Refereed Proceedings

The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering

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PRESENTATION SLIDES: Measuring the Gas-Solids Distribution in Fluidized Beds - A Review

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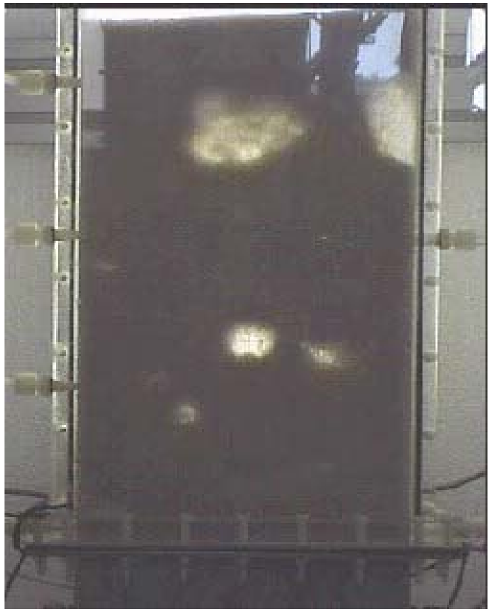
Measuring the Gas-Solids Distribution in Fluidized Beds – a Review



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The 12th International Conference on Fluidization, 13-18 May 2007

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Measurement techniques in fluid beds

Werther, Powder Technol. 102 (1999) 15

Industrial routine measurements

- Pressure
- Temperature

Occasional industrial measurements

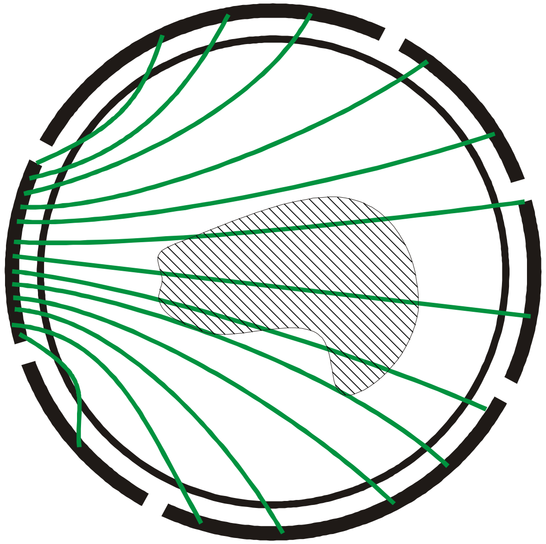
- Heat transfer probes
- Solids flow measurements
- Solids volume concentration (e.g. capacitance probes)
- Particle size measurements
- γ-ray transmission tomography

New developments / measurement techniques in academicia

This presentation

- Tomography
- Optical probes
- Capacitance probes
- Pressure measurements

Tomography



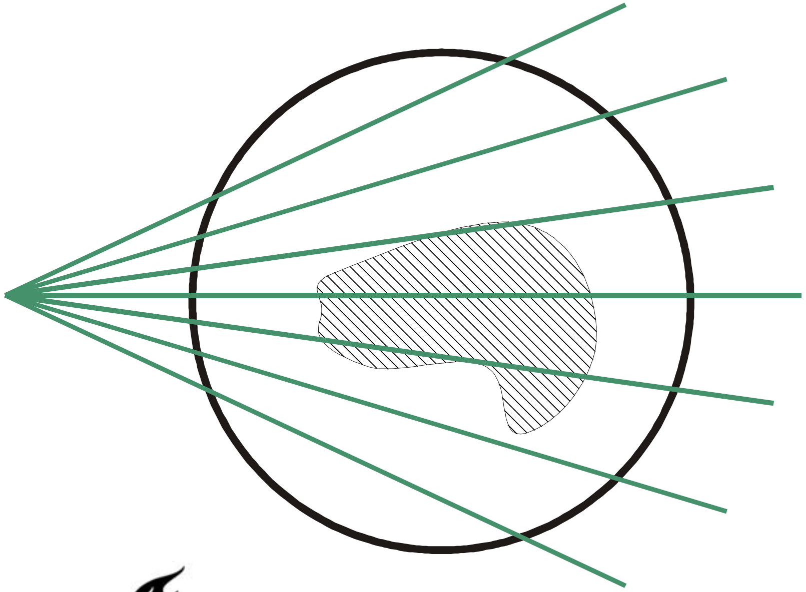
Soft field

Voidage distribution influences shape of field lines

→ non-linear field lines
→ non-local response

Fluidization research:

electric capacitance tomography



Hard field

Field lines only attenuated

→ linear field lines
→ local response

Fluidization research:

X-ray and γ-ray tomography

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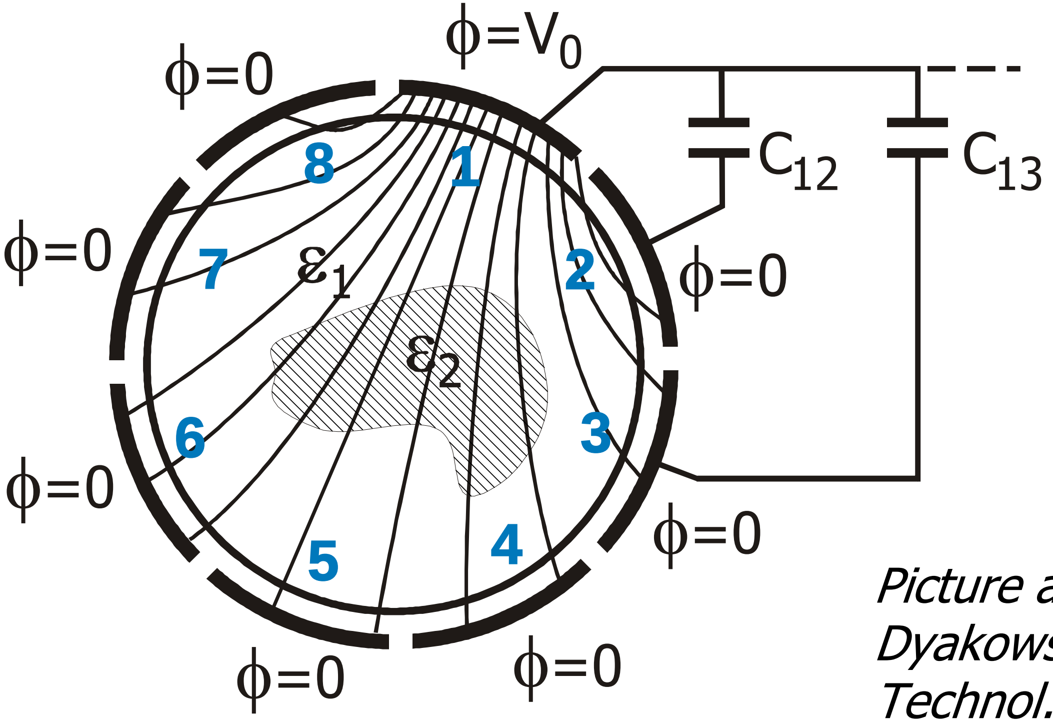
Electric Capacitance Tomography: principle

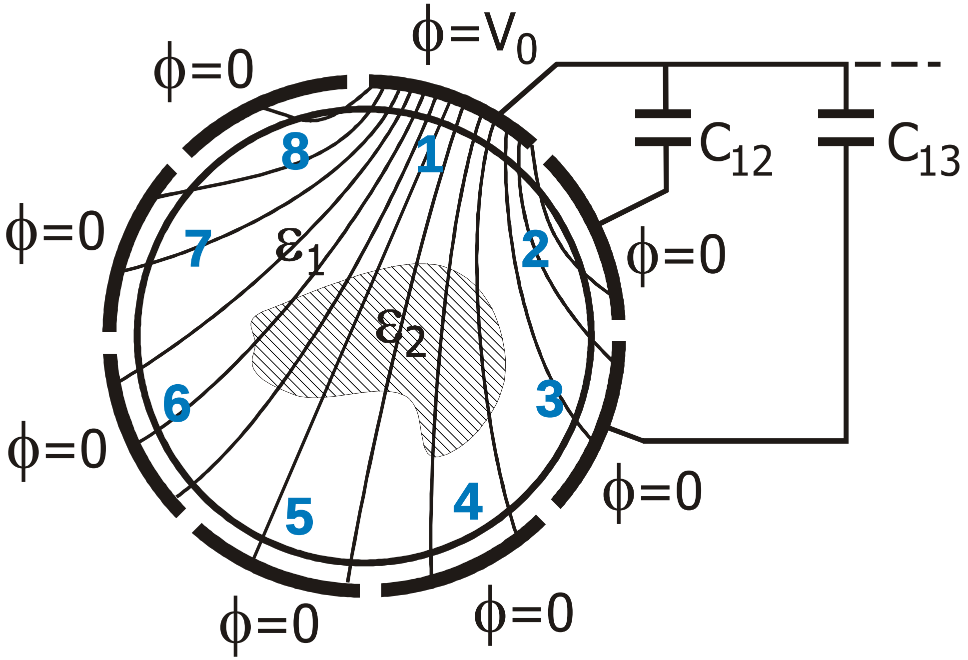


Picture adapted from Dyakowski et al., Powder Technol. 112 (2000) 174

N electrodes
$N(N-1)/2$ independent measurements C_{ij}

N=8 → 28 meas.
N=16 → 120 meas.

Electric Capacitance Tomography: reconstruction



Varying permittivity, no charge:

$$\nabla \cdot \left[\varepsilon(x,y)\nabla\phi(x,y)\right]=0$$

permittivity distribution ε is directly connected to voidage

For every electrode pair:

$$C_{ij}=\frac{Q_i}{\Delta V_{ij}}=\frac{\oint \varepsilon(x,y)\nabla\phi(x,y)\cdot\hat{n}dl}{\Delta V_{ij}}$$

Electric Capacitance Tomography: challenges

- Spatial resolution typically ~ 5-10% of bed diameter.
- Resolution deteriorates towards the bed center of the fluidized bed.
- Electrostatic charge can distort the picture.

X-ray and γ-ray tomography

photons

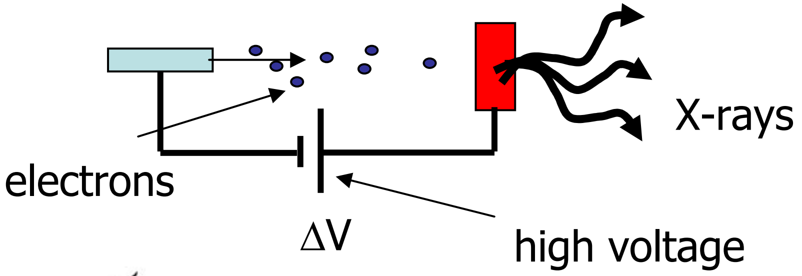
Röntgen (X) ↕ excited electrons

gamma's (γ) ↕ excited nuclei

Energy: 1 – 200 keV

Energy: 10 – 10,000 keV

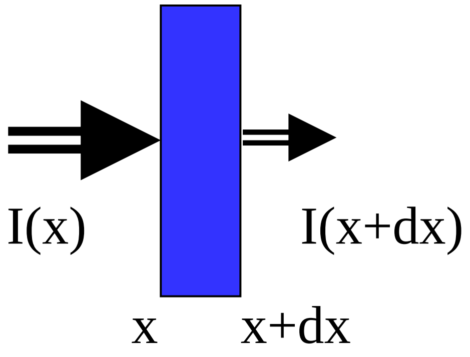
overlap: difference in generation



high energy: high penetration depth
dangerous

X/γ-ray tomography: principle

principle: absorption/scattering of original radiation



intensity = photons/m²s

of given energy

$$\frac{dI}{dx} = -\mu I$$

linear absorption coeff. (m^{-1})

= material property

= function of photon energy

$$I = I_0 \exp(-\mu x)$$

transmitted

initial

Lambert-Beer

holds only for fixed energy

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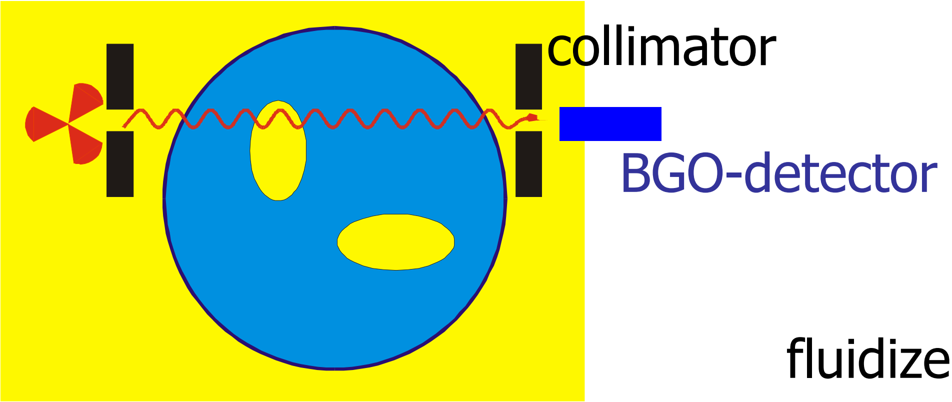
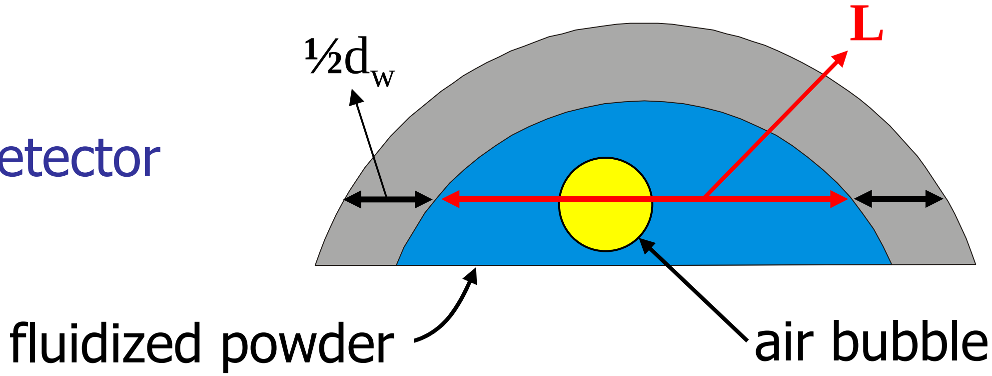
X/γ-ray tomography: principle





transmitted photons of original energy

absorption by wall

absorption by particles

absorption by air

$$I = I_0 \exp(-\mu x) = I_0 \exp[-\{\mu_w d_w + \mu_s(1-\alpha)L + \mu_{air}\alpha L\}]$$

distance through wall (≠wall thickness)

(line) fraction of bubbles

count rate: $R(E) = I(E)\,\eta(E)$

counting efficiency of detector: energy dependent!

X/γ-ray tomography: accuracy

nuclear decay: statistical process

if **N** = average counts in time Δt $\xrightarrow{\textit{Poison statistics}}$ st.dev. $\sigma_{\mathbf{N}} = \sqrt{\mathbf{N}}$

(assuming decay is dominating error-source)

count rate: $R = N/\Delta t \longrightarrow \sigma_R = \sigma_N/\Delta t = \sqrt{\mathbf{N}}/\Delta t = \sqrt{(\mathbf{R}/\Delta t)}$

Measuring longer decreases the error, provided the flow field is ‘frozen’!!!

1. Optimize measurement time

count rate: $R = R_0 \exp(-\mu x) \xrightarrow{\textit{error analysis}} \mu x = 2$ minimizes the error

x is the path length

attenuation coeff. $\mu=\mu(E)$ → the photon energy is a ‘design variable’

2. Optimize photon energy

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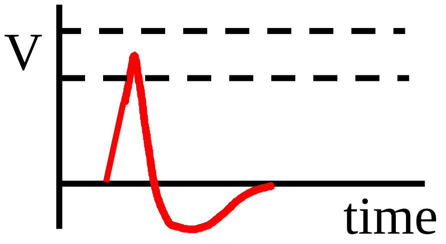
X/γ-ray tomography: detector limitations

Detector: incoming photon → … → … → electric pulse

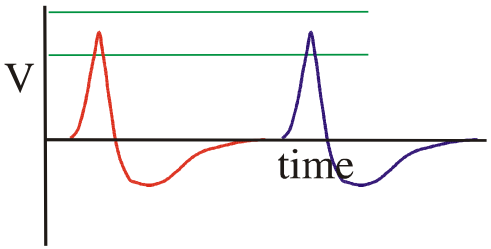
pulse height $\propto$ photon energy

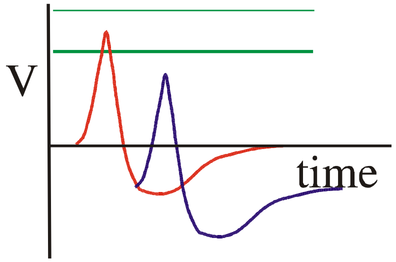


no AD-conversion (too slow), but two-level test

Problem: pile-up (summing up) of pulses

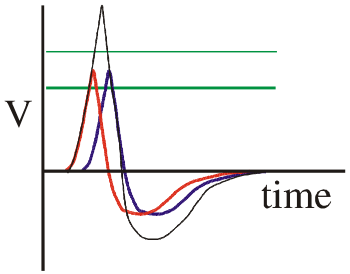
no pile-up

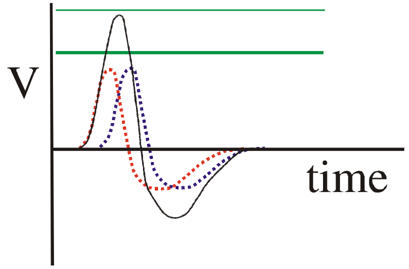




pile-up: one count lost

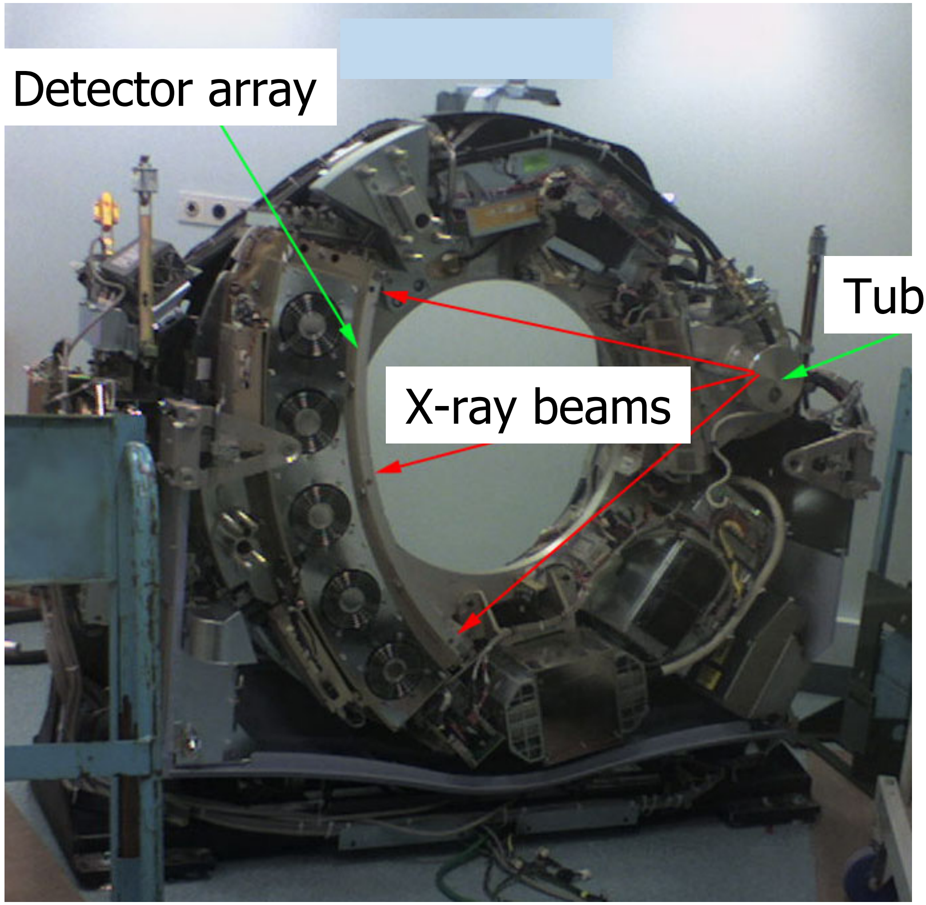
pile-up: two counts lost





pile-up: one false count

Computed tomography



Projection data is obtained by rotating the source and detector-array around the object → Static images

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Time-resolved computed tomography

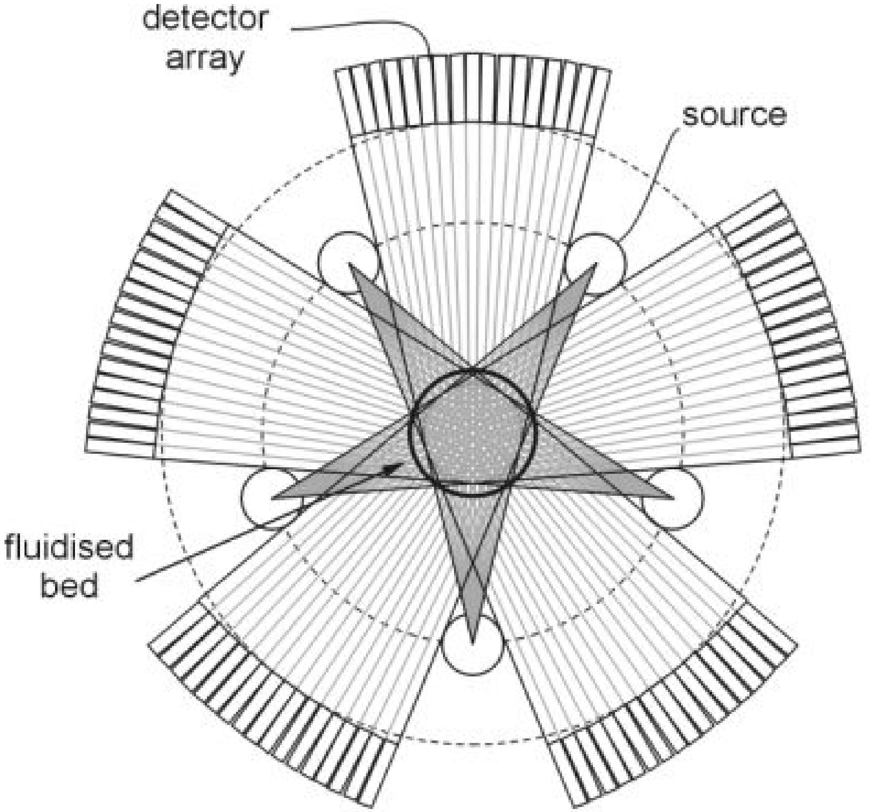
- Bubble diameter ~ 10^{-2} *m*
- Velocity ~ 10^{-1} *m/s*

$\boxed{\tau \sim 100 \ ms}$

Required temporal resolution:
<10 *ms*

Multi-source setup

- Alternative image reconstruction methods
- Improved spatial resolution



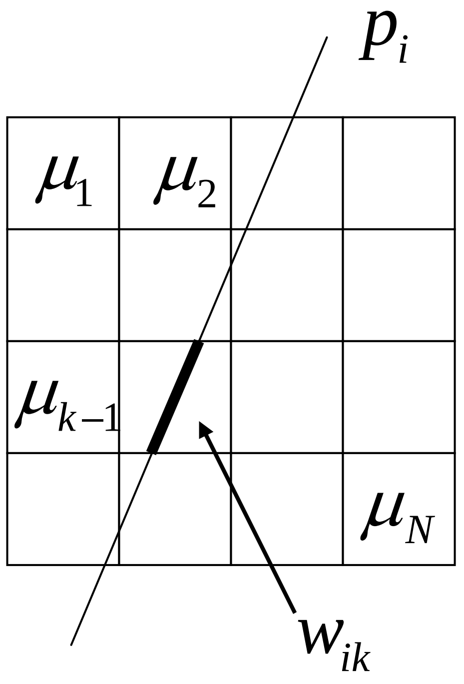
Iterative image reconstruction

$$\begin{pmatrix} w_{11} & w_{12} & \cdots & w_{1N} \\ w_{21} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ w_{M1} & \cdots & \cdots & w_{MN} \end{pmatrix} \begin{pmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_N \end{pmatrix} = \begin{pmatrix} p_1 \\ p_2 \\ \vdots \\ p_M \end{pmatrix}$$

weighting coefficient matrix

image vector

projection data vector



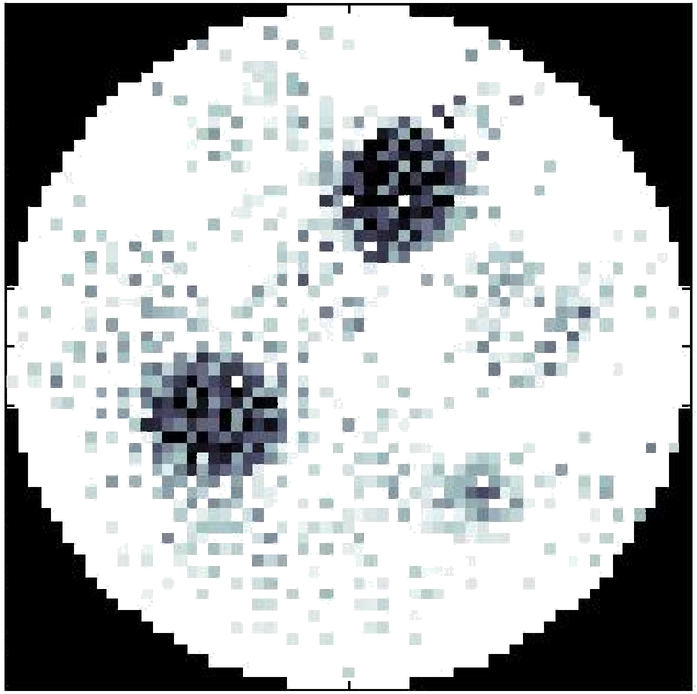
iterative solution, via algebraic reconstruction technique

number of pixels >number of detectors $\Rightarrow$ ill-posed

Example

- Column diameter 23 cm
- 3 artificial 'bubbles'
- Reconstruction *61x61 pixels*
- *5x30* detectors
- Data-aqcuisition time:

400 μs



Remove pepper & salt noise:

- simultaneous reconstruction
- median filter

Optical probes

purpose:

local measurement of gas fraction

bubble size & velocity

characteristics:

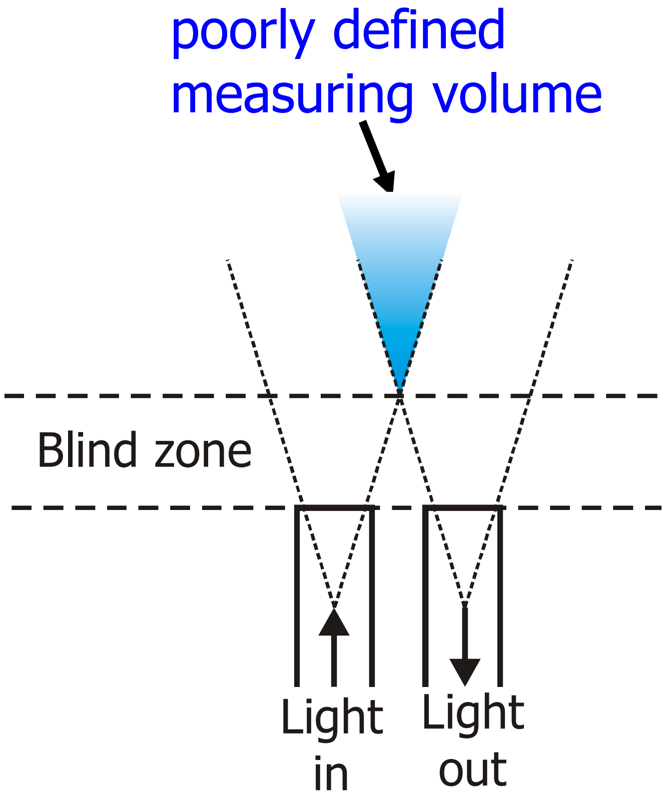
- point measurement
- thin but intrusive
- fast
- low noise level

typical material: glass fiber

different principles:

- light scattering/reflection
- light transmission

Optical probes: reflection type



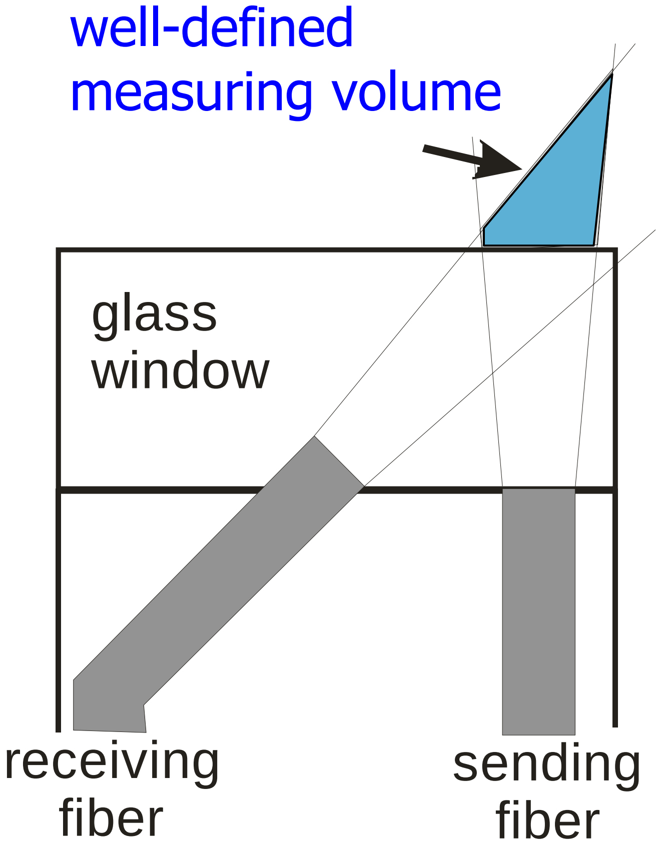
poorly defined
measuring volume

Blind zone

Light
in

Light
out

Liu et al., AIChE J.
49 (2003) 1405



well-defined
measuring volume

glass
window

receiving
fiber

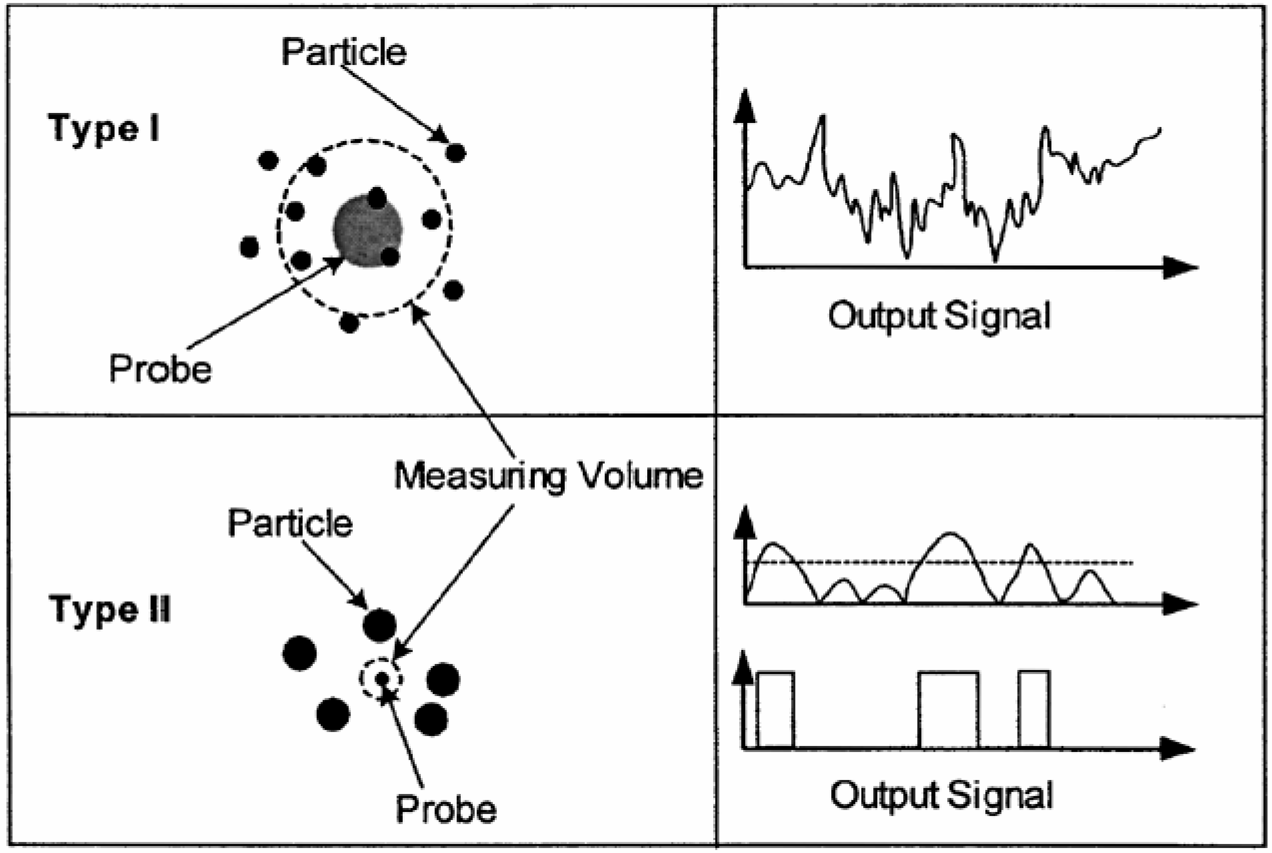
sending
fiber

Rundqvist et al., Exp Fluids
35 (2003) 572

Optical probes: probe size vs particle size

probe large,
particles small:
swarm measured

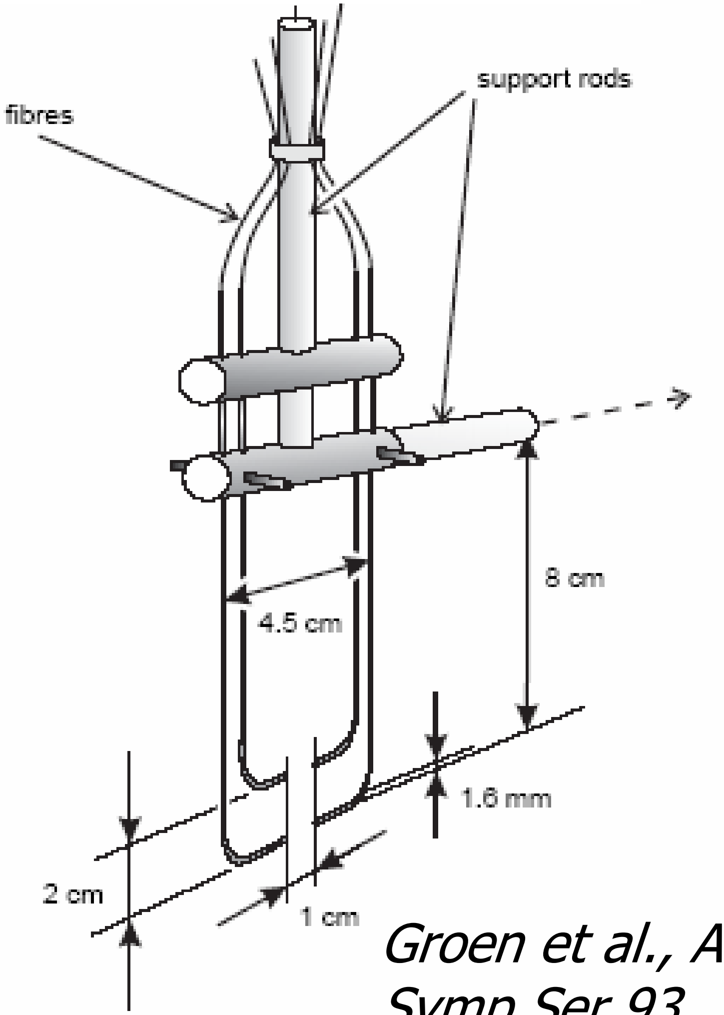
probe small,
particles large:
individual particles
measured

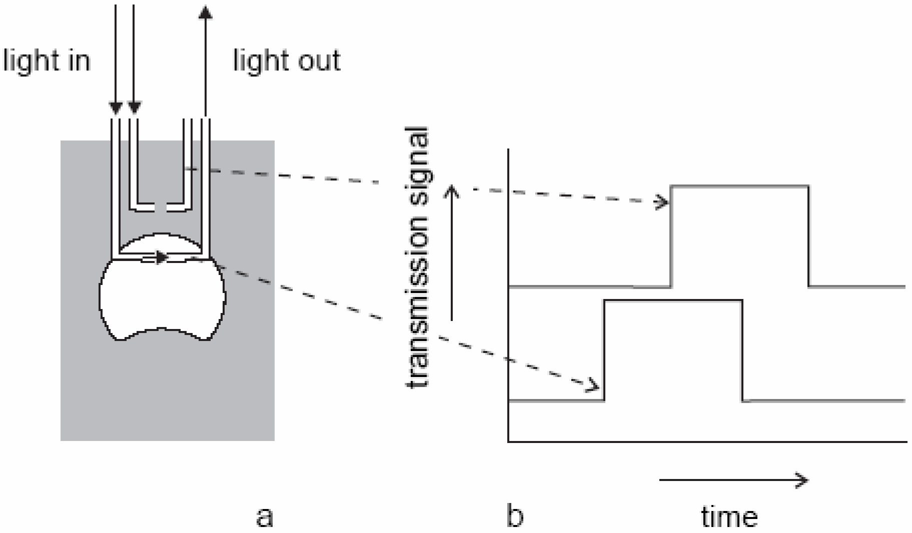


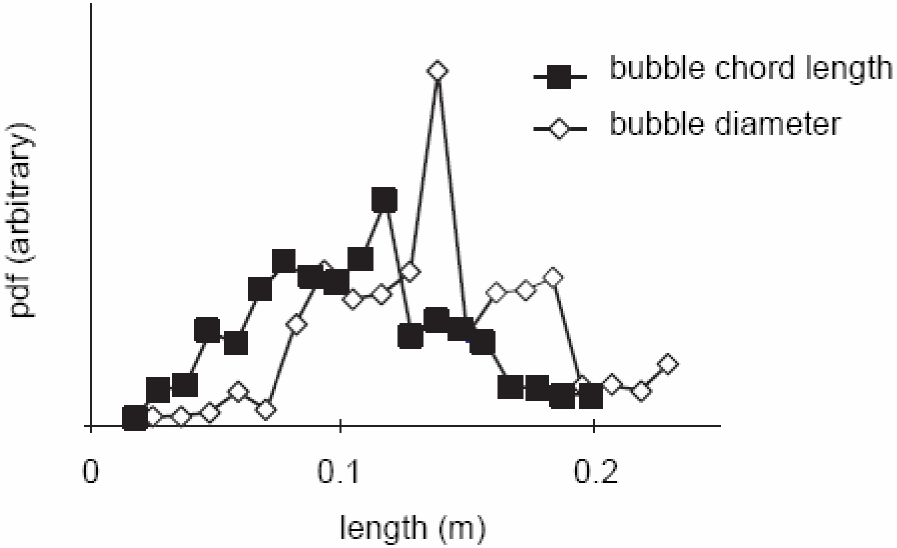
Liu et al., AIChE J., 49 (2003) 1405

Optical probes: transmission type

Double horse shoe probe



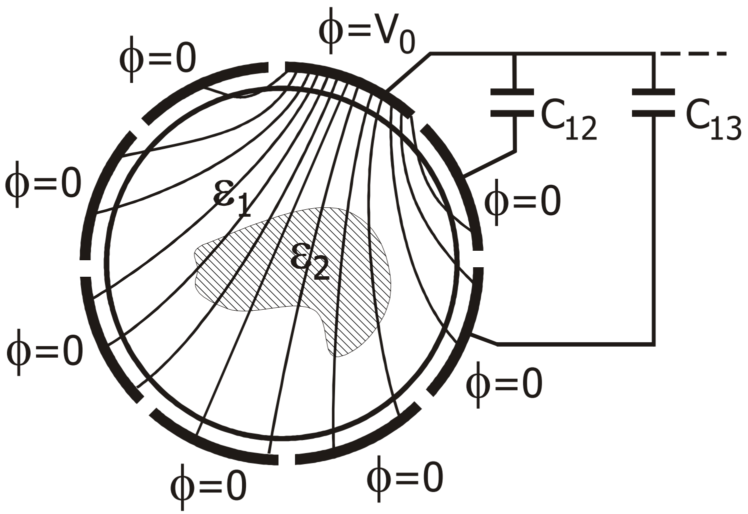




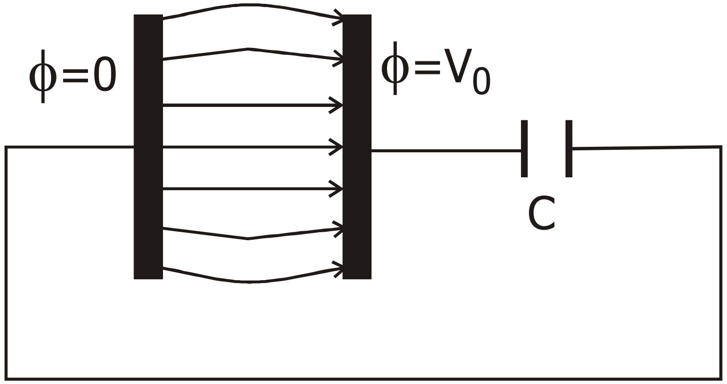
Groen et al., AIChE Symp Ser 93, 1997

Capacitance measurements

Electric capacitance tomography

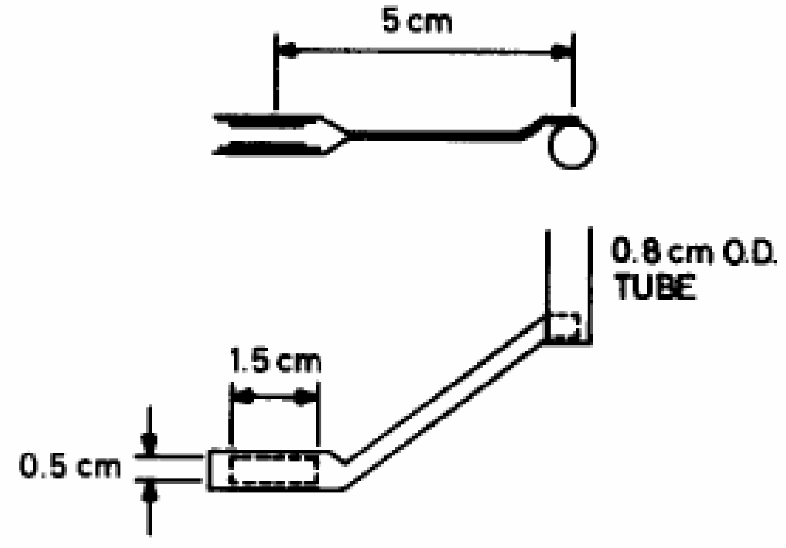


Capacitance probe



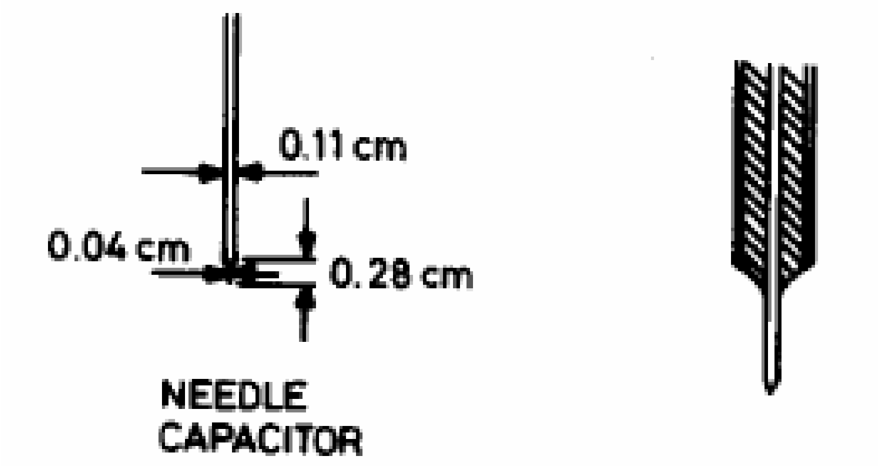
Capacitance probes

Plate probe



Geldart & Kelsey, Powder Technol. 6 (1972) 45

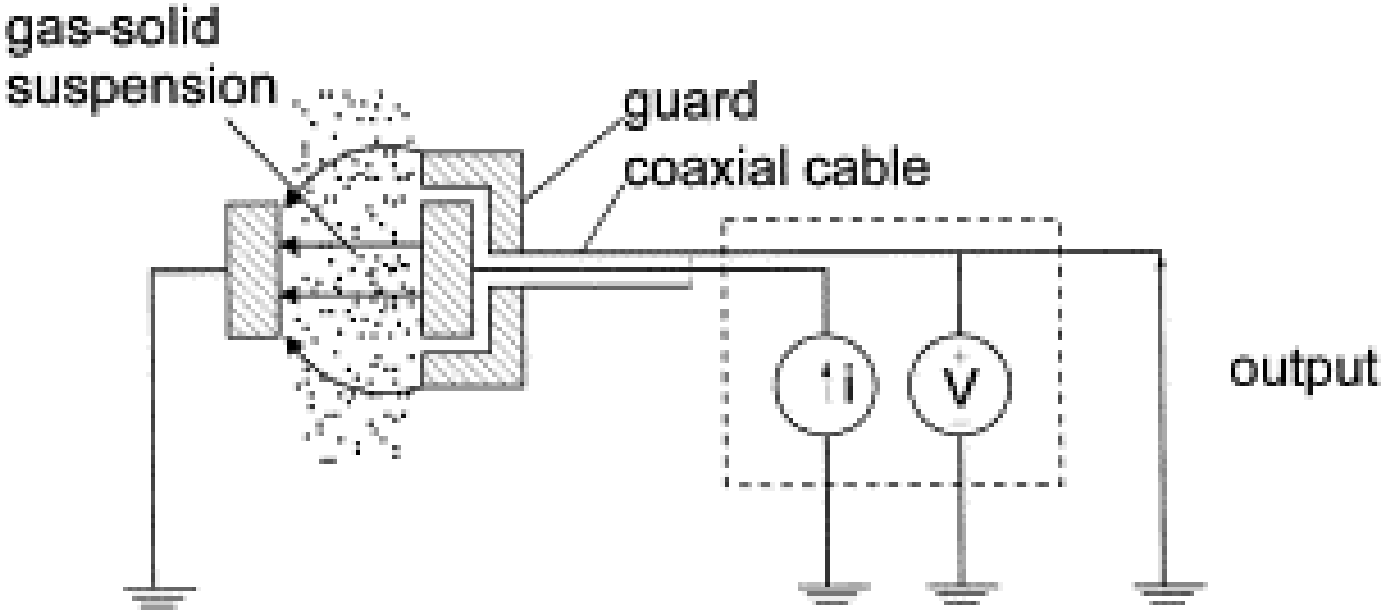
Needle probe



Werther & Molerus, Int. J. Multiphase Flow 1 (1973) 103

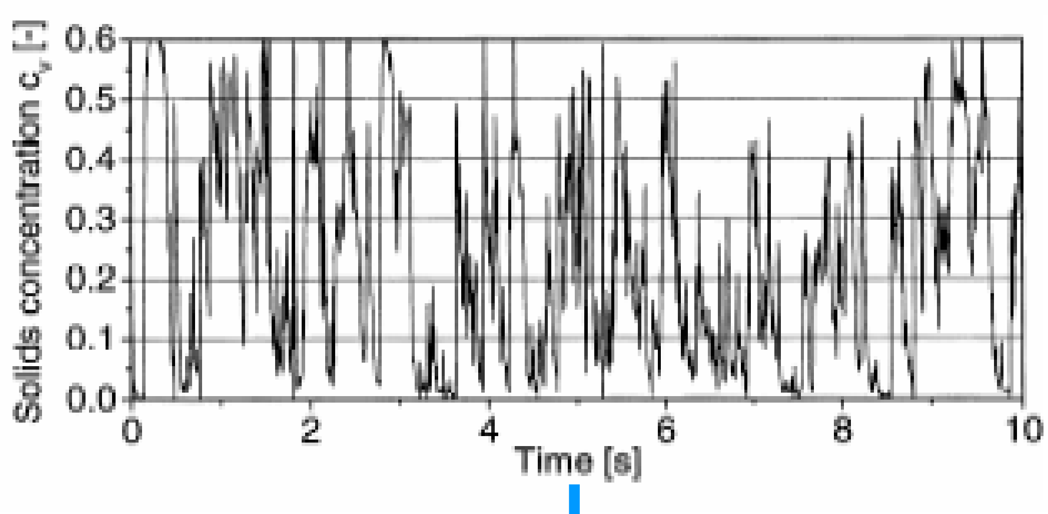
Capacitance probes: guard electrode

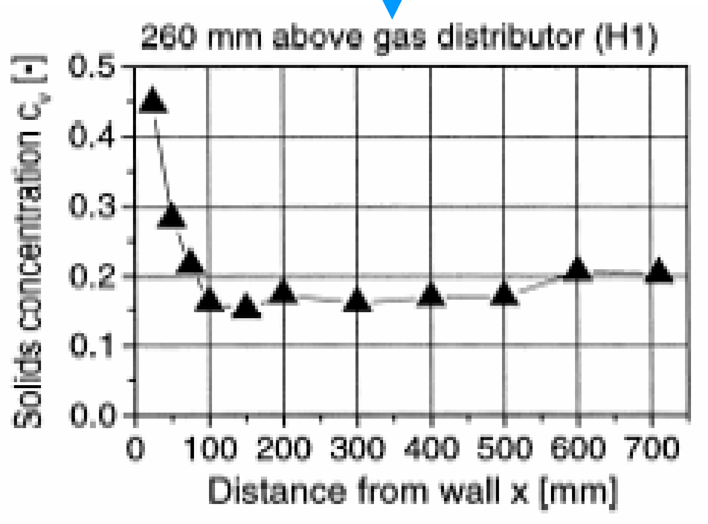
Guard electrode at same voltage as sensor:
absorbs disturbances from outside sources
→ more accurate signal



M. Louge, Experimental techniques, in: J.R. Grace, T. Knowlton, A.A. Avidan (Eds.), Circulating Fluidized Beds, Chap. 9, Chapman & Hall, London, 1996.

Example of capacitance probe results





Chalmers CFB boiler, Wiesendorf & Werther, Powder Technol. 110 (2000) 143.

Pressure measurements

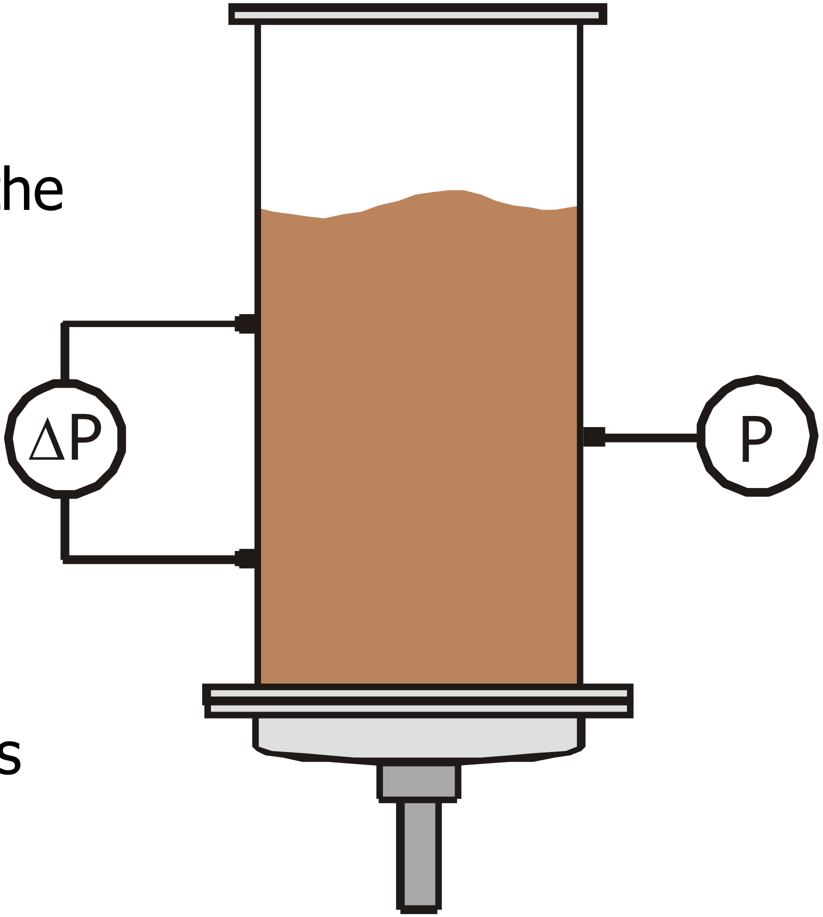
Pressure drop versus local pressure

Pressure drop
(time-aveaged):

Good estimate of the average density.

$$\rho_{avg} = \frac{\Delta P}{g \cdot \Delta h}$$

Deviations due to acceleration effects possible!



Info about dynamics:

Local pressure measurements (interpretation is less difficult).

Sample frequency: ~200Hz

Pros and cons pressure fluctuation measurements

+ Applicable both in lab and in full-scale units
+ Cheap
+ Virtually non-intrusive
+ High frequency info → characterization of dynamics
+ Large measurement volume

– Ill-defined measurement volume
– Pressure signal difficult to interpret

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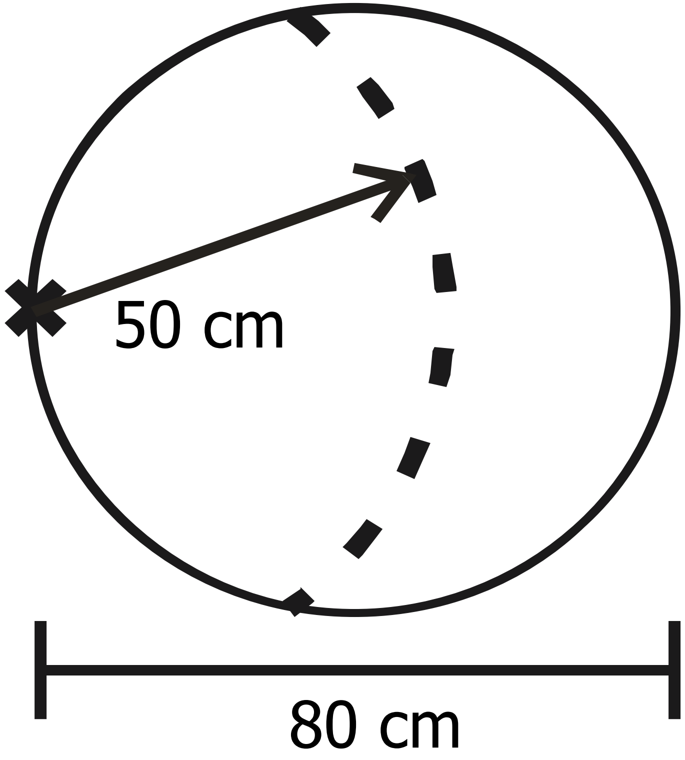
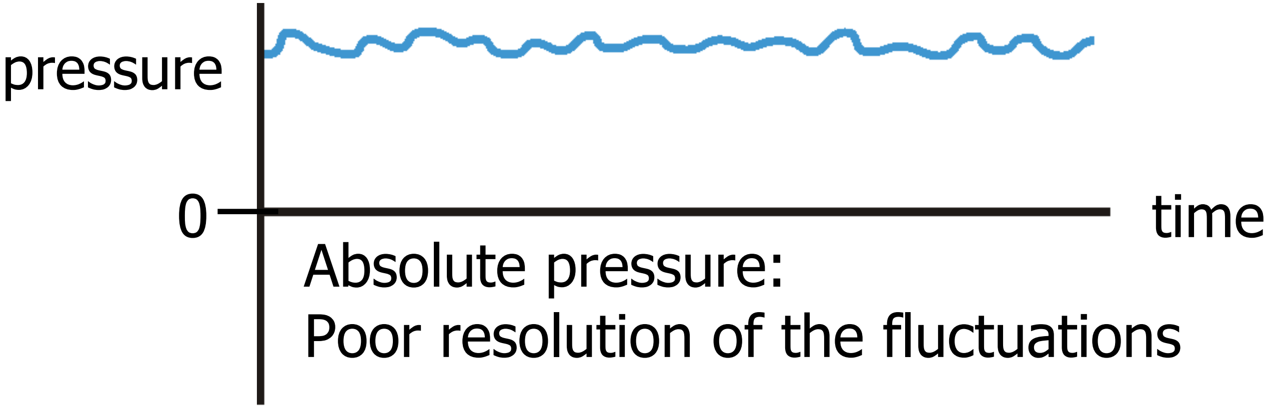
‘Measurement volume’ of pressure probe

In the horizontal plane, pressure probes can detect phenomena up to about 50 cm away.

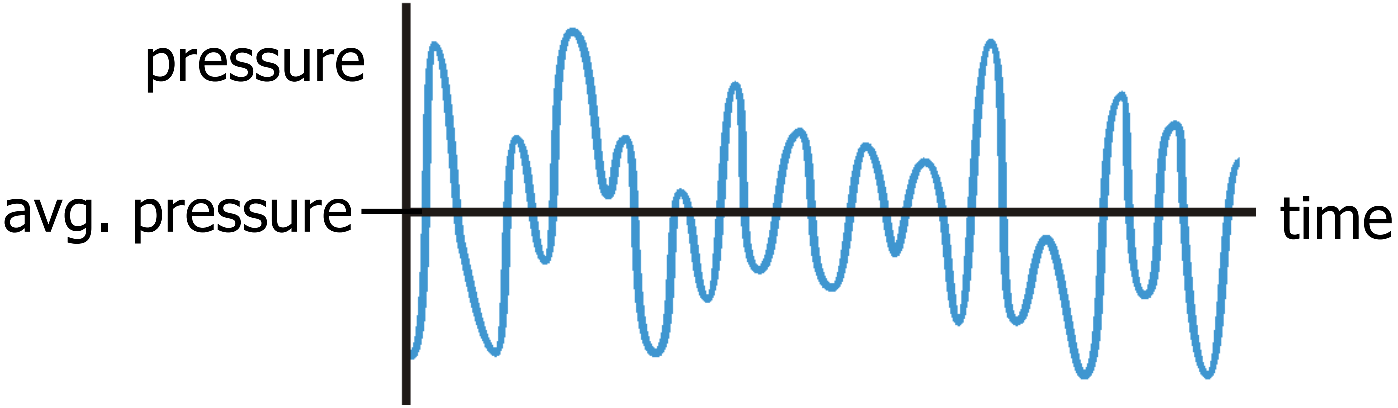


Van Ommen et al., Powder Technol. 139 (2004) 264

Absolute pressure versus relative pressure



Absolute pressure:
Poor resolution of the fluctuations



Relative pressure:
Optimal use of measurement range

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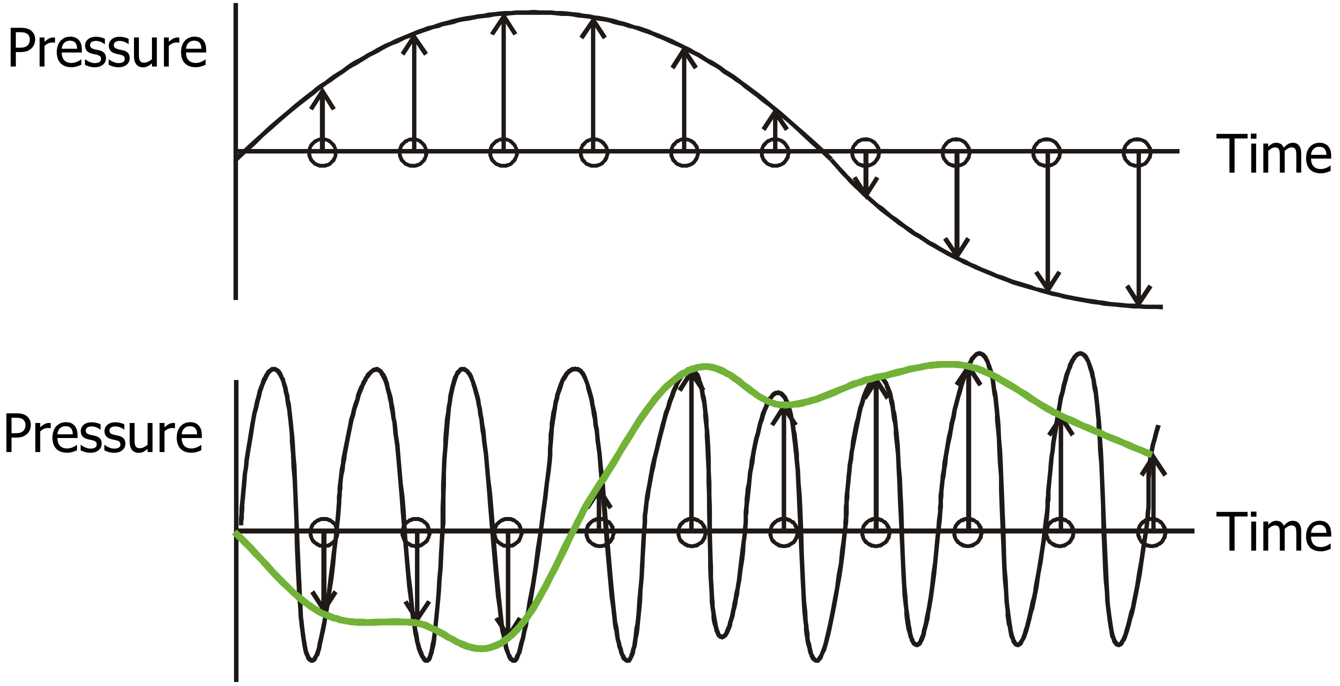
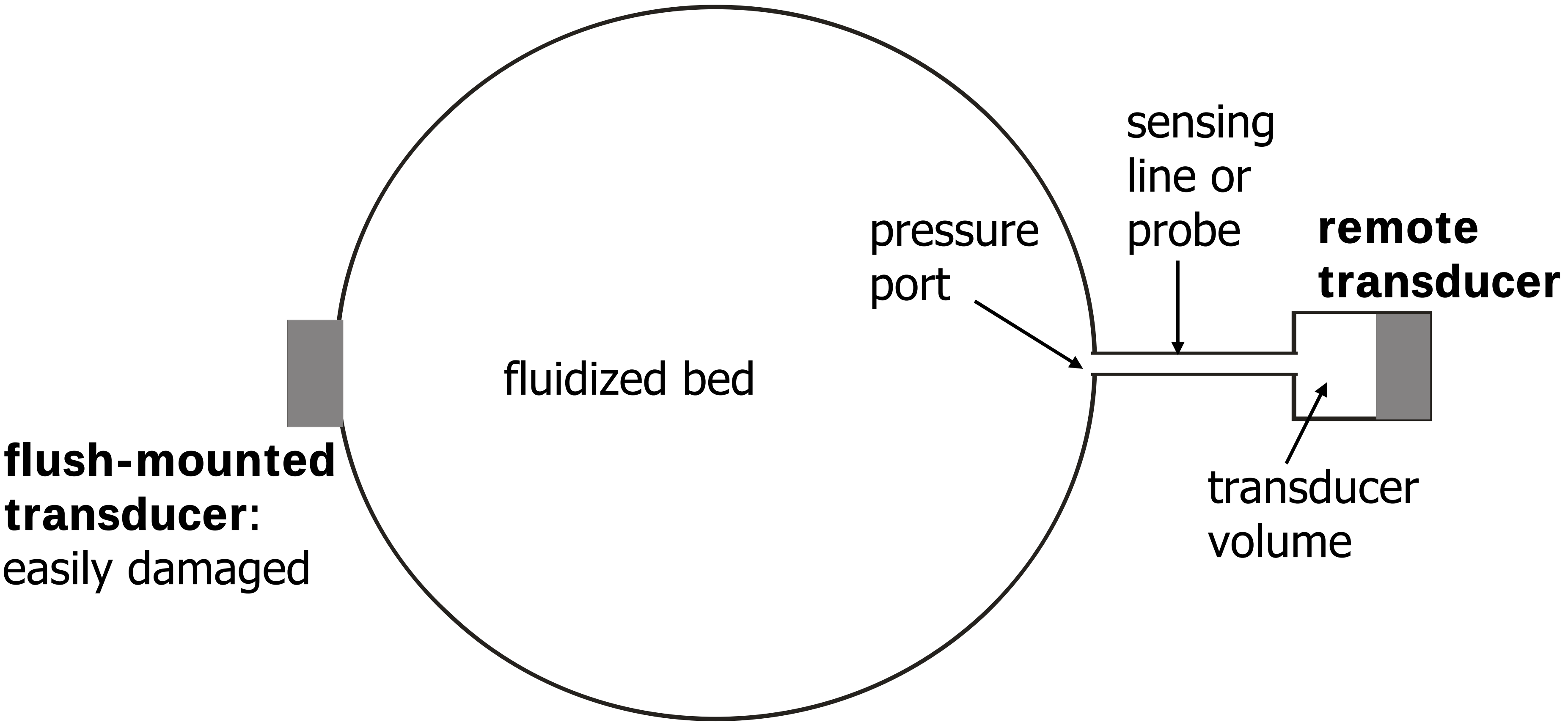
Filtering

High-pass filter (cut-off frequency ~ 0.1 Hz):
remove baseline and trend

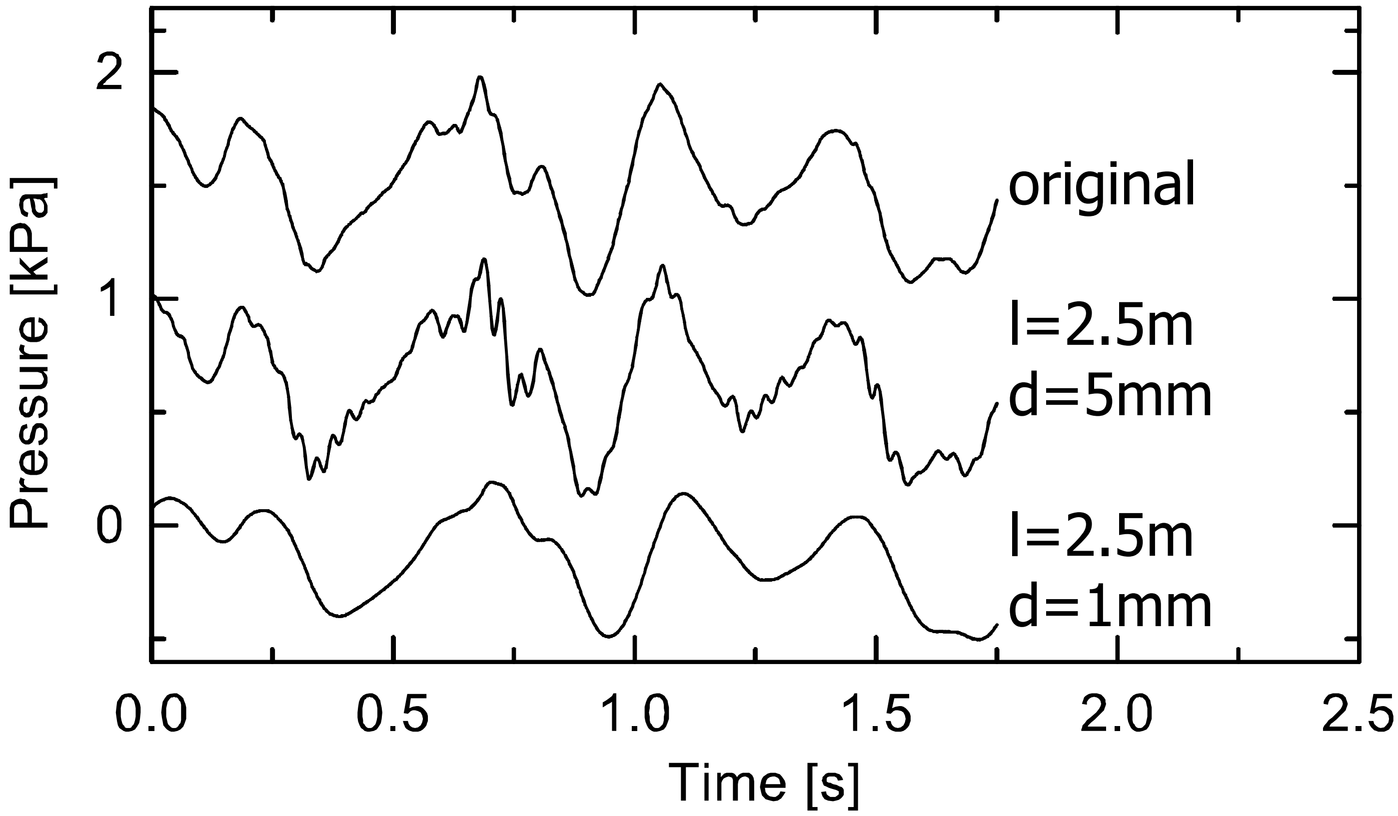
Low-pass filter (cut-off freq.: 0.5 * sample freq. or lower):
avoid aliasing (Nyquist-Shannon sampling theorem)



Two ways of mounting transducer



Effect of probe dimensions on measurements



van Ommen et al., Powder Technol. 106 (1999) 199 (Erratum: 113 (2000) 217)

Optimal length: as short as possible

Optimal internal diameter: ~ 4mm

Wire gauze versus purge flow

Two common ways of preventing particles from intruding the probe:

- **Wire gauze at probe tip**
  - Easy, but not suited for very small particles.
  - Can give problems at high temp.: sintering.
- **Purge flow**
  - Better protection: against fines, aggressive gases, sintering.
  - Flow should be very constant!
  - Beware of effect of creating bubbles.

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Several analysis methods available

(1) Time domain methods (‘standard’ statistic)

- *standard deviation*
- *probability density function*

(2) Frequency domain methods (spectral analysis)

- *power spectrum*
- *coherence function*

(3) State space methods (non-linear or chaos analysis)

- *Kolmogorov entropy*
- *attractor comparison method*

Overview: Johnsson et al., IJMF 26 (2000) 663

Applications of pressure signals

- Identification of various phenomena
  formation, coalescence, and eruption of bubbles
- Characterisation
  discrimination of regimes
- Validation
  results obtained by computations fluid dynamics
- Monitoring
  early detection of agglomeration

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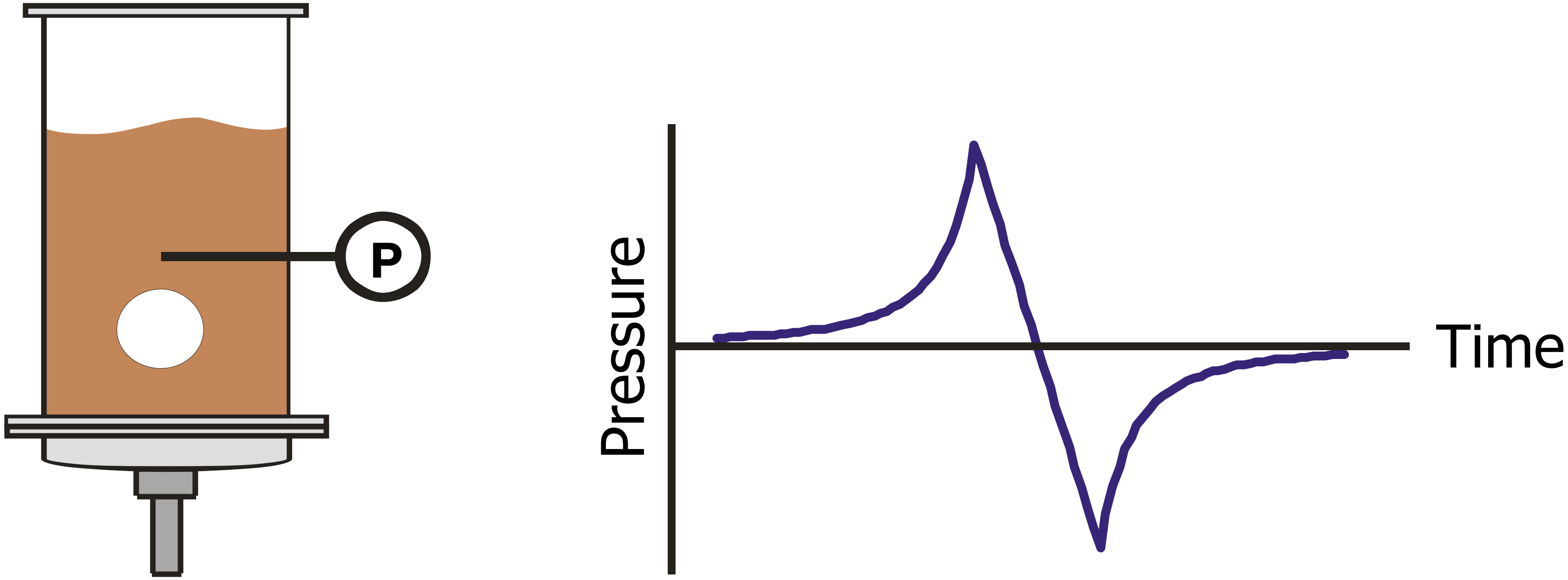
Different phenomena in pressure signal

Theoretical pressure signal of a spherical bubble

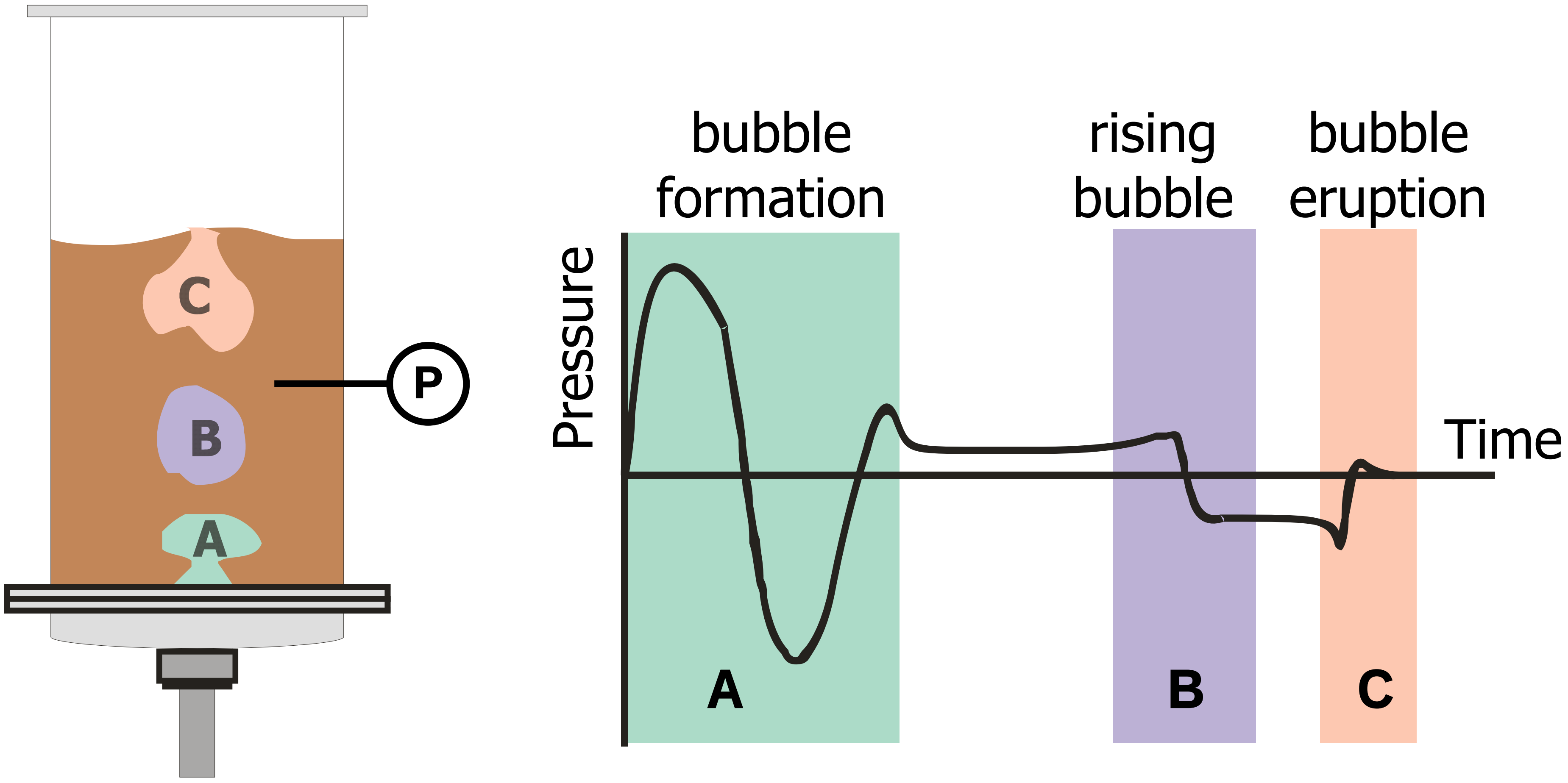


Davidson, Trans. Inst. Chem. Eng. 39 (1961) 230

The results on the following slides are all obtained for Geldart B particles (particles ~ 400 μm).

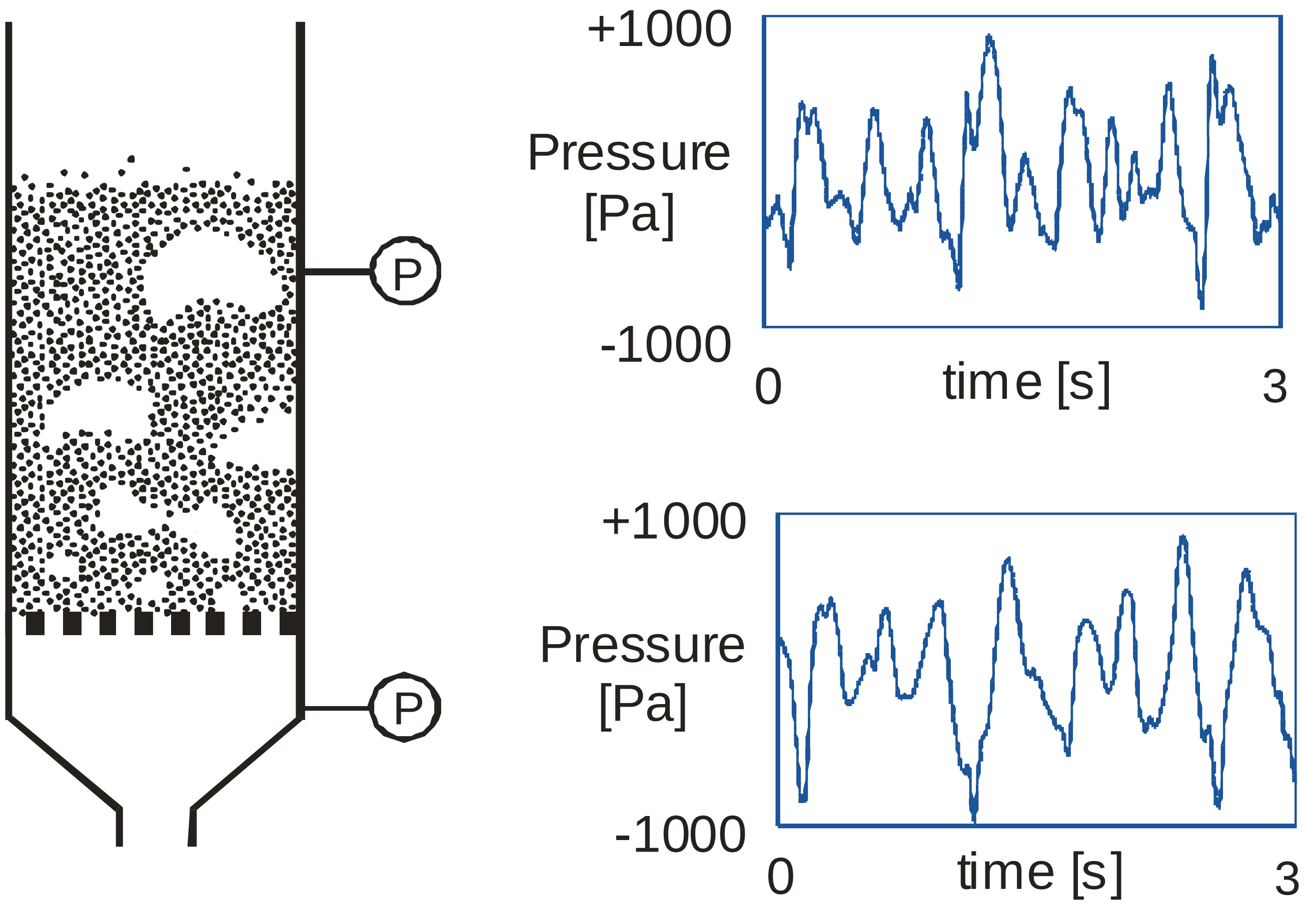
Different phenomena in pressure signal

Single bubble injection



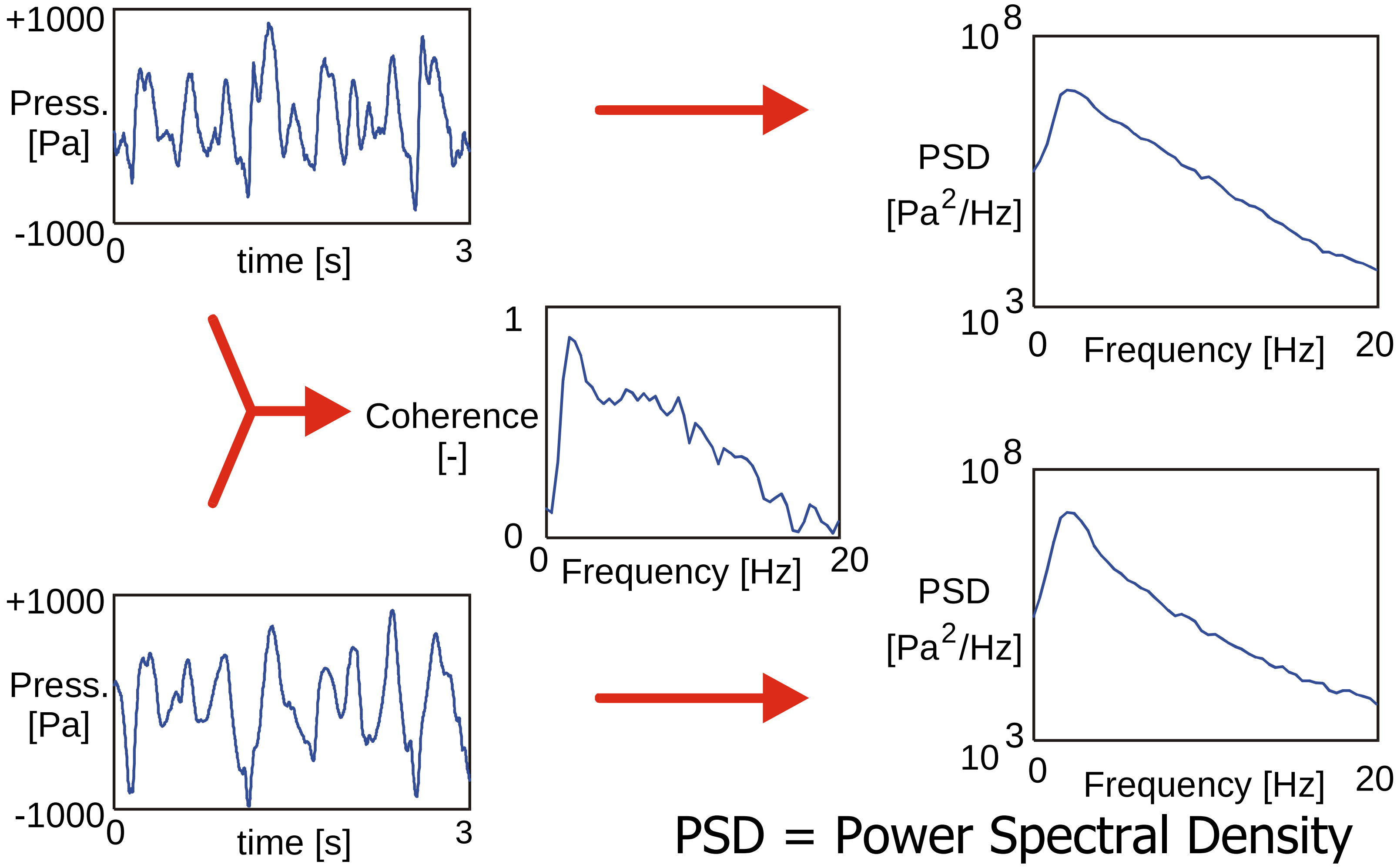
Van der Schaaf et al., Powder Technol. 95 (1998) 220

Decomposition of pressure signal



Decomposition of pressure signal

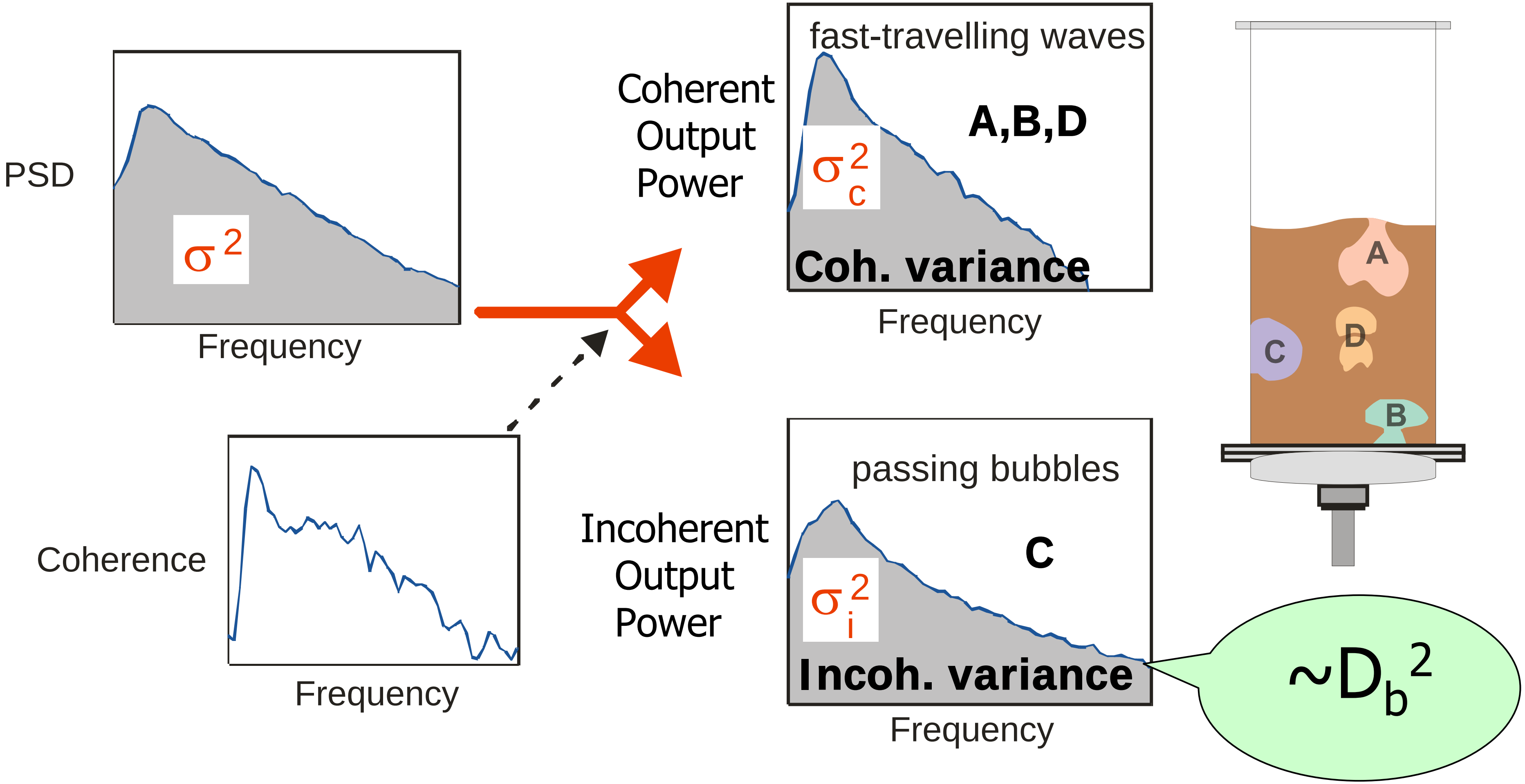
using spectral analysis



PSD = Power Spectral Density

Van der Schaaf et al., IJMF 28 (2002) 865

Decomposition of pressure signal



PSD

σ^2

Frequency

Coherence

Frequency

Coherent Output Power

fast-travelling waves

σ_c^2

A,B,D

Coh. variance

Frequency

Incoherent Output Power

passing bubbles

σ_i^2

C

Incoh. variance

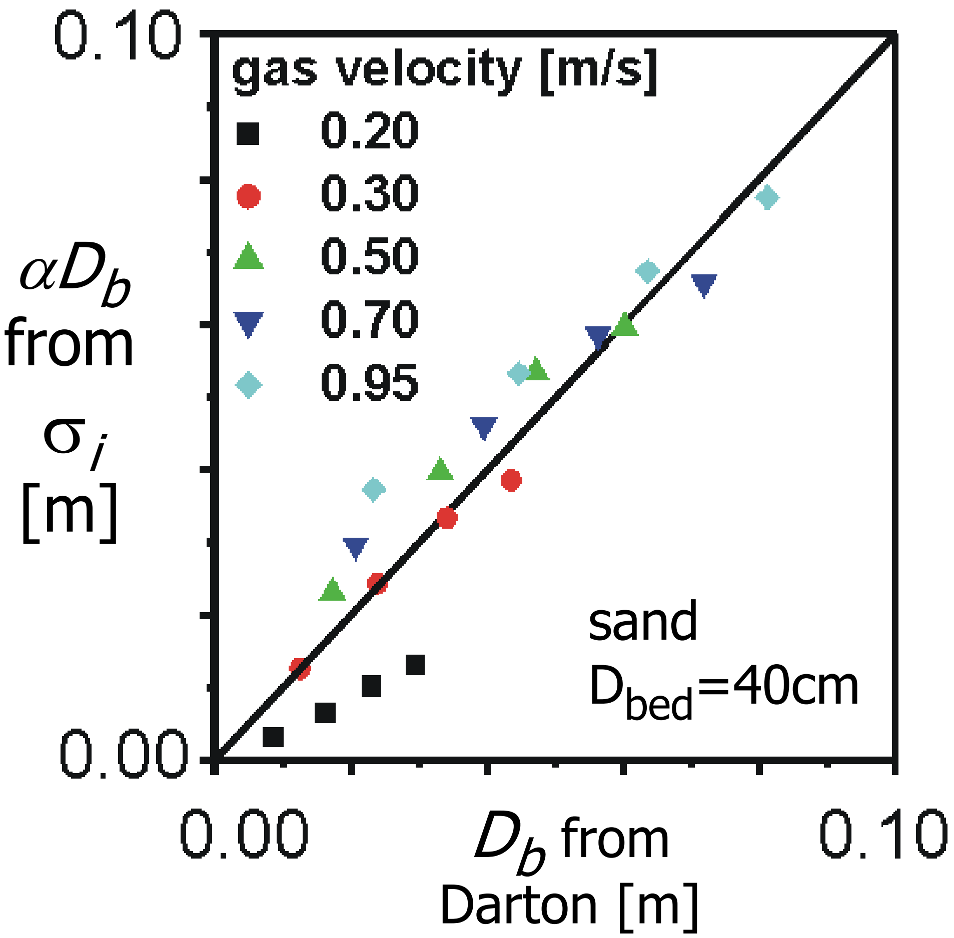
Frequency

$\sim D_b^2$

Incoherent Output Power = (1-coherene) · PSD

Decomposition of pressure signal

Is the obtained bubble size info realistic?



In this particular case:
α=1 (coincidence!!).

This is normally not the case:
Kleijn van Willigen et al., Int. J. Chem. Reactor Eng., 1 (2003) A21

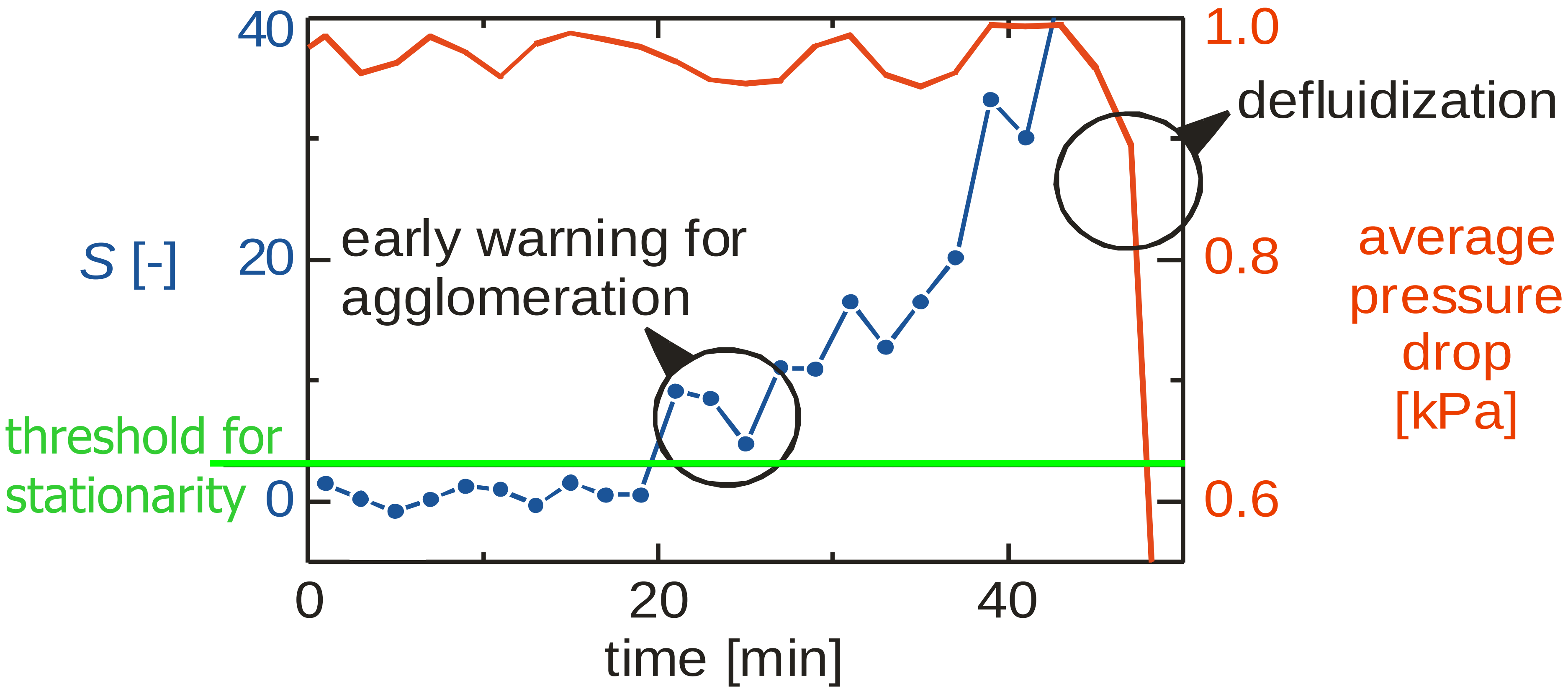
Darton et al., Trans. Inst. Chem. Eng. 55 (1977) 274

Applications of pressure signals

- Identification of various phenomena
  formation, coalescence, and eruption of bubbles
- Characterisation
  discrimination of regimes
- Validation
  results obtained by computations fluid dynamics
- Monitoring
  early detection of agglomeration

Example: monitoring

Early detection of agglomeration during lab-scale straw gasification



Van Ommen et al., Proc. 16th Int. Conf. on Fluid. Bed Comb. (2001) paper 131

Concluding remarks

- **Electric capacitance tomography**: fast, but spatial resolution is troublesome.
- **X- and γ-ray tomography**: quite good spatial resolution, but temporal resolution needs improvement
- **Optical probes and capacitance probes** determine $\varepsilon(t)$ in a small measurement volume. They are reasonably well-developed.
- **Time-averaged pressure measurements** are commonly used to determine the average bed density and bed height.
- Obtaining quantitative voidage data from **pressure fluctuations** (or acoustic measurements) is not straight-forward, but they are very useful to determine changes in the voidage dynamics and distribution.