CPERI/CERTH

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A critical review of cluster diameter correlations in CFB modelling of Fluidized Beds

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Introduction

- The study of **clusters** has led to numerous **experimental** and **numerical** works worldwide

- The **meso-scale structure (cluster)** strongly affects the drag coefficient, mass and heat transfer, solids mixing, entrainment and a **comprehensive study is of major importance**

- The cluster **shape** and **size** are two key parameters in two-phase granular flows

- An **analytical correlation** that accurately predicts the cluster size is a **critical issue** in fluidized bed simulations

Introduction

Agglomerate: group of particles held together by **inherent interparticle forces** (Van der Waals forces, liquid bridge forces, ...)
Cluster: dynamic dense formations consisting of particles that are held together as a result of hydrodynamic effects (unstable gas-solid suspensions) **[1]**

Two scales of clusters: (i) **micro**-clusters (ii) **macro**-clusters depending on operating conditions and material properties

(i) **micro-clusters** consist of only up to 20 or more particles
(ii) **macro-clusters** consist of hundreds of particles that may exist as spheres, strands or streamers. **[2]**

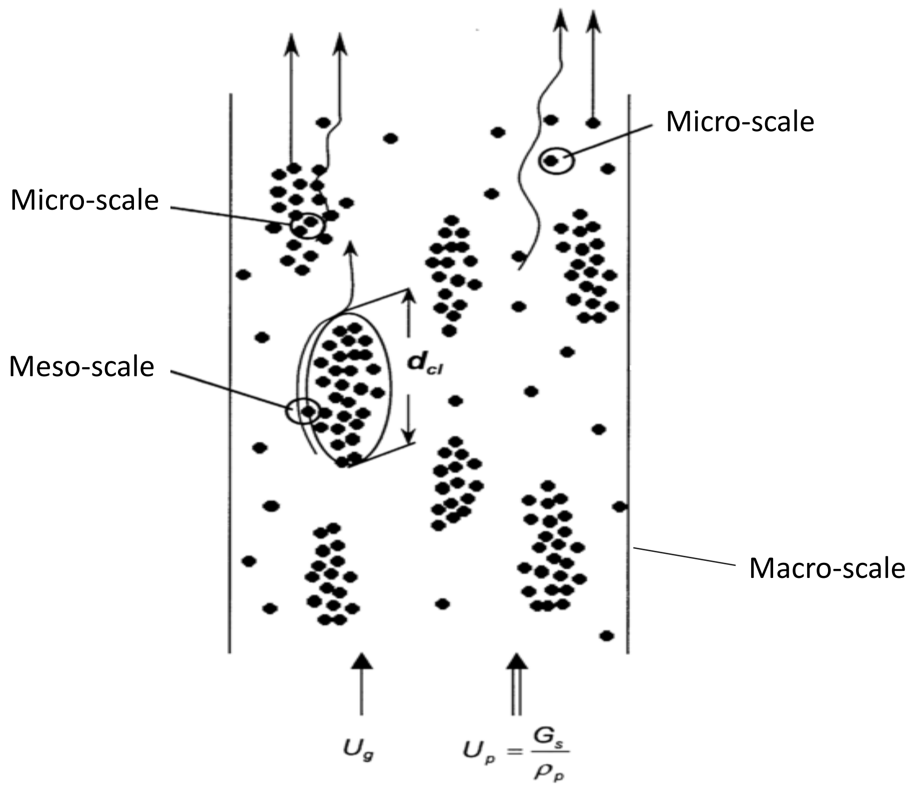
In such systems most particles tend to gather in clusters, strands or packets in order to reduce their flow resistance. As a result, the drag force is reduced.

Properties of the two-phase flow attributed to particles clustering:
- Solid hold-up
- Pressure gradient
- Choking
- High slip velocity between the two phases **[3]**

Introduction

Meso-Scale Structures in Fluidized Beds

✓The mechanisms of **clusters formation** and the underlying dependencies are still mainly unknown



Micro and meso-scale structures in a FB [4]

Clusters tend to deform, interact, break-up, and coalesce constantly (**dynamic formations**)

✓**Meso-scales** are a common challenge for understanding various **multi-scale phenomena**

✓**Micro-mechanisms** and **macro-mechanisms** can be correlated only when the meso-scales are physically understood

- In **dilute flows** micro and meso-scales **overlap** and their distinction is difficult

Experimental Works

In 1948 **Wilhelm and Kwauk** were among the first to observe through experiments clusters of particles and multi-scale heterogeneity in gas-solid fluidized beds. **[5]**

Other primary experimental works and observations followed:

- *Happel, J. et al. (1960)* **[6]**
- *Jackson, R. (1963)* **[7]**
- *Johne R. (1966)* **[8]**
- *Crowley J.M. (1976)* **[9]**
- *Graham, A. L. et al. (1984)* **[10]**
- *Hartge et al. (1986)* **[11]**
- *Fortes et al. (1987)* **[12]** *etc.*

Experimental Works

Two phase flow structure visualization in FFB [18]		
High-speed video camera	Study of the particle motion at the wall: Arch-shaped clusters near the wall descended with a velocity range 0.3-0.4 m/s	Rhodes et al, 1990 **[13]**
Micrographs with micro video system (Provided with optical fiber probes)	The clusters transform from strands at the center of the bed into spheres near the wall. Shape: irregular (direct visualizations) Cluster concentration: dilute at the center, dense near the wall. Cluster mean size: larger near the wall than at the center of the bed.	Li et al., 1991 **[14]**
Video	Observations in a Two-Dimentional Fast Fluidized bed: clusters may be either U-shaped for higher solid hold-ups or striped stands at lower solid concentrations	Bai et al., 1991 **[15]**
Micrographs	Prediction of extreme cluster size under certain conditions	Xia et al., 1993 **[16]**

The coexistence of a dispersed phase and a cluster phase in a CFB was observed

These studies display the meso-scale structure near the wall. Need for observation in high density gas-solids flow. Moreover, need for quantitative analysis and search of a parameter for the cluster shape and size

Experimental Works

Geldart B particles vs Geldart A

Geldart A	Geldart B
1. small more tightly packed clusters **[17]**, **[2]** 2. Formed due to **cohesive** forces 3. Sometimes easy to measure	1. Form clusters of obscure shape and long narrow strands **[17]** 2. Difficult to measure their size 3. The local riser position has a strong influence on cluster characteristics (Chew et al.) 4. High bed inventory: U-shaped clusters, Low bed inventory: inverted U-shaped structures

Cluster Diameter

Cluster diameter: (or more generally, the characteristic length of meso-scale structures) is an equivalent dimension to represent the meso-scale interaction, rather than the true size of amorphous and dynamic clusters

The cluster size is difficult to define

- **Li and Kwauk (1994):** Implementation of an analytical equation in the frame of EMMS model and inversely proportional to *Nst.* More appropriate for Geldart A particles
- **Zou (1994):** Was among the first to implement a correlation for the cluster size and a roundness factor that takes into account cluster shape
- **Xu and Li (1998):** Development of a simple equation for local equivalent diameter to replace the complicated one derived by Li and Kwauk in the EMMS model →Clusters are suspended both by the interstitial fluid in the cluster and the surrounding dilute phase
- **Harris et al (2002):** Properties of particles clusters travelling near the riser walls. Based on experimental data on vertical risers (laboratory to industrial scale). Predicts cluster diameters of an order of $10d_p$ for FCC particles
- **Subbarao (2010):** Implementation of a correlation that takes into account the riser diameter

Cluster Correlations

- *For the calculation of d_{cl} the following most well-known correlations are proposed in the literature:*

Li& Kwauk (1994), [18]
$$d_{cl} = \frac{d_p[U_s/(1-\varepsilon_{max}) - (U_{mf} + \varepsilon_{mf}U_s/(1-\varepsilon_{mf}))]g}{N_{st}\rho_s/(\rho_s-\rho_g) - (U_{mf} + \varepsilon_{mf}U_s/(1-\varepsilon_{mf}))g}$$

Gu & Chen (1998), [19]
$$d_{cl} = d_p + (0.27 - 10d_p)\varepsilon_s + 32\varepsilon_s^{\ 6}$$

Harris et al. (2002), [20]
$$\bar{d}_{cl} = \frac{\bar{\varepsilon}_s}{40.8 - 94.5\bar{\varepsilon}_s}$$

Zou et al. (1994), [21]
$$d_{cl} = 1.8543[\varepsilon_g^{\ -1.5}(1-\varepsilon_g)^{0.25}/(\varepsilon_g - \varepsilon_{mf})^{2.41}]^{1.3889} d_p + d_p$$

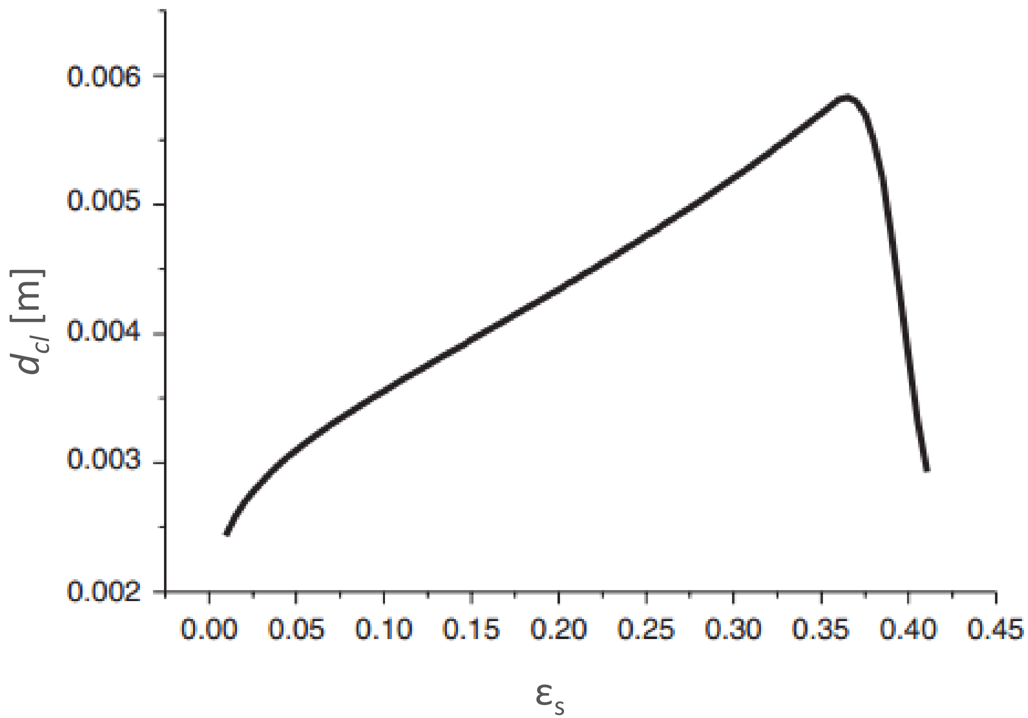
Empirical correlations

Xu and Li (1998), [22]
$$d_{cl} = A/(\frac{\rho_{sus}}{\rho_p})^n$$

Subbarao (2010), [23]
$$d_{cl} = (\frac{1-\varepsilon_g}{\varepsilon_g - \varepsilon_c})^{\frac{1}{3}} d_v + d_p$$

Cluster Correlations

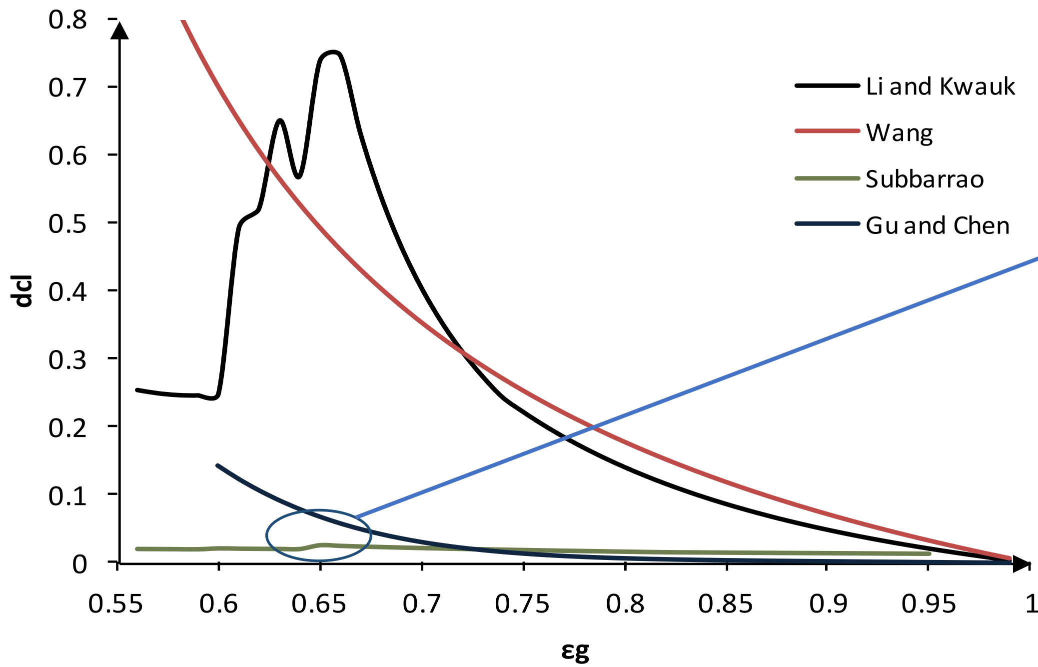
- **Wang et al. (2006) [4]**: Implemented correlation by Li and Kwauk and came to some important conclusions.

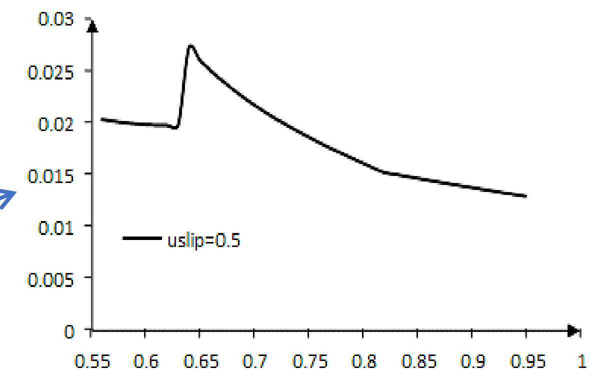


- Particles aggregate until a turning point (1-ε_{mf}) were the clustering is prevented.
- This decrease maybe attributed to a change in flow patterns (homogeneous fluidization)

Correlations comparison by CERTH

Geldart B particles





Gas-Solid properties	
Particle Diameter	350 μm
Particle Density	1800 kg/m^3
Gas Density	0.38838 kg/m^3
Gas Viscosity	3.941022 10^{-5} kg/(ms)
$\varepsilon_{mf}/\varepsilon_{max}$	0.55/0.9997
Riser Diameter	0.07m

* *Only the correlation of Gu and Chen was checked due to the fact that compared to Harris and Zhou et al. are of the same order of magnitude (Wang et al. 2008) !!!!*

Cluster Correlation by CERTH

$$d_{cl} = Min(d_{cl1}, d_{cl2})$$

Subbarao

$$d_{cl1} = D_v \left(\frac{f}{1-f}\right)^{\frac{1}{2}} + d_p$$

$$D_V = \frac{2u_t^2}{g}\left(1+\frac{u_t^2}{u_{sr}^2}\right)^{-1}$$

$$u_{sr} = 0.35(gD_t)^{1/2}$$

Li and Kwauk

$$d_{cl2} = \frac{d_p[U_s/(1-\varepsilon_{\max}) - (U_{mf} + \varepsilon_{mf}U_s/(1-\varepsilon_{mf}))]g}{N_{st}\rho_s/(\rho_s-\rho_g) - (U_{mf} + \varepsilon_{mf}U_s/(1-\varepsilon_{mf}))g}$$

$$N_{st} = \frac{\rho_s-\rho_g}{\rho_s}\left[U_g - \frac{(\varepsilon_f-\varepsilon_g)f(1-f)U_f}{1-\varepsilon_g}\right]g$$

The riser diameter is taken into account!!

Riser diameter is considered to be a limiting factor for excessive cluster growth

$$u_t = u_t^*\left[\frac{\mu_g(\rho_s-\rho_g)g}{\rho_g^2}\right]^{\frac{1}{3}} \quad u_t^* = \left[\frac{18}{(d_p^*)^2} + \frac{2.335-1.744\phi}{(d_p^*)^{0.5}}\right]^{-1} \quad d_p^* = d_p\left[\frac{\rho_g(\rho_s-\rho_g)g}{\mu_g^2}\right]^{\frac{1}{3}} = Ar^{\frac{1}{3}}$$

Cluster Correlation by CERTH

EMMS model

Momentum conservation

$$\frac{3}{4}\cdot C_{df}\frac{(1-f)(1-\varepsilon_f)}{d_p}\rho_g U_{sf}\left|U_{sf}\right| = (1-f)(1-\varepsilon_f)\cdot(\rho_s-\rho_g)(g+a_f)$$

$$C_{df}\frac{(1-\varepsilon_f)\cdot\rho_g}{d_p}U_{sf}\left|U_{sf}\right| + \frac{f}{1-f}C_{di}\frac{\rho_g}{d_{cl}}U_{si}\left|U_{si}\right| = C_{dc}\frac{(1-\varepsilon_c)\cdot\rho_g}{d_p}U_{sc}\left|U_{sc}\right|$$

$$C_{df}\frac{(1-\varepsilon_f)\cdot\rho_g}{d_p}U_{sf}\left|U_{sf}\right| + \frac{f}{1-f}C_{di}\frac{\rho_g}{d_{cl}}U_{si}\left|U_{si}\right| = C_{dc}\frac{(1-\varepsilon_c)\cdot\rho_g}{d_p}U_{sc}\left|U_{sc}\right|$$

Objective function

$$N_{st} = \left|\frac{1}{(1-\varepsilon_g)\cdot\rho_s}\left[m_f\cdot F_f\cdot U_f + m_c\cdot F_c\cdot U_c + m_i\cdot F_i\cdot U_f\cdot(1-f)\right]\right|$$

$$\to \min imum$$

$$F_{EMMS} = \varepsilon_g\cdot\left[f\cdot(1-\varepsilon_c)\cdot(g+a_c)+(1-f)\cdot(1-\varepsilon_f)\cdot(g+a_f)\right]\cdot(\rho_s-\rho_g)$$

Results

$$H_d = \frac{F_{Wen,Yu}}{F_{Emms}}$$

** C_{doi} derived from the work of [1] for f=1 were implemented as the final ones and not the ones depicted in the table*

Mass conservation

$$U_f(1-f)+U_c f = u_g\cdot\varepsilon_g \qquad U_{pf}(1-f)+U_{pc}f = u_s\cdot(1-\varepsilon_g)$$

$$\varepsilon_g = f\cdot\varepsilon_c+(1-f)\cdot\varepsilon_f$$

Semi – empirical equations

$$\varepsilon_c = \varepsilon_g - n\cdot\sigma_\varepsilon$$

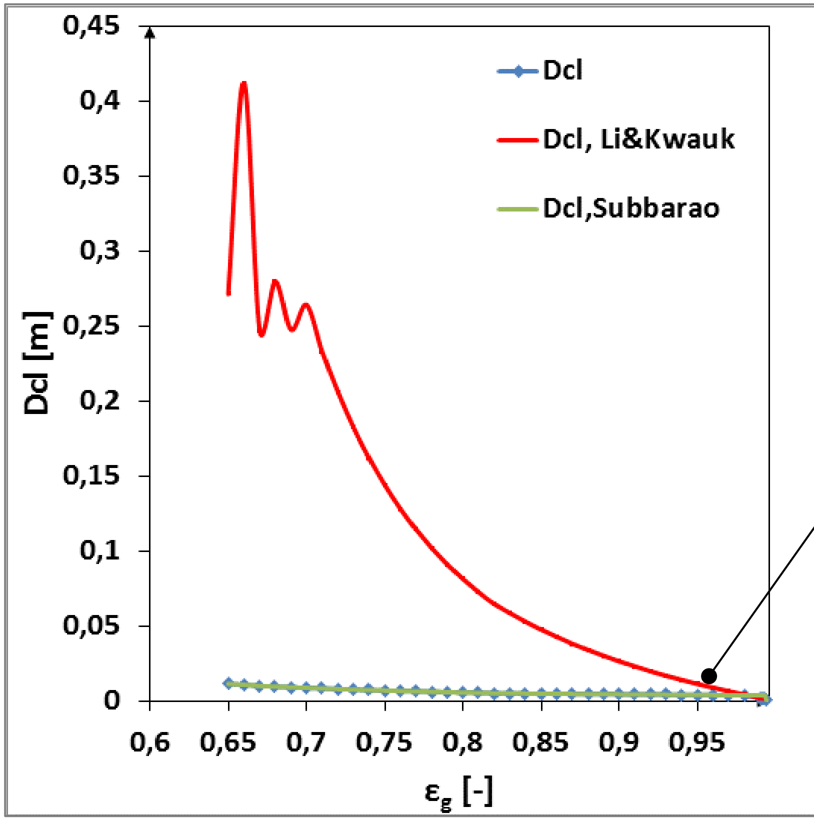
$$d_{cl} = Min(d_{cl1}, d_{cl2})\begin{cases} d_{cl1} = D_v\left(\frac{f}{1-f}\right)^{\frac{1}{2}} + d_p \quad D_v = f(D_t, u_t)^{**} \text{ Subbarao et al.} \\ d_{cl2} = dcl(Wang\,\&\,Li) \end{cases}$$

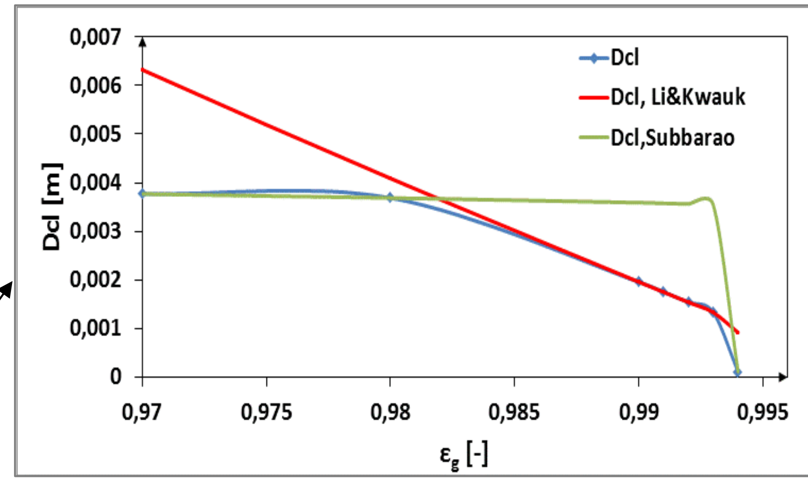
Closure equations

	Dense phase	Dilute Phase	Inter-phase
Effective drag coef.	$C_{dc} = C_{d0}\varepsilon_c^{-4.65}$	$C_{df} = C_{d0f}\varepsilon_f^{-4.65}$	$C_{Di} = C_{Doi}(1-f)^{-4.65}$
Standard drag coef.	$C_{d0c} = \frac{24}{Re_c}+\frac{3.6}{Re_c^{0.313}}$	$C_{d0f} = \frac{24}{Re_f}+\frac{3.6}{Re_f^{0.313}}$	$C_{d0i} = \frac{24}{Re_i}+\frac{3.6}{Re_i^{0.313}}$ *
Reynolds number	$Re_c = \frac{\rho_g d_p}{\mu_g}\left|U_{sc}\right|$	$Re_f = \frac{\rho_g d_p}{\mu_g}\left|U_{sf}\right|$	$Re_i = \frac{\rho_g d_{cl}}{\mu_g}\left|U_{si}\right|$
Slip velocity	$U_{sc} = U_c - \frac{\varepsilon_c\cdot U_{pc}}{1-\varepsilon_c}$	$U_{sf} = U_f - \frac{\varepsilon_f\cdot U_{pf}}{1-\varepsilon_f}$	$U_{si} = (1-f)\cdot\left(U_f - \frac{\varepsilon_f\cdot U_{pc}}{1-\varepsilon_c}\right)$
Drag force	$F_c = C_{dc}\frac{\pi d_p^2}{4}\cdot\frac{\rho_g}{2}\cdot U_{sc}\cdot\left|U_{sc}\right|$	$F_f = C_{df}\frac{\pi d_p^2}{4}\cdot\frac{\rho_g}{2}\cdot U_{sf}\cdot\left|U_{sf}\right|$	$F_i = C_{di}\frac{\pi d_{cl}^2}{4}\cdot\frac{\rho_g}{2}\cdot U_{si}\cdot\left|U_{si}\right|$
Numbers of particles or clusters	$m_c = \frac{f\cdot(1-\varepsilon_c)}{\frac{\pi d_p^3}{6}}$	$m_f = \frac{(1-f)\cdot(1-\varepsilon_f)}{\frac{\pi d_p^3}{6}}$	$m_i = \frac{f}{\frac{\pi d_{cl}^3}{6}}$

Cluster Correlation by CERTH

Implementation in TUD Carbonator (1 MW_{th})

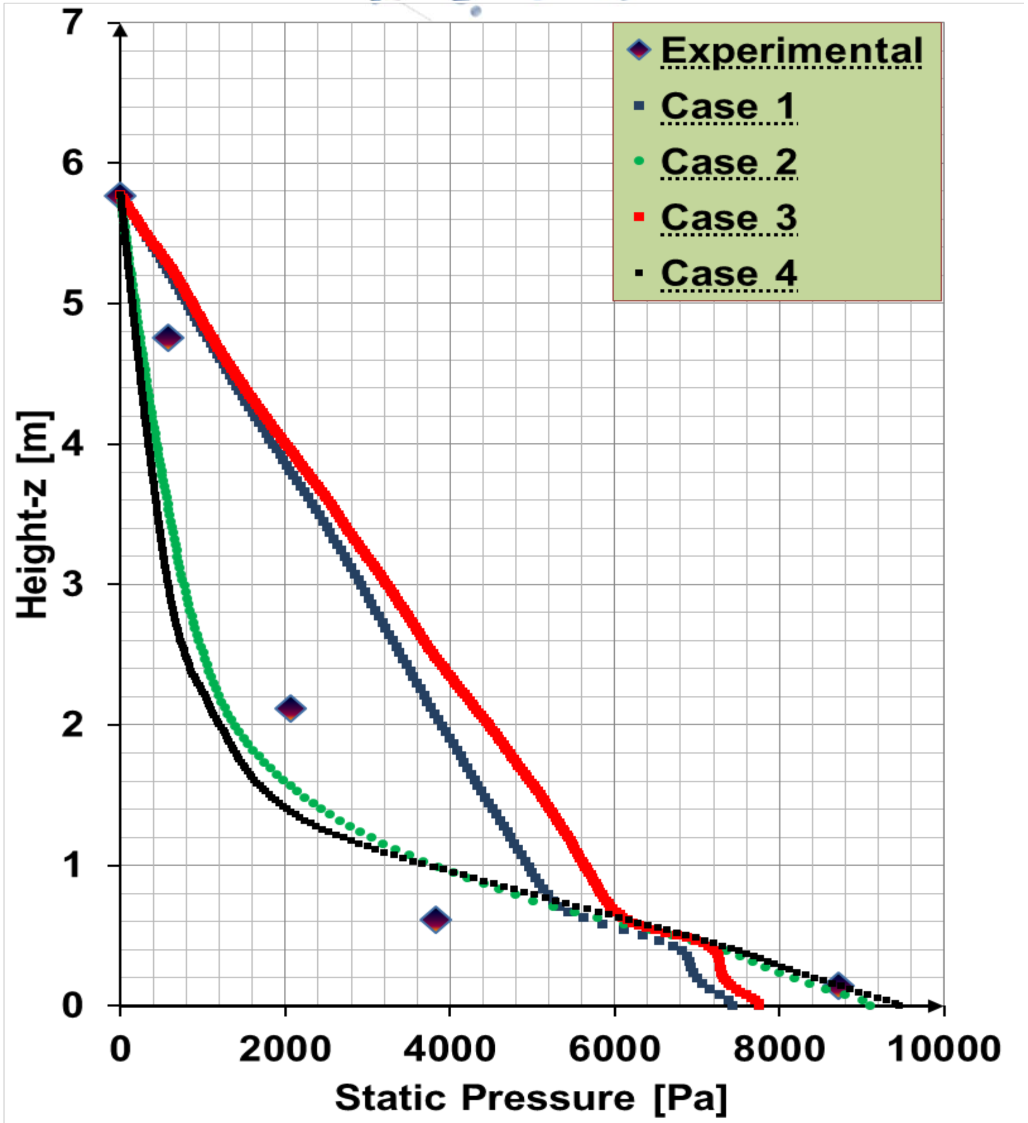




Parameter	Value
d_p, μm	91.39*
ε_{mf}, (-)	0.55
ε_{max}, (-)	0.9997
μ_g, kg $m^{-1}s^{-1}$	3.91085 $*10^{-5}$
ρ_g, kg/m^3	0.389
ρ_s, kg/m^3	1650

Cluster Correlation by CERTH

Implementation in TUD Carbonator (1 MW_{th})

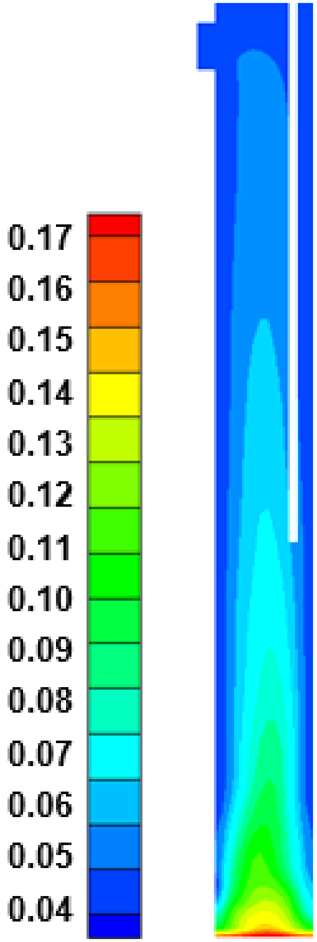


Test Case	Grid	Drag Force Model
Case 1	Coarse	Gidaspow
Case 2	Coarse	EMMS
Case 3	Dense	Gidaspow
Case 4	Dense	EMMS

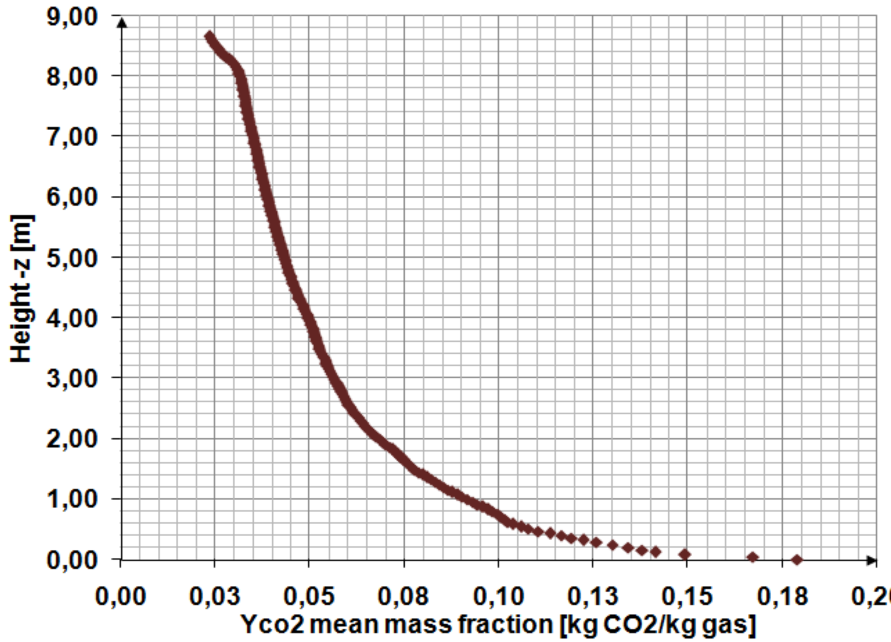
CO_2 capture Efficiency	
E_{CO2} (numerical)	85 %
E_{CO2} (experimental)	82.7 %

Cluster Correlation by CERTH

Implementation in TUD Carbonator (1 MW_{th})



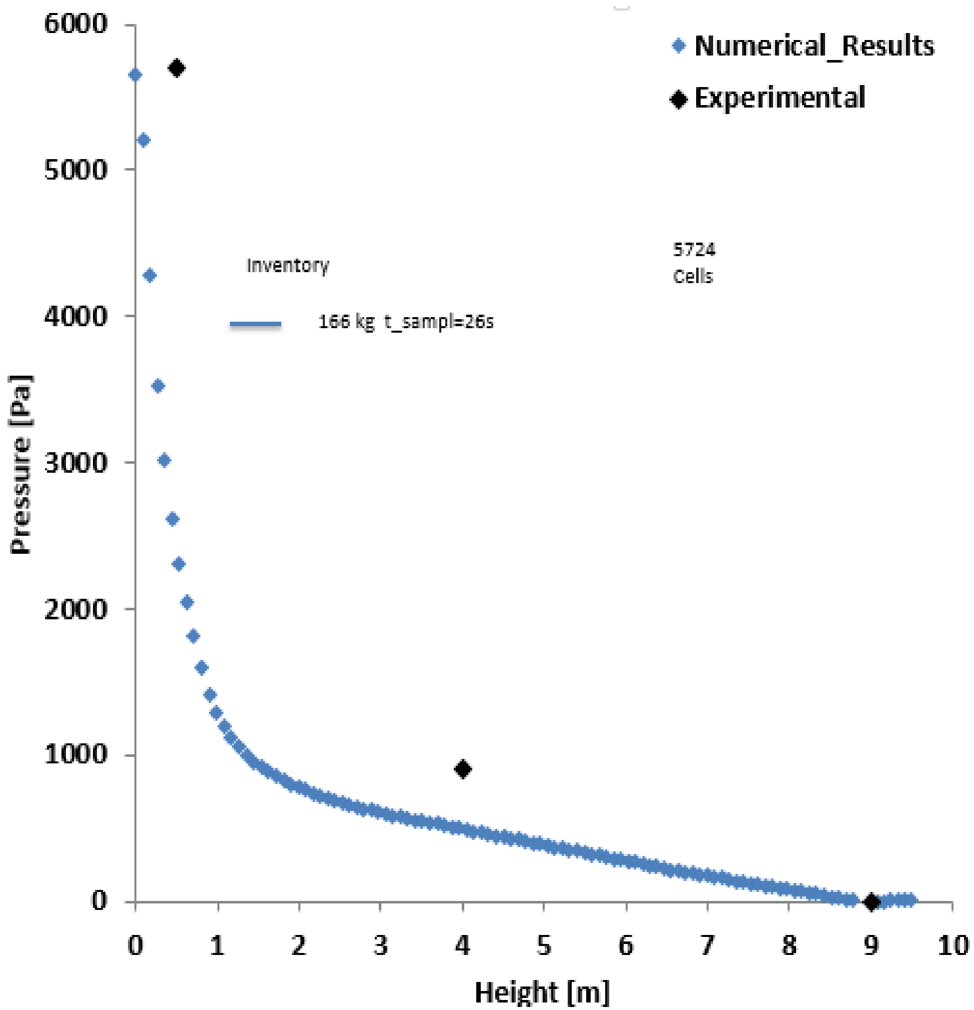
Mass weighted CO_2 mean mass fraction at plane X=0, for a time averaging equal to t_{aver}= 65 s



Mean Y_{CO2} mass fraction along the riser axis for a time averaging equal to t_{aver}= 65 s

Cluster Correlation by CERTH

Implementation in a pilot scale plant 1.2 MWth



Parameter	Value
d_p, μm	260 (Geldart B)
ε_{mf}, (-)	0.55
ε_{max}, (-)	0.9997
μ_g, kg $m^{-1}s^{-1}$	4.2277 10^{-5}
ρ_g, kg/m^3	0.3068
ρ_s, kg/m^3	2600

Gas-solid properties

Concluding Remarks

- The accurate prediction of the **cluster size** is a critical issue and still under research
- The cluster correlation proposed by CERTH is a combination of Subbarao and Li and Kwauk correlations
- The correlation has been implemented in the EMMS model coupled with the TFM
- After some simulation tests in **two units**, the numerical results concerning the pressure profile distribution are quite promising

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Thank you for your attention!!!!.

Questions ????

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Appendix

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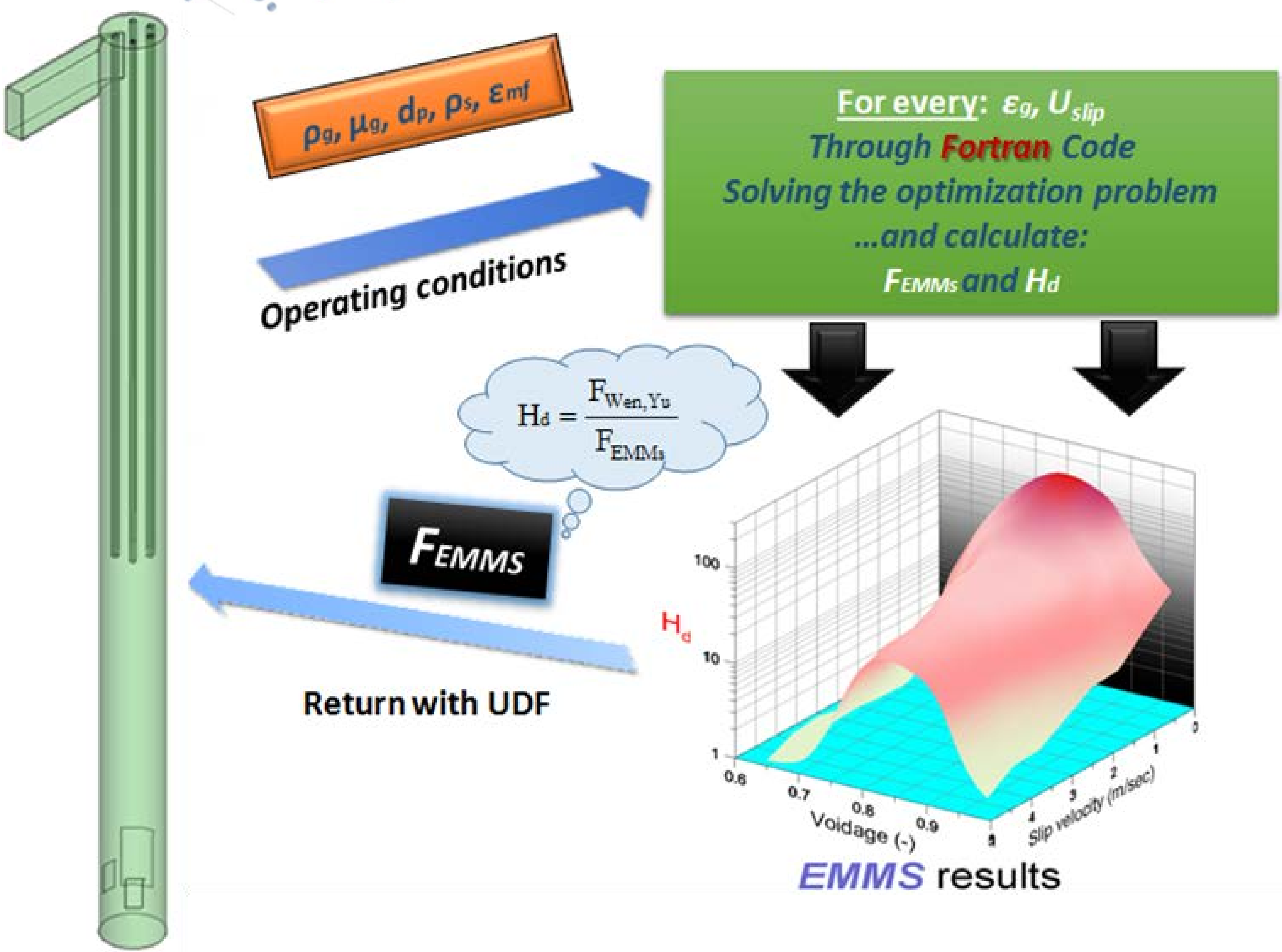
$\rho_g, \mu_g, d_p, \rho_s, \varepsilon_{mf}$
Operating conditions
For every: ε_g, U_{slip}
Through Fortran Code
Solving the optimization problem
...and calculate:
F_{EMMs} and H_d
$H_d = \frac{F_{Wen,Yu}}{F_{EMMs}}$
F_{EMMS}
Return with UDF
H_d
100
10
1
0.6
0.7
0.8
0.9
Voidage (-)
Slip velocity (m/sec)
EMMS results