

Characteristics:

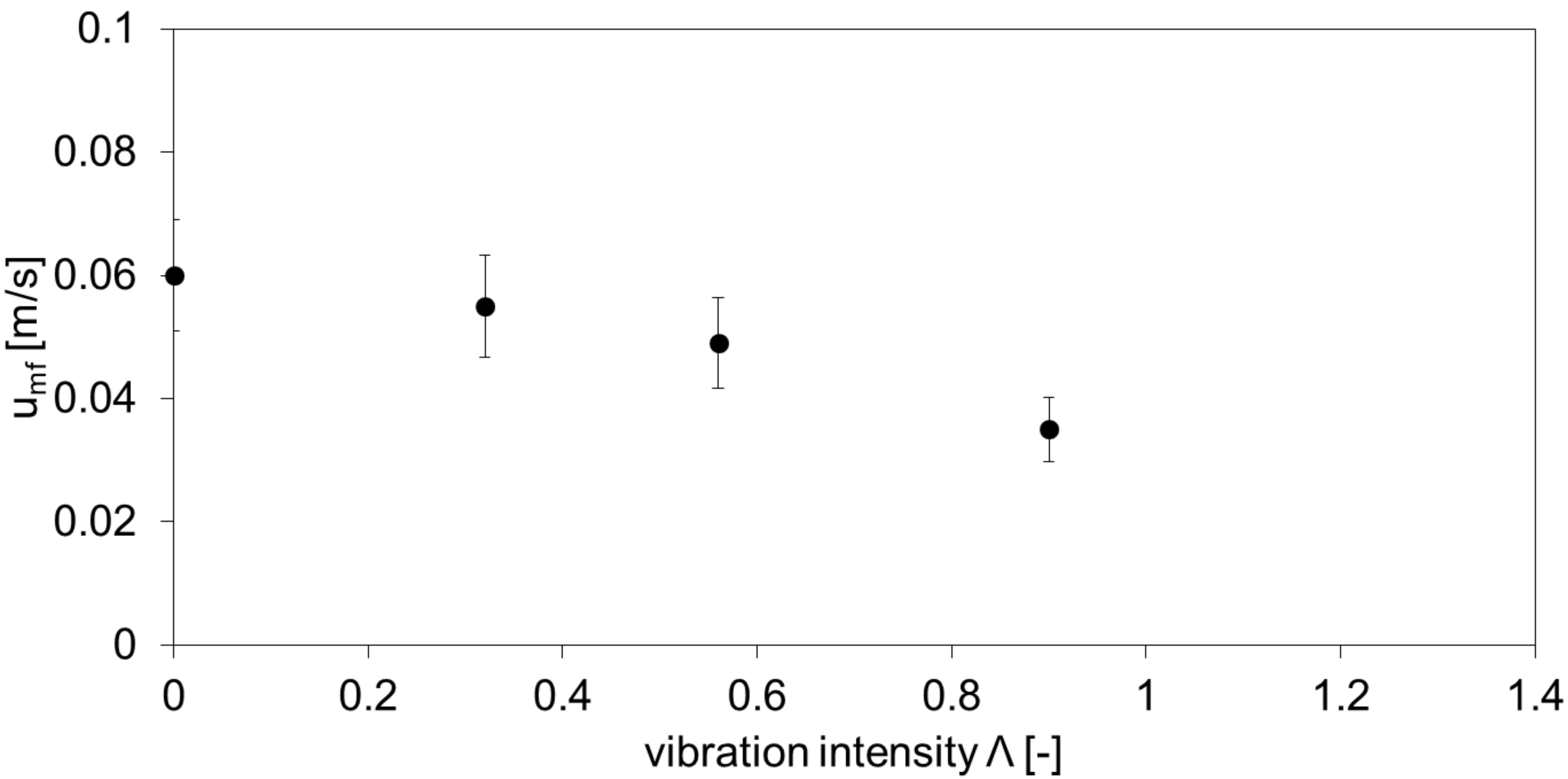
- bed expansion
- gas hold-up / bubble volume fraction
- lower limit of fluidization (u_{mf})

frequency	f	[Hz]	0	4	6	8	10
amplitude	A_{vib}	[mm]	0	5	4	3.5	3
intensity	Λ	[-]	0	0.32	0.58	0.90	1.21

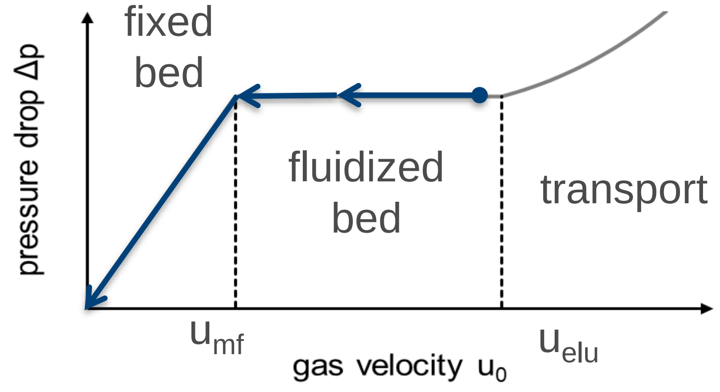
ρ_s: particle density; d_{32}: Sauter mean diameter; X: powder moisture content; f: frequency; A_{vib}: amplitude, g: gravitational acceleration; Λ: vibration intensity

Whole milk powder:
x = 4 wt.%
m = 25 kg

Minimum fluidization velocity u_{mf}:



Determination method:

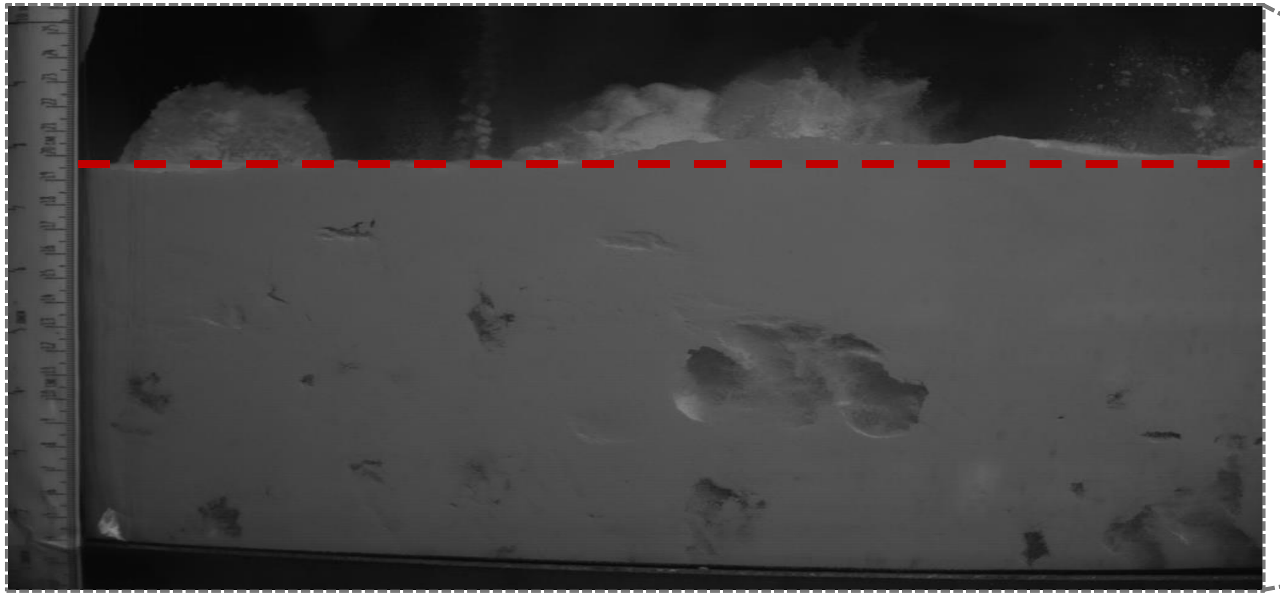


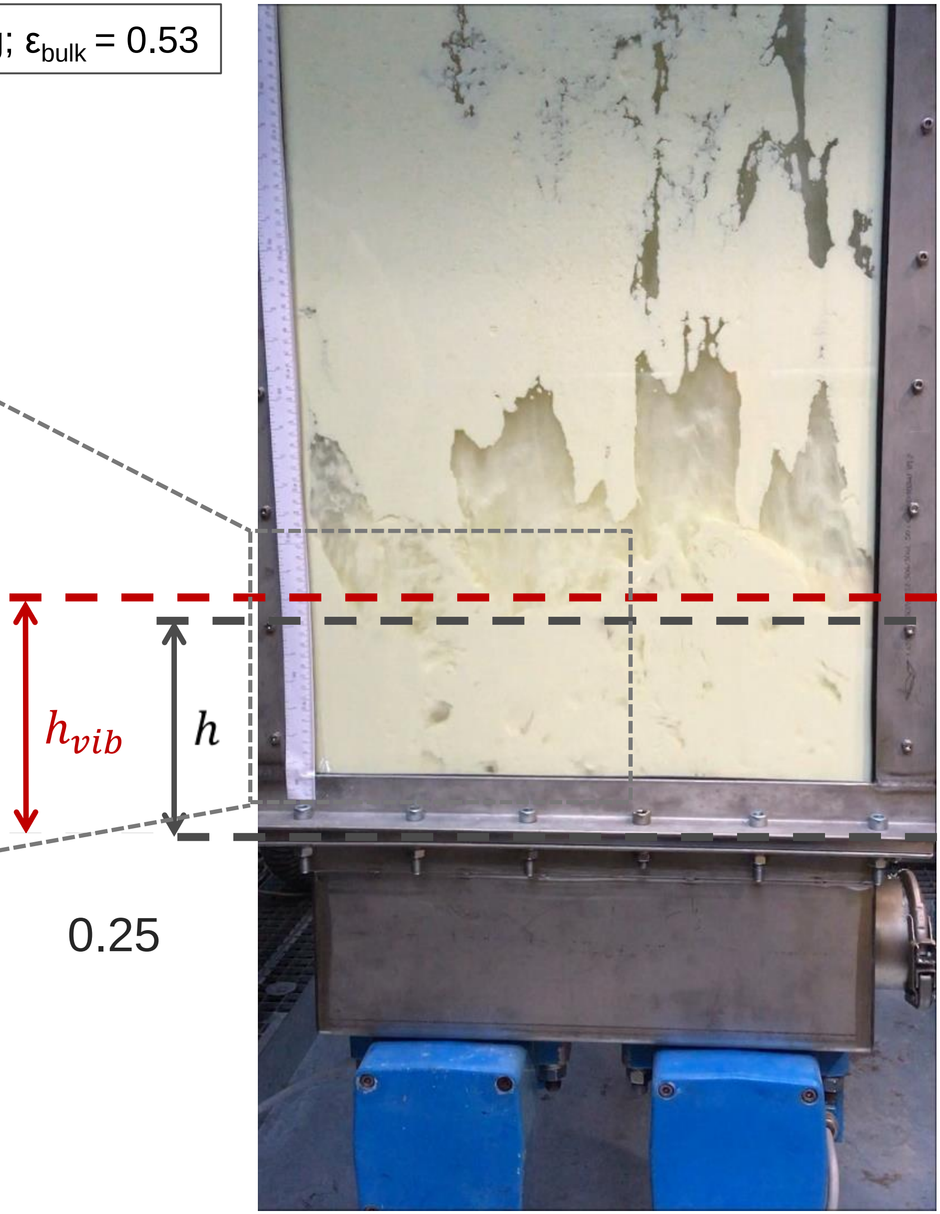
- vibration decreases u_{mf}

Whole milk powder: x = 4 wt.%, m = 12.5 kg; $\varepsilon_{bulk} = 0.53$

Bed expansion:

- read bed height h from high speed camera images



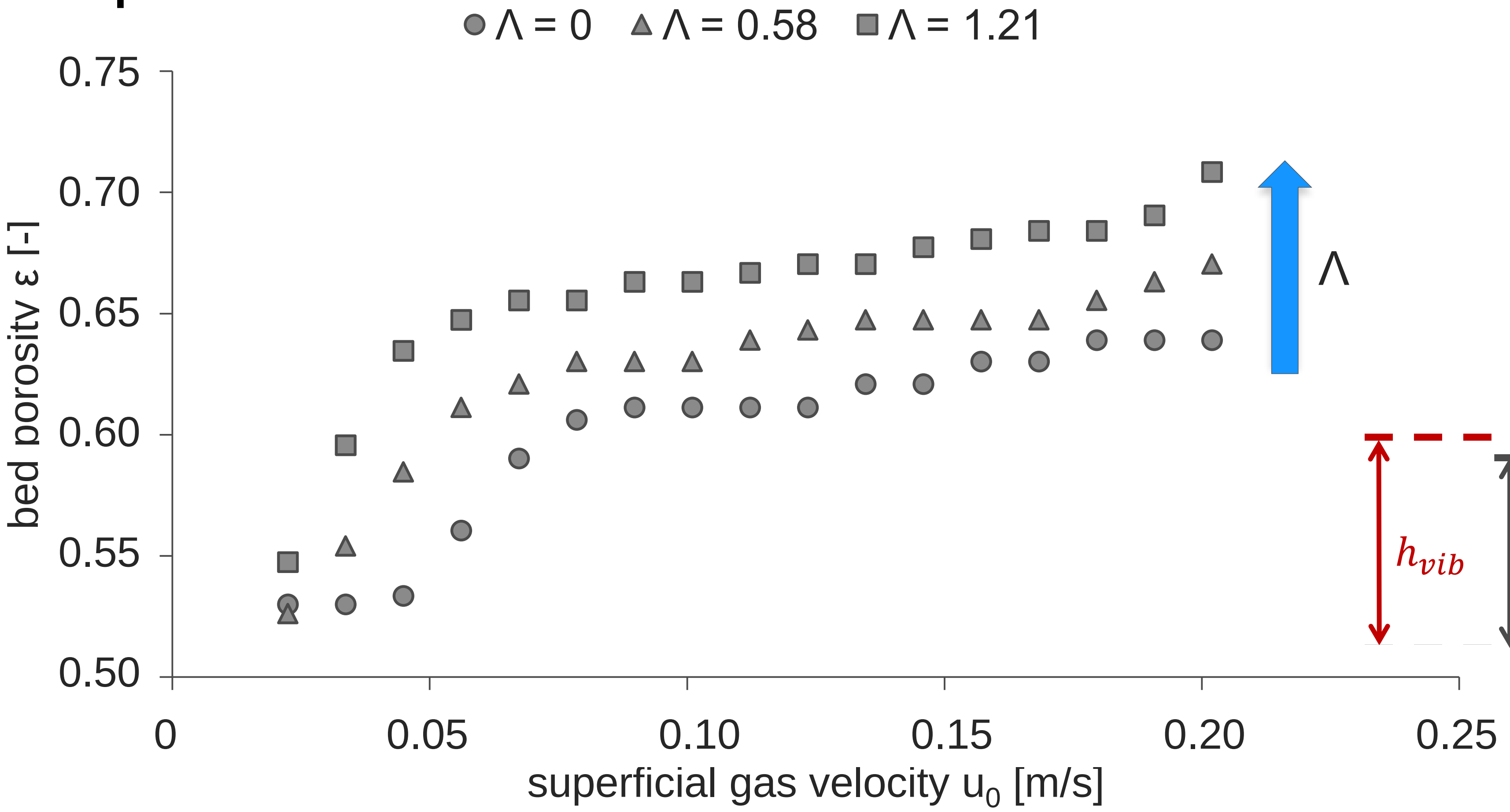


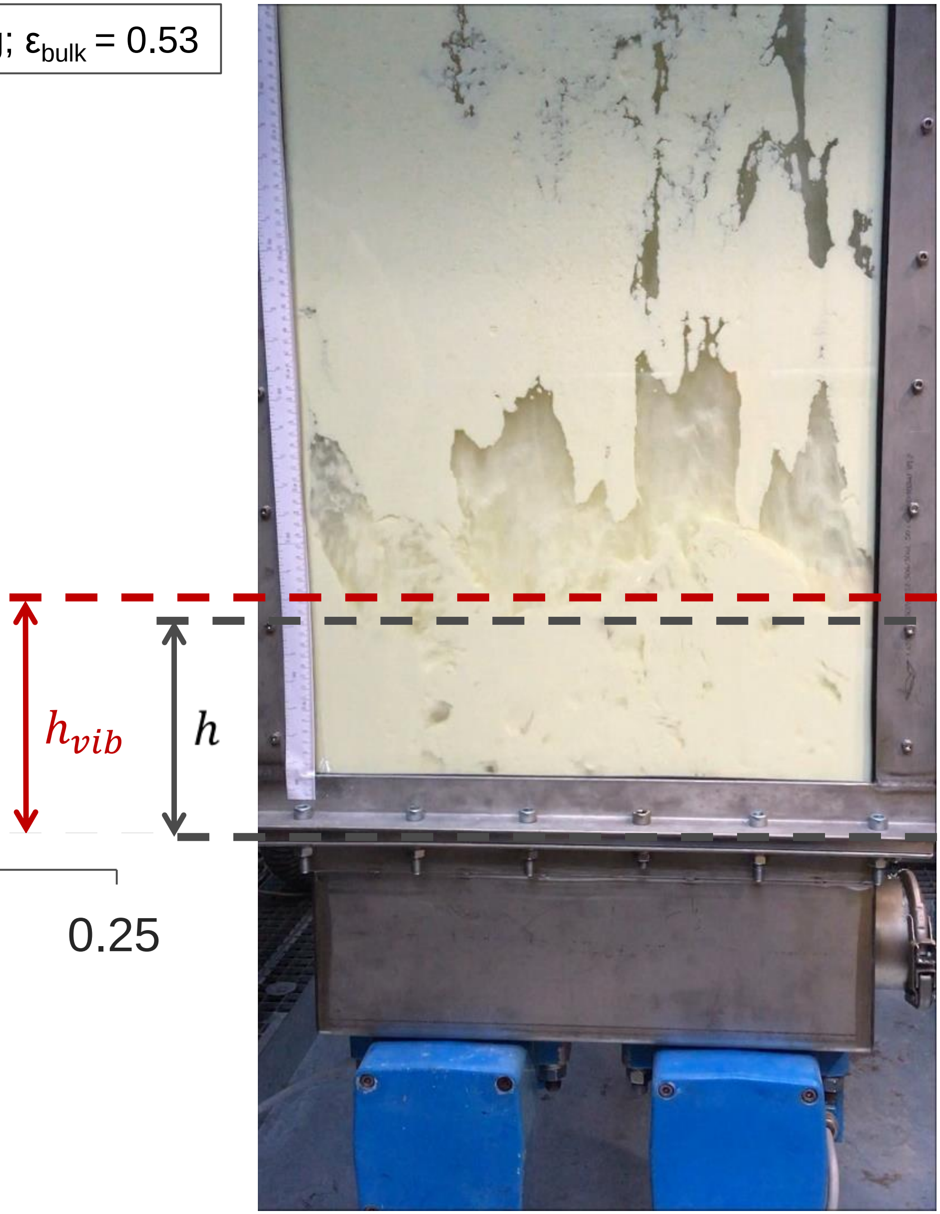
- ca 0 0.05 0.10 0.15 0.20 0.25

$$\varepsilon = 1 - \frac{m}{A \cdot h \cdot \rho_s}$$

Whole milk powder: x = 4 wt.%, m = 12.5 kg; ε_{bulk} = 0.53

Bed expansion:



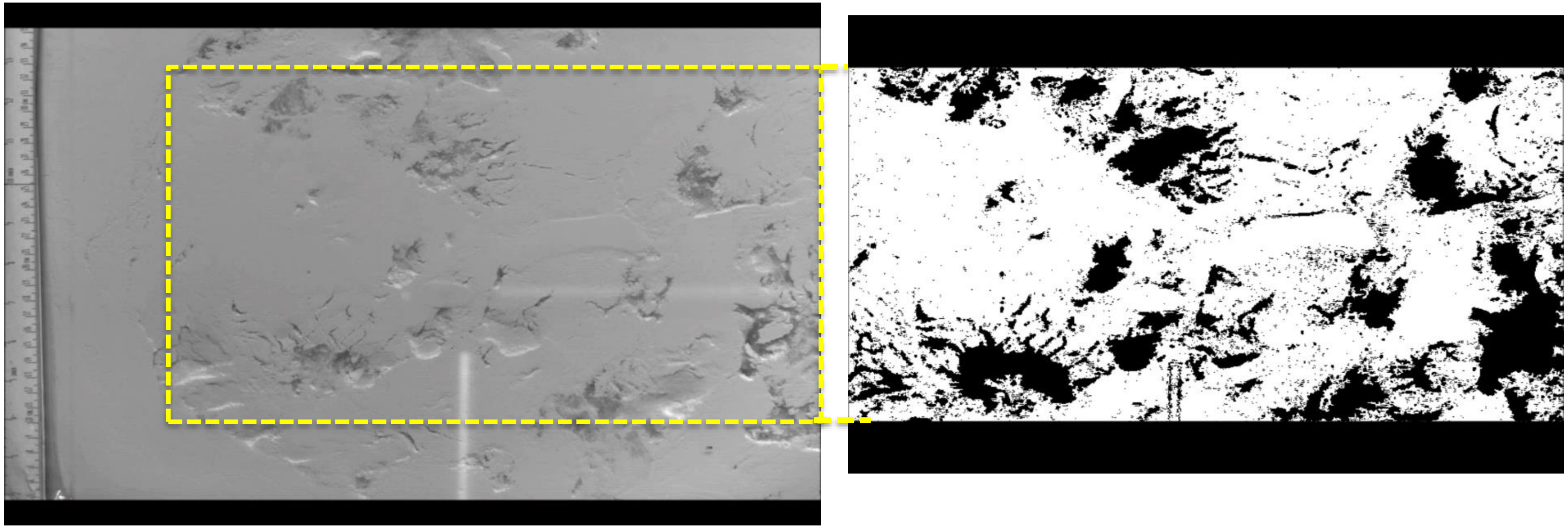


- high bed expansion indicates Geldart A behavior
- vibration increases bed expansion

Image analysis:

- high speed image series (100 fps)
- segmentation of grey scale image series (Matlab)
- calculate bubble volume fraction (Matlab)
- non-invasive
- global measurement
- only at the glass wall (2D plane)

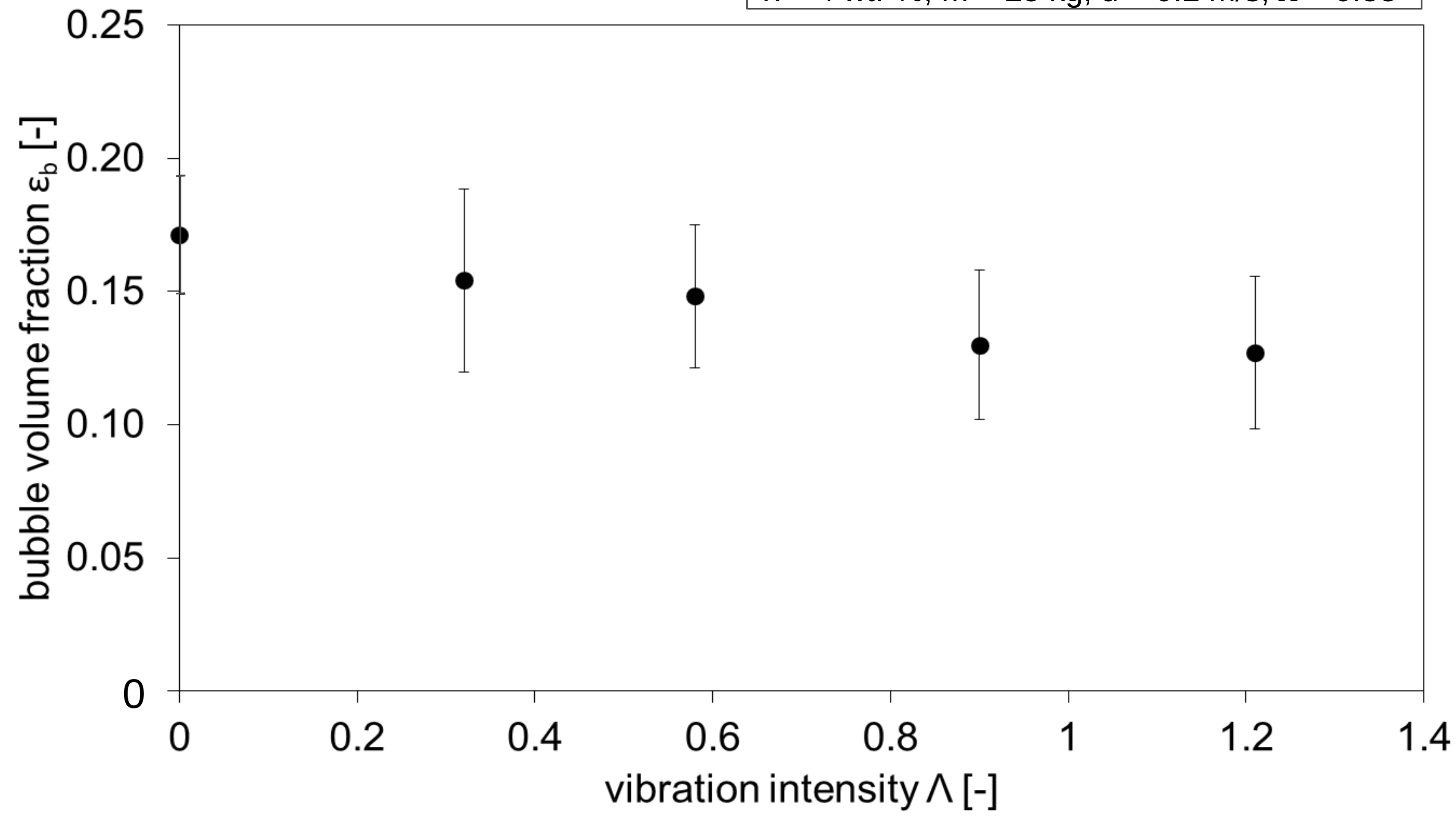
Valid representation of hydrodynamics inside the bed for low excess gas velocities ($u\text{-}u_{mf}$ < 0.25) [7]

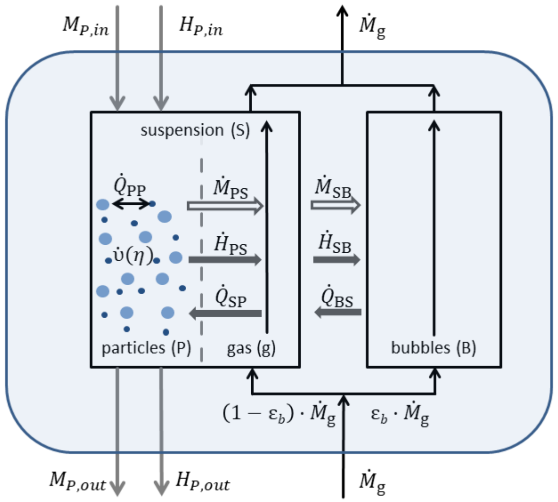


[7] Lehmann et al., Fluidization characteristics of cohesive powders in vibrated fluidized bed drying at low vibration frequencies, Powder Technology, accepted

Bubble volume fraction ε_b:

Whole milk powder:
x = 4 wt.-%; m = 25 kg; u = 0.2 m/s; Λ = 0.58





- slight decrease of bubble volume fraction
- increase of bed expansion

- ➢ vibration causes expansion of suspension phase
- ➢ explains increased heat and mass transfer rates

[8] Hilligardt and Werther, Ger. Chem. Eng. 9 (1986), 215-221
[9] Zou et al., Powder Technology 212 (2011), 258-266

Whole milk powder:
x = 4 wt.-%, m = 25 kg, u = 0.2 m/s

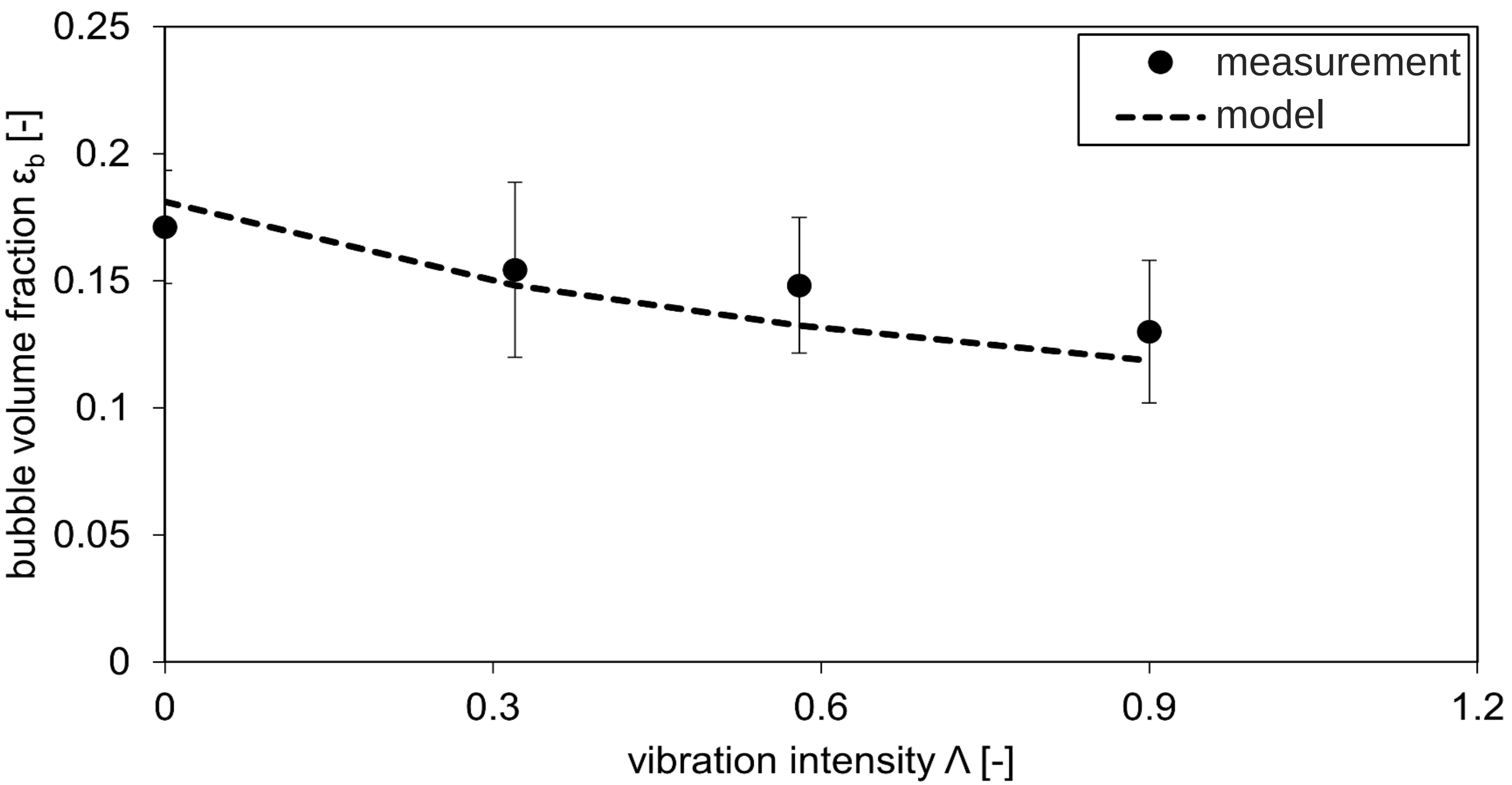
Bubble volume fraction:

- modified correlation from Hilligardt and Werther [8]

$$\varepsilon_b = \frac{\dot{V}_b}{u_b}$$

$$u_b = \dot{V}_b + 0.71 \cdot \vartheta \cdot \sqrt{g \cdot d_v}$$

$$\dot{V}_b = \Psi \cdot (u - \boldsymbol{u_{mf}}) \cdot \frac{\mathbf{1}}{(\mathbf{1} + \boldsymbol{\Lambda})}$$



Bubble diameter:

- correlation from Zou et al. [9]
- for cohesive particles

$$d_v = 0.21 \cdot \frac{(u - \boldsymbol{u_{mf}})^{0.49} \cdot \left(h + 4\sqrt{A_0}\right)^{0.48}}{g^{0.2}}$$

red: adjustments to established correlations

bold: vibration dependent parameter

d_v: bubble diameter; h: height over distributor; ε_b: local bubble volume fraction; u_b: bubble rise velocity; g: gravitational acceleration; ϑ: hydrodynamic constant; u: gas velocity; u_{mf}: minimum fluidization velocity; $\dot{V}_b$: apparent gas flow rate per bubble cross sectional area; Ψ: hydrodynamic parameter for bed dimensions; A_0: cross sectional area of distributor orifices ($A_0 \approx 0$ for porous plate)

Bed porosity:

$$\varepsilon = 1 - (1 - \varepsilon_b)(1 - \varepsilon_d)$$

Porosity of dense phase:

- modified Richardson and Zaki correlation [10]

$$\varepsilon_d = \boldsymbol{\varepsilon_{mf}} \cdot \left(\frac{u_d}{\boldsymbol{u_{mf}}}\right)^{\frac{1}{4.65\cdot\boldsymbol{(1+\Lambda)}}}$$

Gas velocity in dense phase:

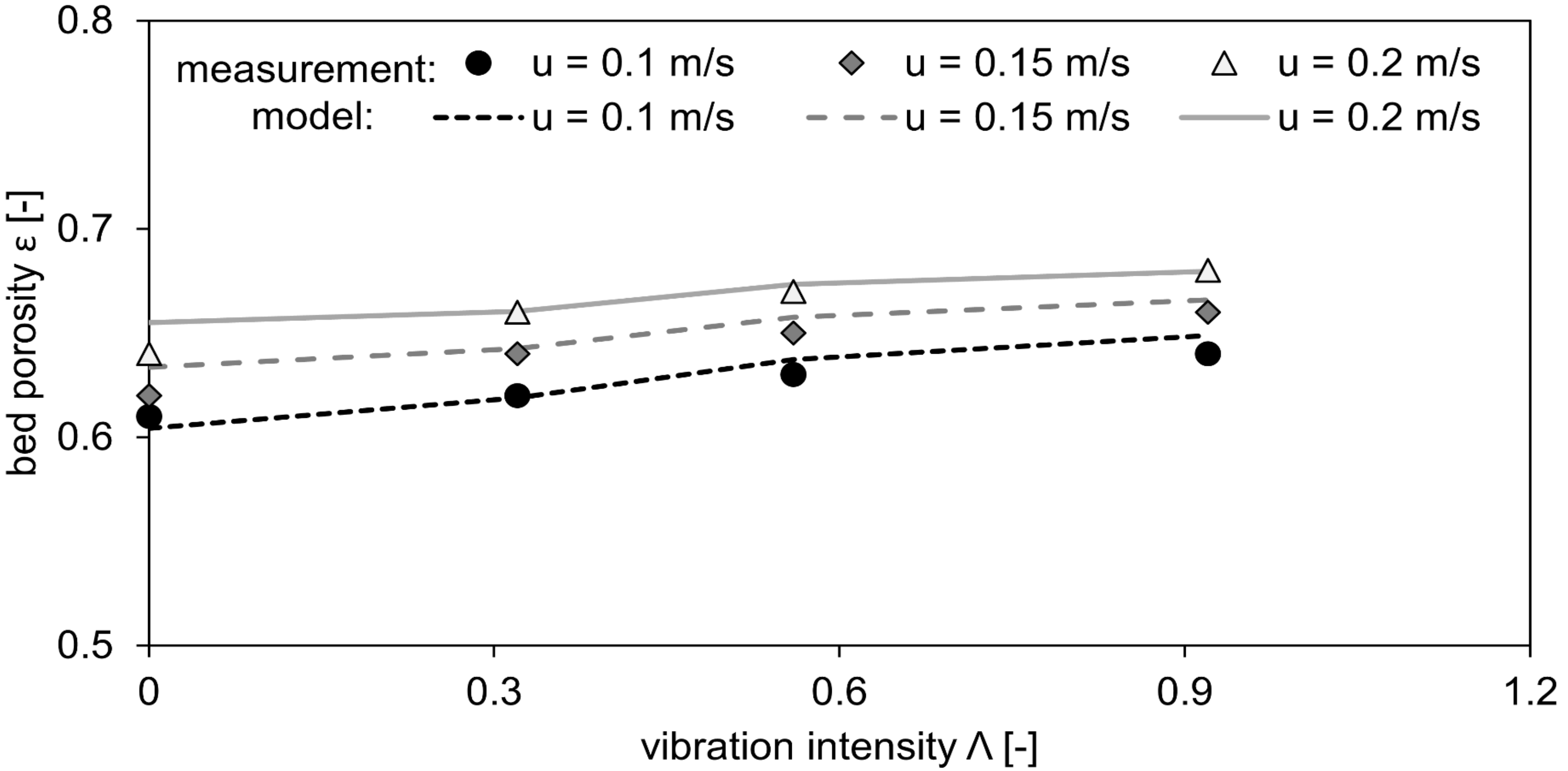
- according to Clift et al. [11]

$$u_d = \boldsymbol{u_{mf}} \cdot (1 + 1.5 \cdot \boldsymbol{\varepsilon_b})^{\frac{2}{3}}$$

[10] Richardson and Zaki, Chem. Eng. Sci., 3 (1954), 65-73
[11] Clift et al., Fluidization 4 - Proceedings, (1983), 77-85

ε: bed porosity; ε_d: porosity of dense phase; ε_b: local bubble volume fraction; ε_{mf}: bed porosity at minimum fluidization; u_d: gas velocity in dense phase; Λ: vibration intensity; u_{mf}: minimum fluidization velocity

Whole milk powder: x = 4 wt.-%, m = 25 kg

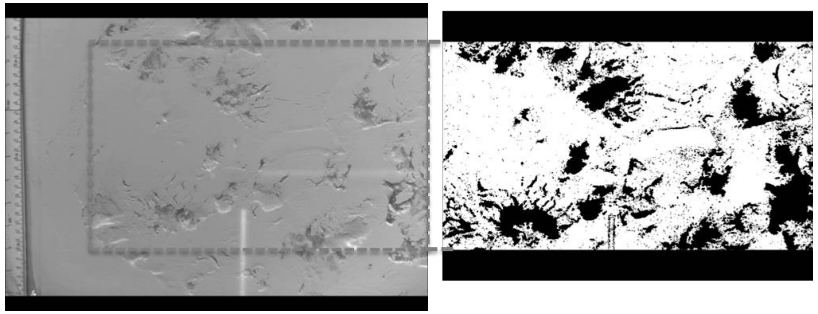


red: adjustments to established correlations

bold: vibration dependent parameter

Set of modified correlations:

➢ good prediction of ε_b and ε under vibration



Summary:

Pilot plant scale VFB dryer for comprehensive experiments:

Effect of vibration:

- reduces u_{mf}
- reduces bubble volume fraction
- increases bed expansion
- ➢ expansion of suspension phase

Modeling of hydrodynamics under vibration:

- set of modified correlations for prediction of
  - bubble volume fraction
  - bed porosity
- correlation are unchanged for non-vibrated cases

Outlook:

- testing model for other cohesive powders
- dynamic modeling of VFB dryers

Thank you
for your attention!

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