Modelling Powder Flow Into a Confined Space

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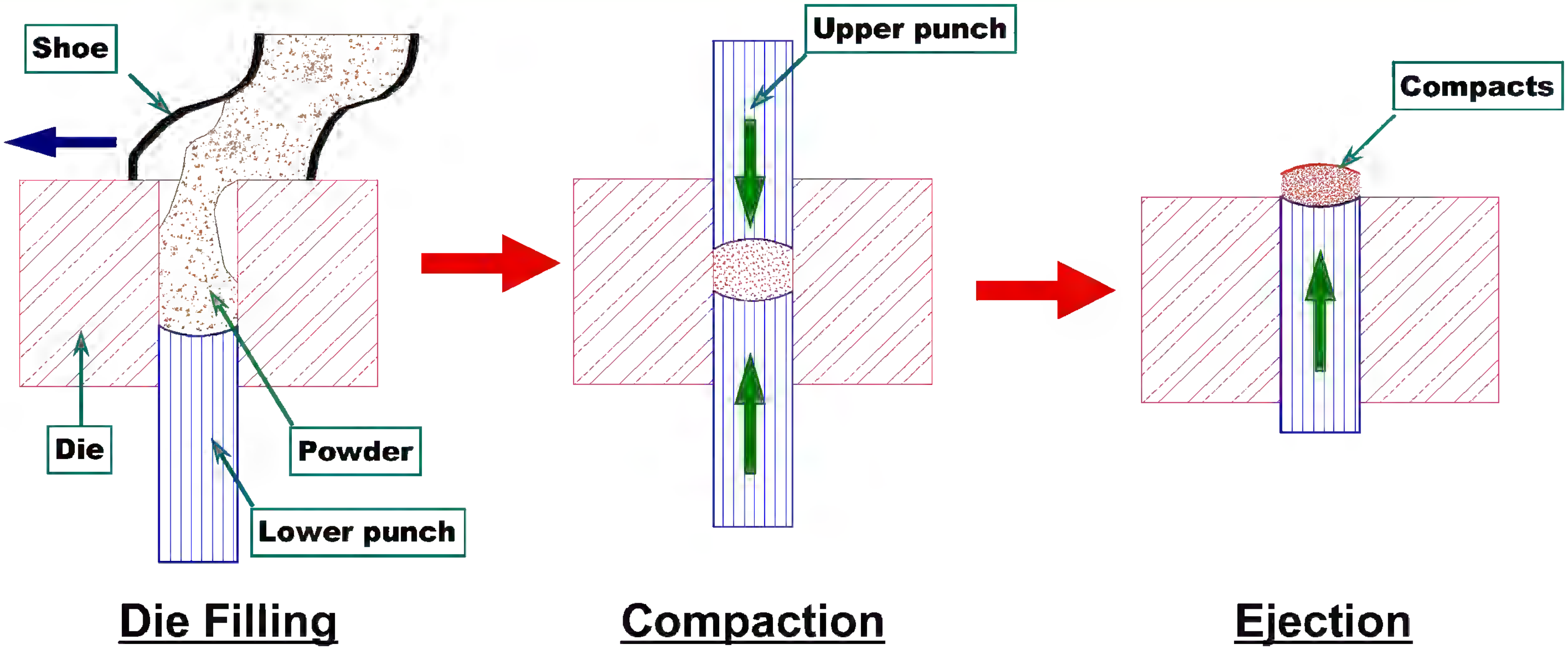
Introduction

Many products are manufacturing through compaction of dry powders, involving powder flow into a confined space.

- Pharmaceutical
- Catalyst
- Automotive
- Chemical
- Ceramic
- Magnetic
- Food

Typical Manufacturing Process



Why Die Filling Is Important?

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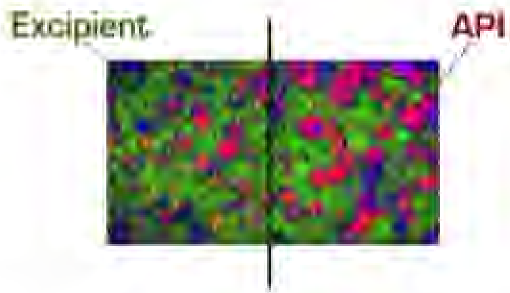
Any problem during die filling will have a direct impact on the quality of the final products.

Failure during die filling can lead to

- Tablets of inaccurate dose!
- Products with large weight variation
- Products with non-uniform contents that detrimentally affect the functionality
- Gears of uneven strength and with weakest links.
- Distortion (and complete failure) during subsequent processes, such as sintering.



"If your doctor prescribed half a tablet a day, which half would you want to take? " (Malvern Instruments, 2008).

Methodology (Exp. + Modelling)

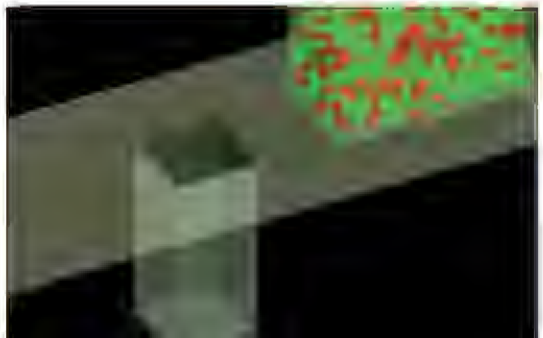
- A combined experimental and numerical approach was employed to understand the die filling process.

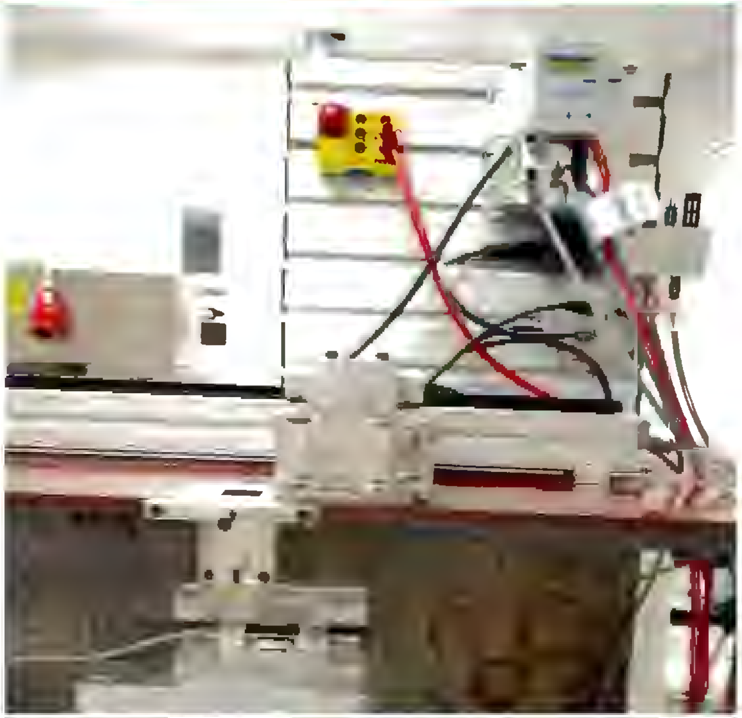
- A model die filling system was developed.

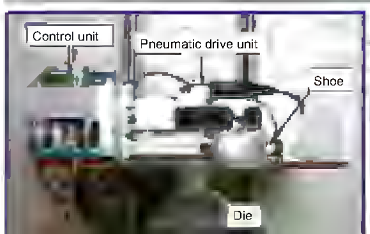
- Die filling behaviour was visualised using a high speed video system.

- Quantitative analysis was also performed using
  - PEPT -> particle velocity
  - A pressure sensor -> time evolution of deposited mass.
  - An air pressure sensor -> air pressure build-up

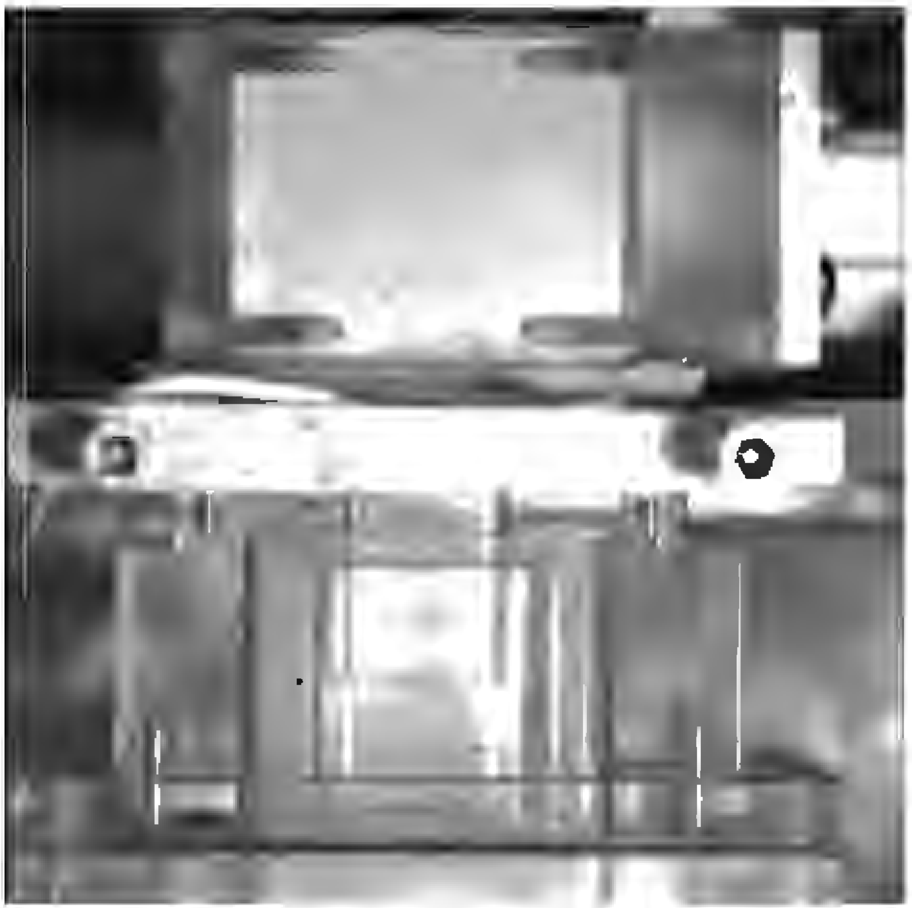
- Mechanistic analysis was performed using DEM-CFD



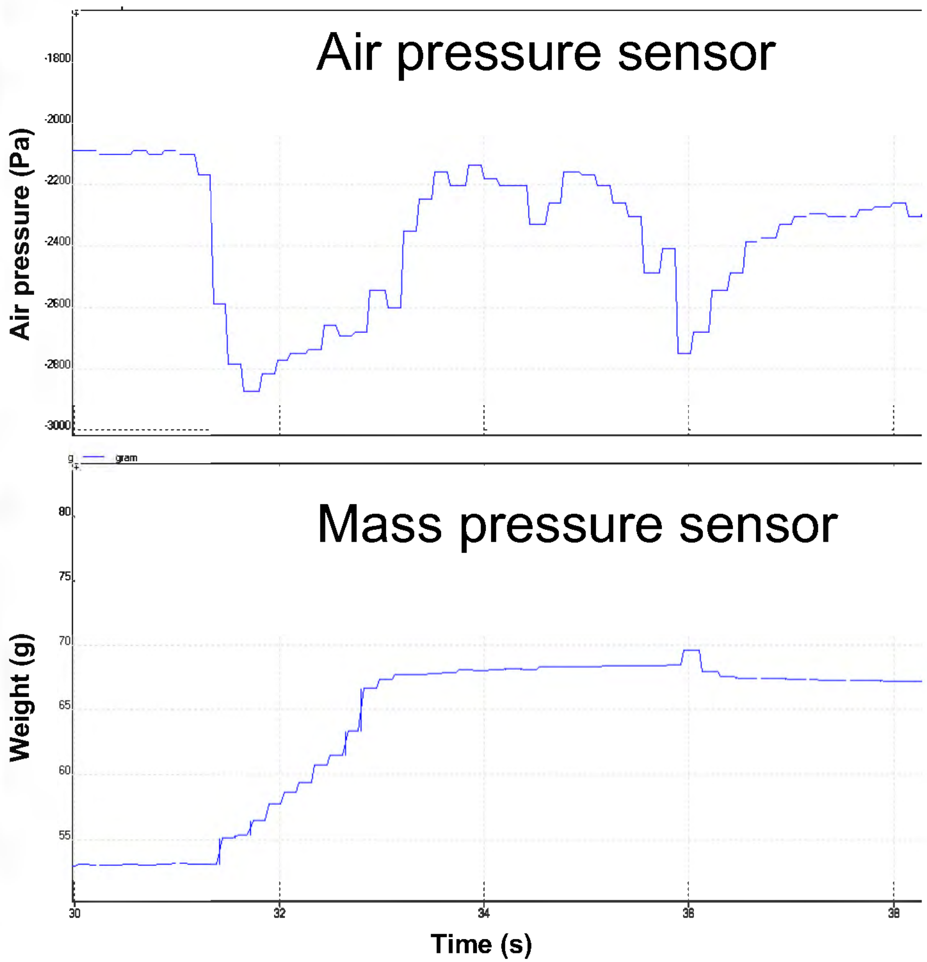




A typical experimental set-up



High speed video



PEPT Study
(Positron Emission Particle Tracking)

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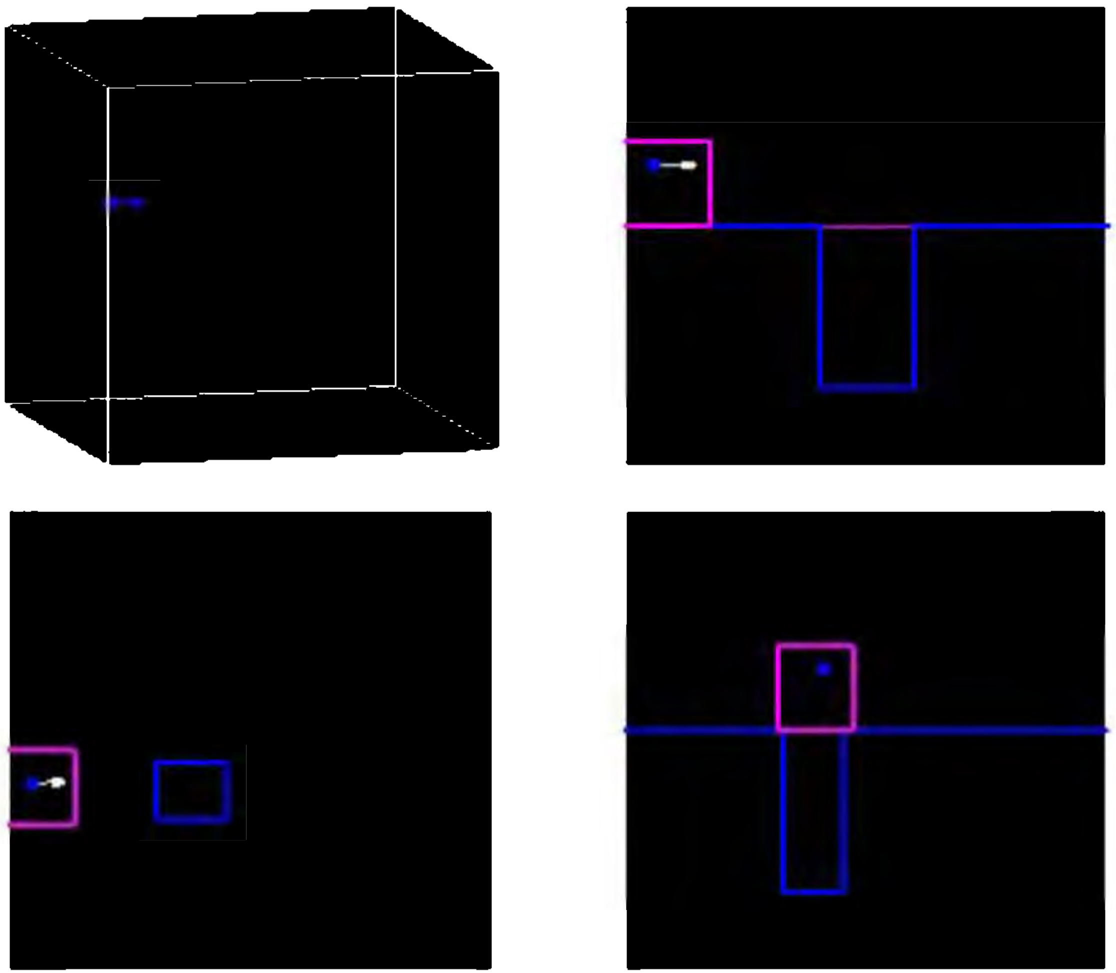
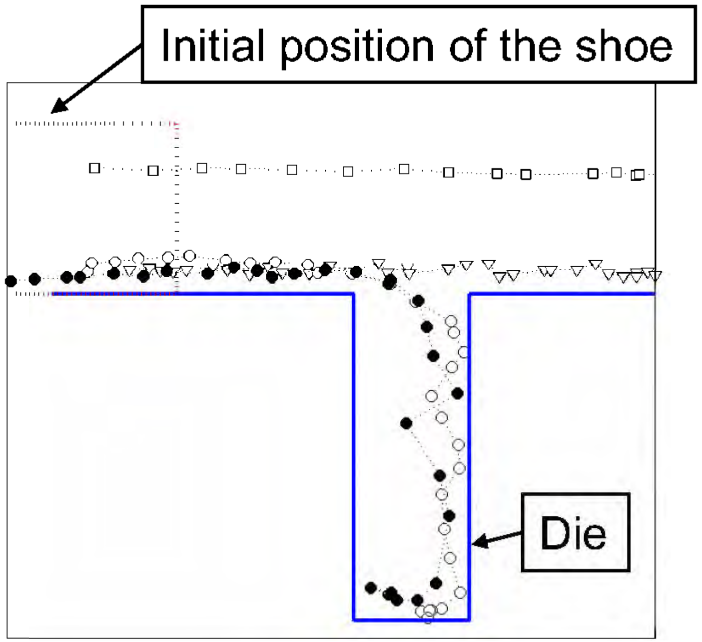
PEPT Study

3D trajectories of individual particles

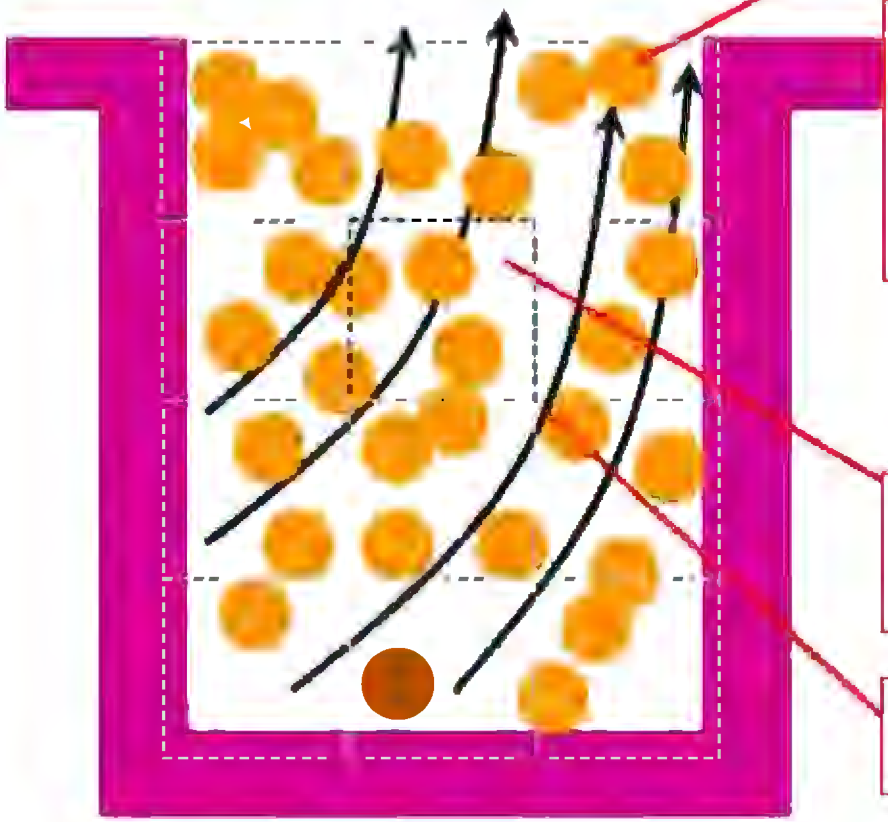
Spherical microcrystalline cellulose (Celphere, CP102)





Wu, C.-Y., X.F. Fan, F. Motazedian, J.P.K. Seville, D.J. Parker, A.C.F. Cocks, (2010). A Quantitative Investigation of Powder Flow during Die Filling Using Positron Emission Particle Tracking (PEPT). *Proceedings of the Institution of Mechanical Engineers, Part E, Journal of Process Mechanical Engineering.* 224(3): 169-175.

DEM-CFD



The flow of particles is modelled using <u>DEM.</u>

The interaction between particles are rigorously modelled using theoretical contact mechanics:

- <u>Hertz-Mindlin-Deresiewicz</u> for elastic particles
- <u>JKR</u> for adhesive particles

The interaction between air and particles is considered.

The flow of air is modelled using <u>CFD.</u>

Particle equations of motion:

$$F_i = F_i^c + F_i^{fp} + F_i^e + m_i g = m_i \ddot{x}_i$$

$$T_i = I_i \ddot{\theta}_i$$

fluid-particle interaction force

$$F_i^{fp} = -V_{pi}\nabla p + V_{pi}\nabla \cdot \boldsymbol{\tau}_f + \varepsilon f_{di}$$

Total fluid-particle interaction force per unit volume

$$F_{fp} = \frac{\sum_{i=1}^{n} F_i^{fp}}{\Delta V_c}$$

Fluid continuity and momentum equations

$$\frac{\partial(\varepsilon\rho_f)}{\partial t} + \nabla \cdot (\varepsilon\rho_f \boldsymbol{u}) = 0$$

$$\frac{\partial(\varepsilon\rho_f \boldsymbol{u})}{\partial t} + \nabla \cdot (\varepsilon\rho_f \boldsymbol{uu}) = -\nabla p_f + \nabla \cdot \tau_f + F_{fp} + \varepsilon\rho_f g$$

DEM-CFD Validation

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- ❑ Validation of DEM models is important.
- ❑ Qualitatitive validation is easy, is it convincing?
- ❑ Case-to-case quantitative validation is difficult.

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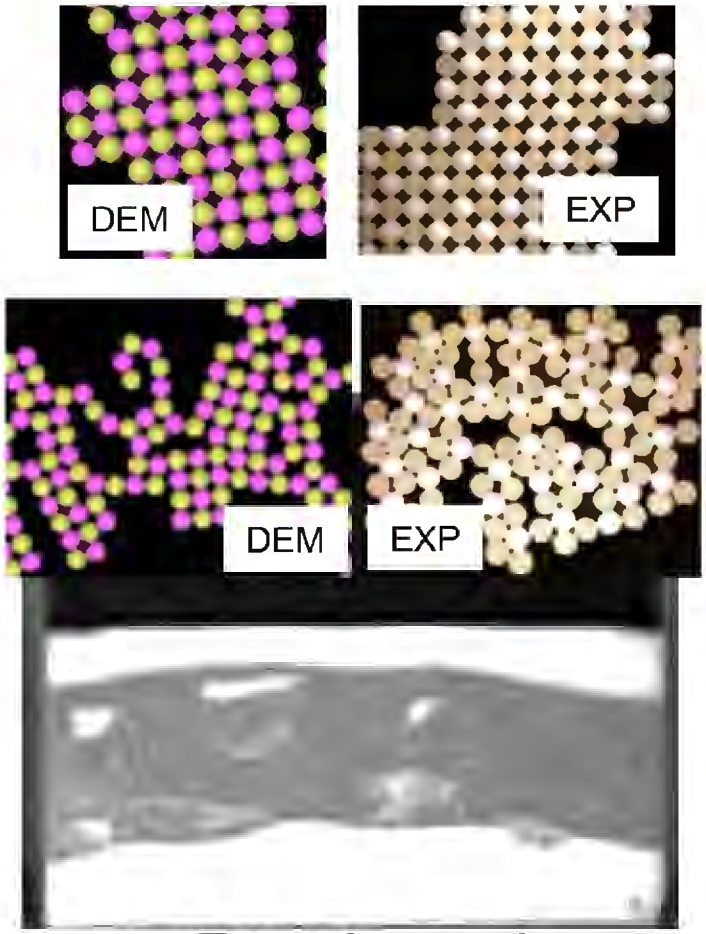
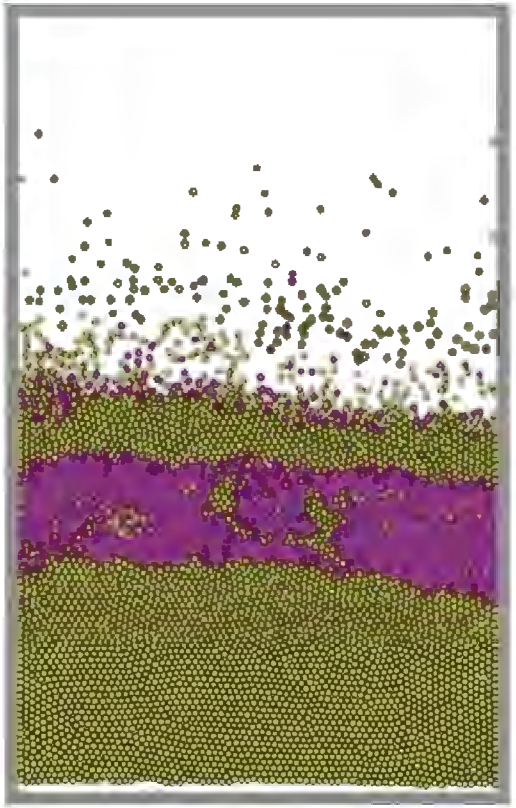


Experimental



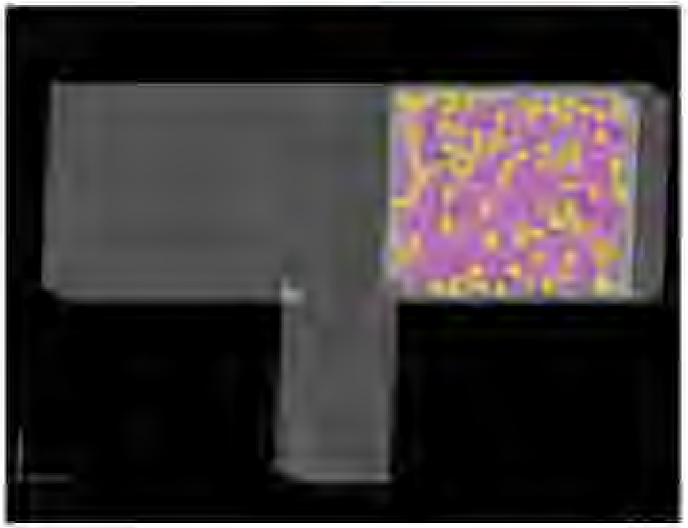
DEM-CFD

[redacted]

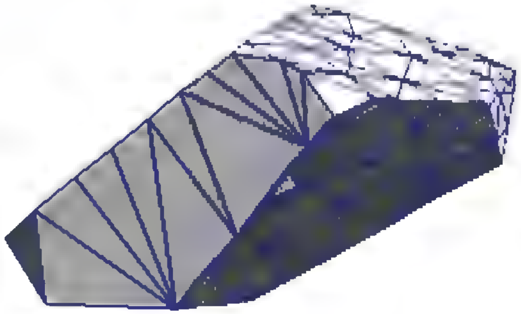
Guo Y, Wu C-Y, Thornton C. (2013) Modeling Gas-Particle Two-Phase Flows with Complex and Moving Boundaries using DEM-CFD with an Immersed Boundary Method. *AICHE JOURNAL*, 59 (4), pp. 1075-1087

DEM-CFD with Non-spherical Particles

- Multi-sphere -> approximate particle shapes using clumped spheres.
- Utilize the rigorous contact laws for modelling particle-particle interaction

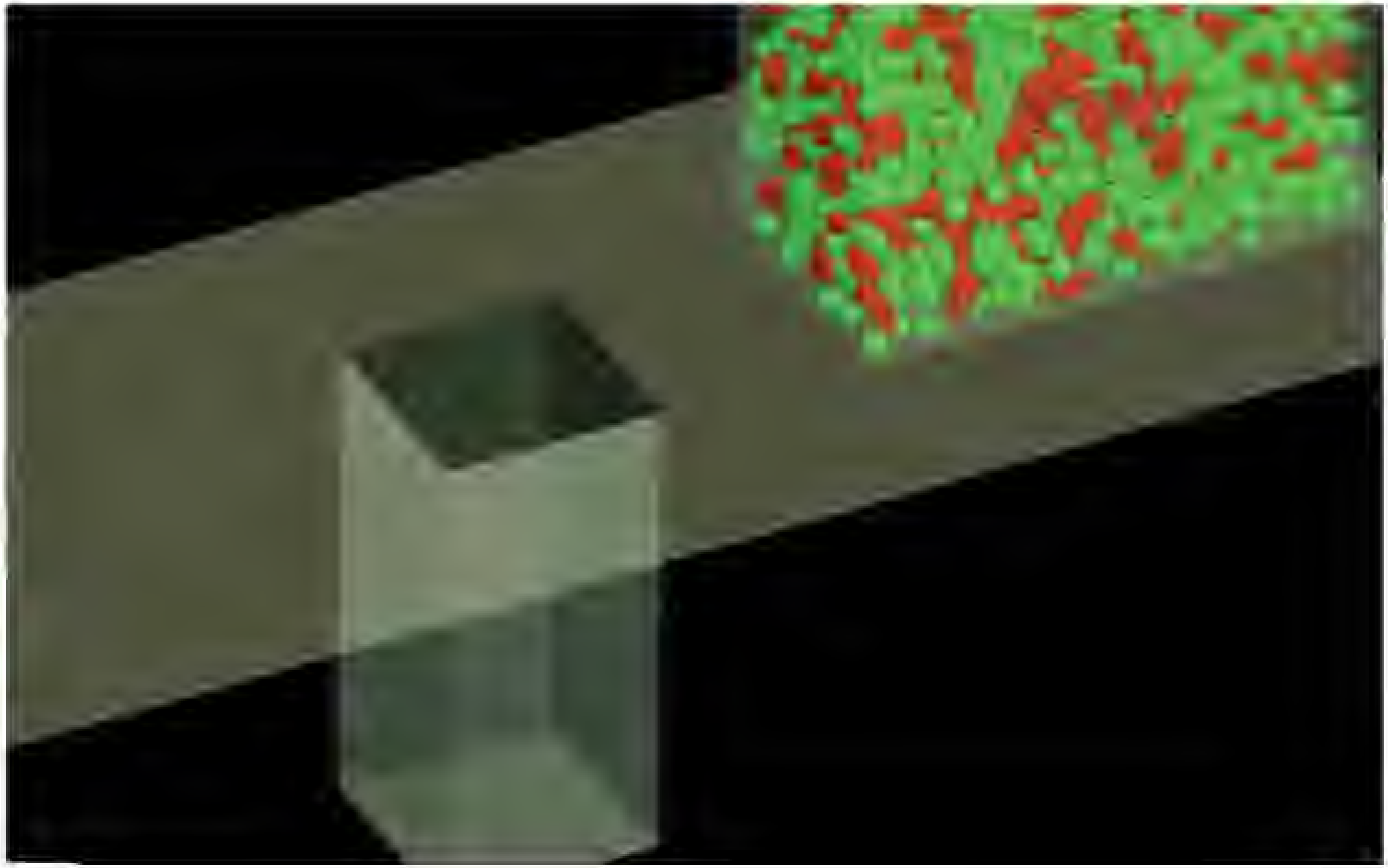


Die filling with real particles (Wu et al. 2016)

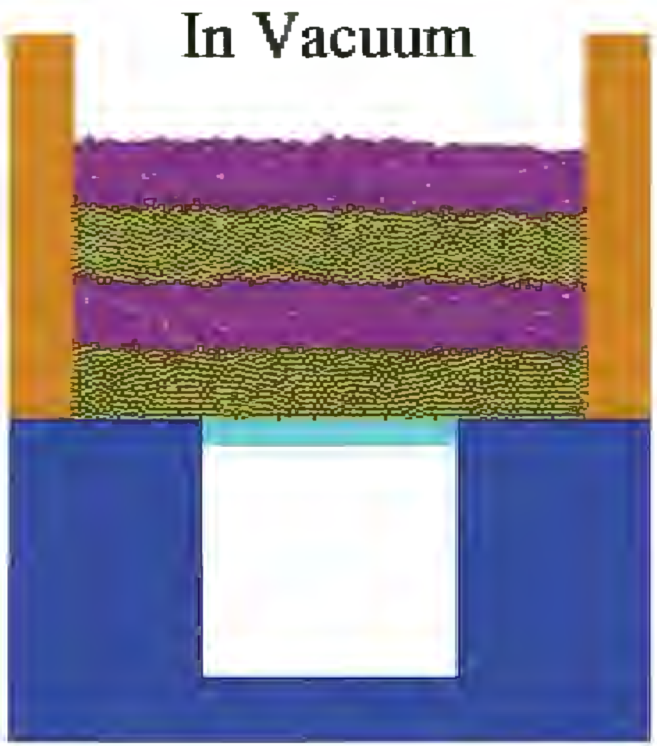


Real crystal

DEM approximation

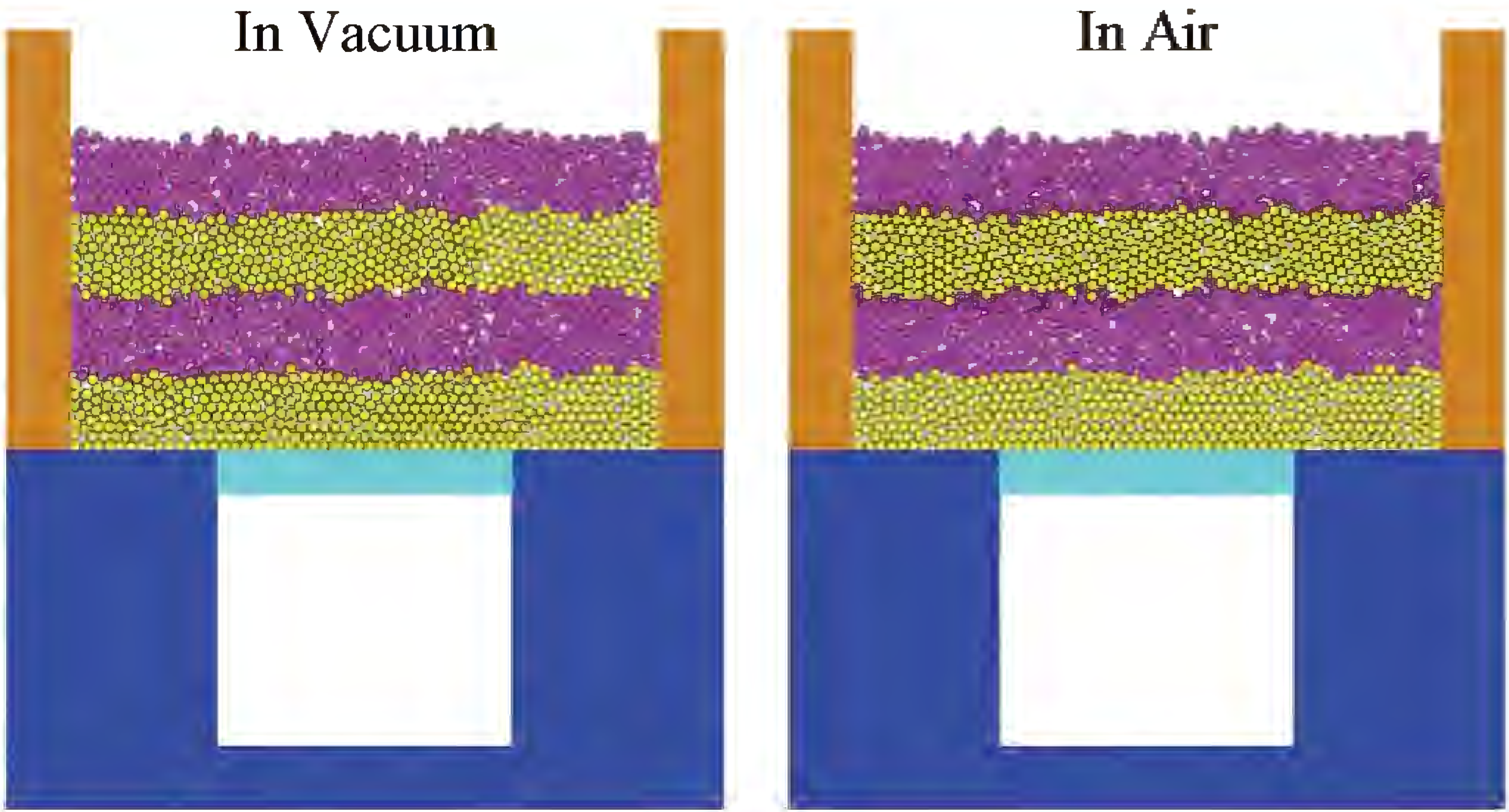


Flow from a stationary feeder



$$\rho_s = 1500 \text{ kg/m}^3, \; d_p = 50 \; \mu\text{m}$$

Flow from a stationary feeder



Flow from a stationary feeder

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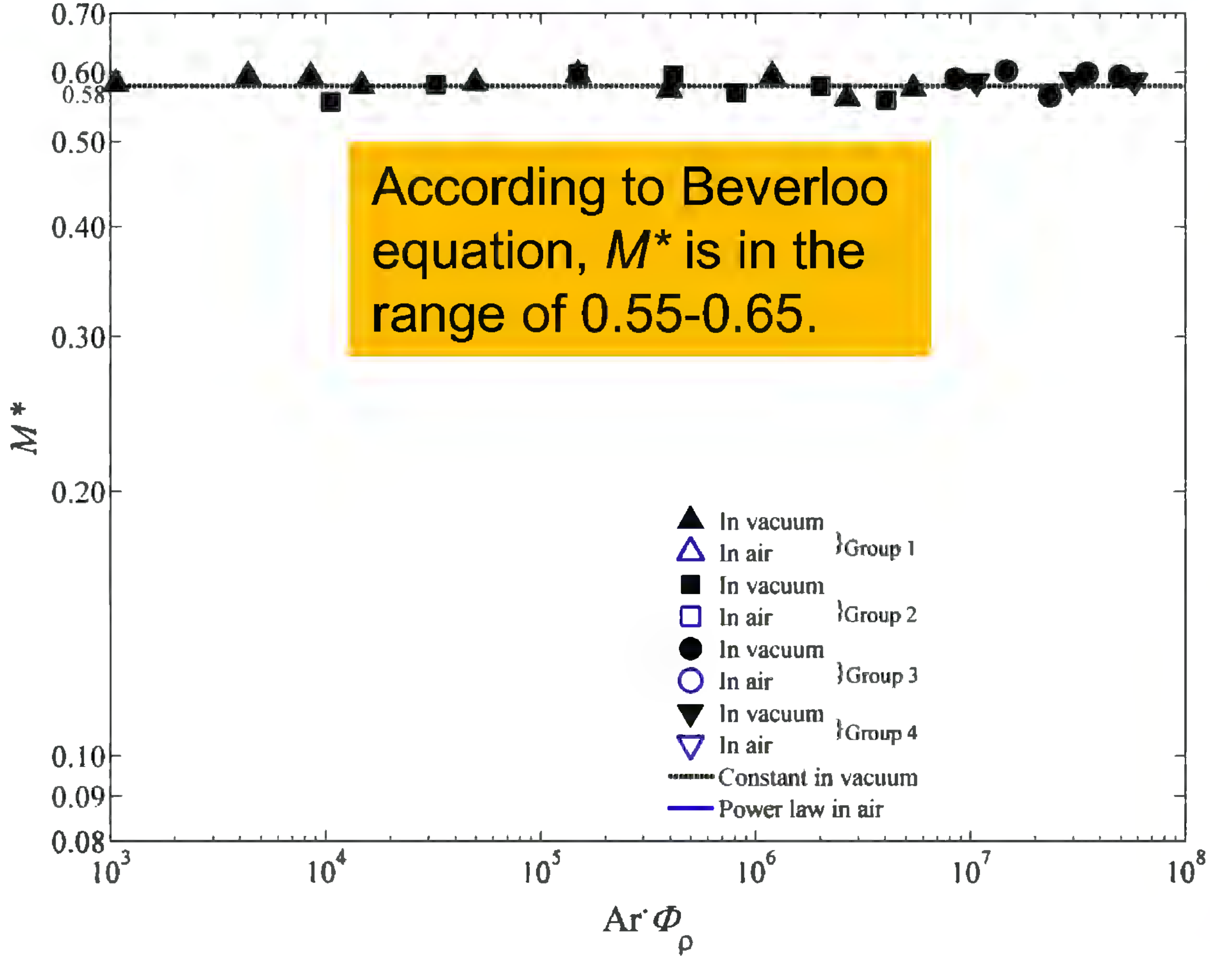


According to Beverloo equation, *M** is in the range of 0.55-0.65.

Normalised mass flowrate

$$M^* = \frac{\overline{M}}{\rho_b g^{1/2} b^{3/2} l}$$

Normalised particle density

$$\Phi_\rho = \frac{\rho_s}{\rho_a}$$

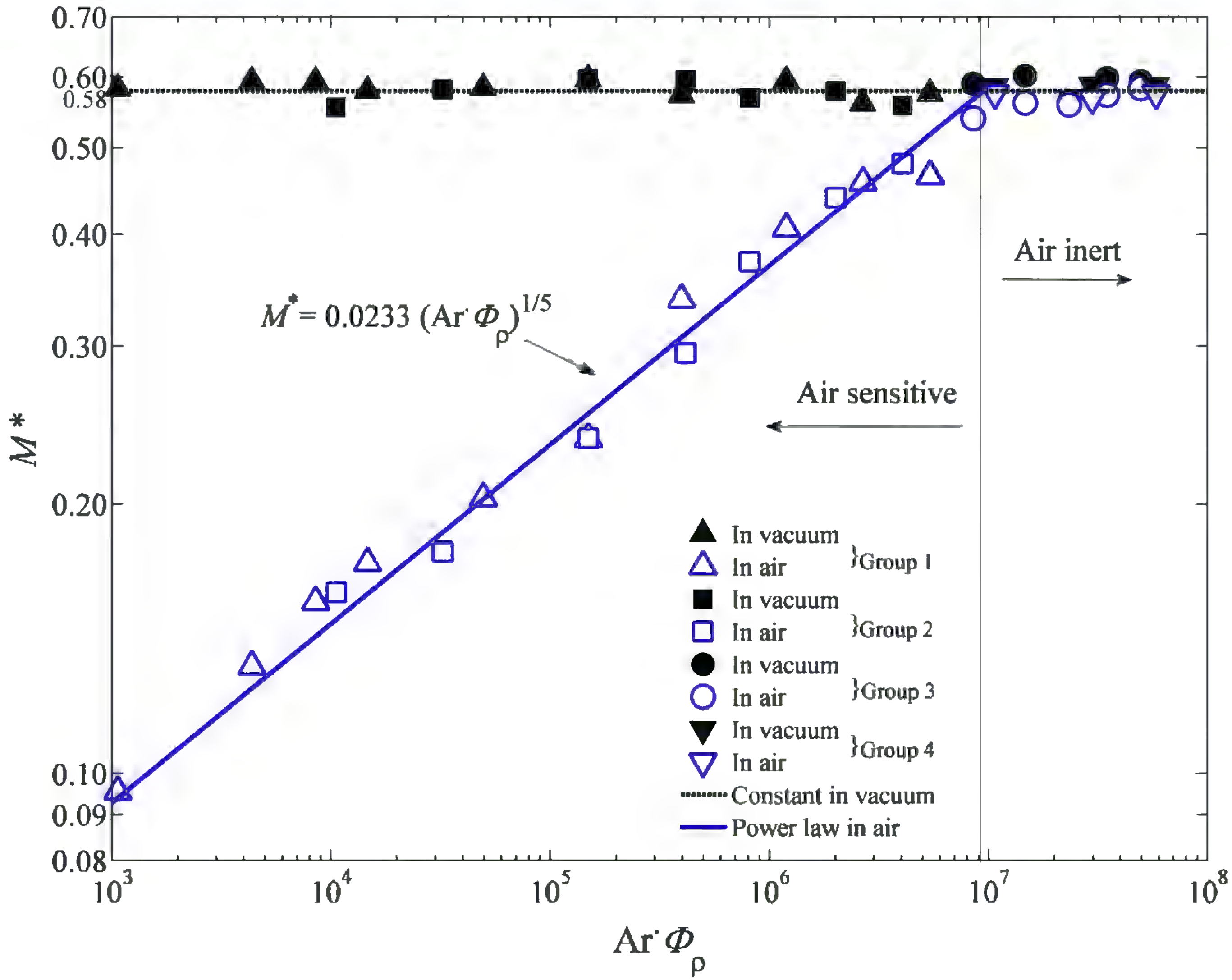
Archimedes Number

$$A_r = \frac{\rho_a(\rho_s - \rho_a) g d_p^3}{\eta^2}$$

- This is in excellent agreement with Berveloo constants obtained experimentally (*C* is in the range of 0.55-0.65, for spherical particle C≈0.58, see Seville et al. 1997).

Guo Y., Kafui K.D., **Wu C.Y.**, Thornton C. and Seville J.P.K., (2009), A coupled DEM/CFD analysis of the effect of air on powder flow during die filling. *AIChE Journal*, 55 (1): 49-62.

Flow from a stationary feeder



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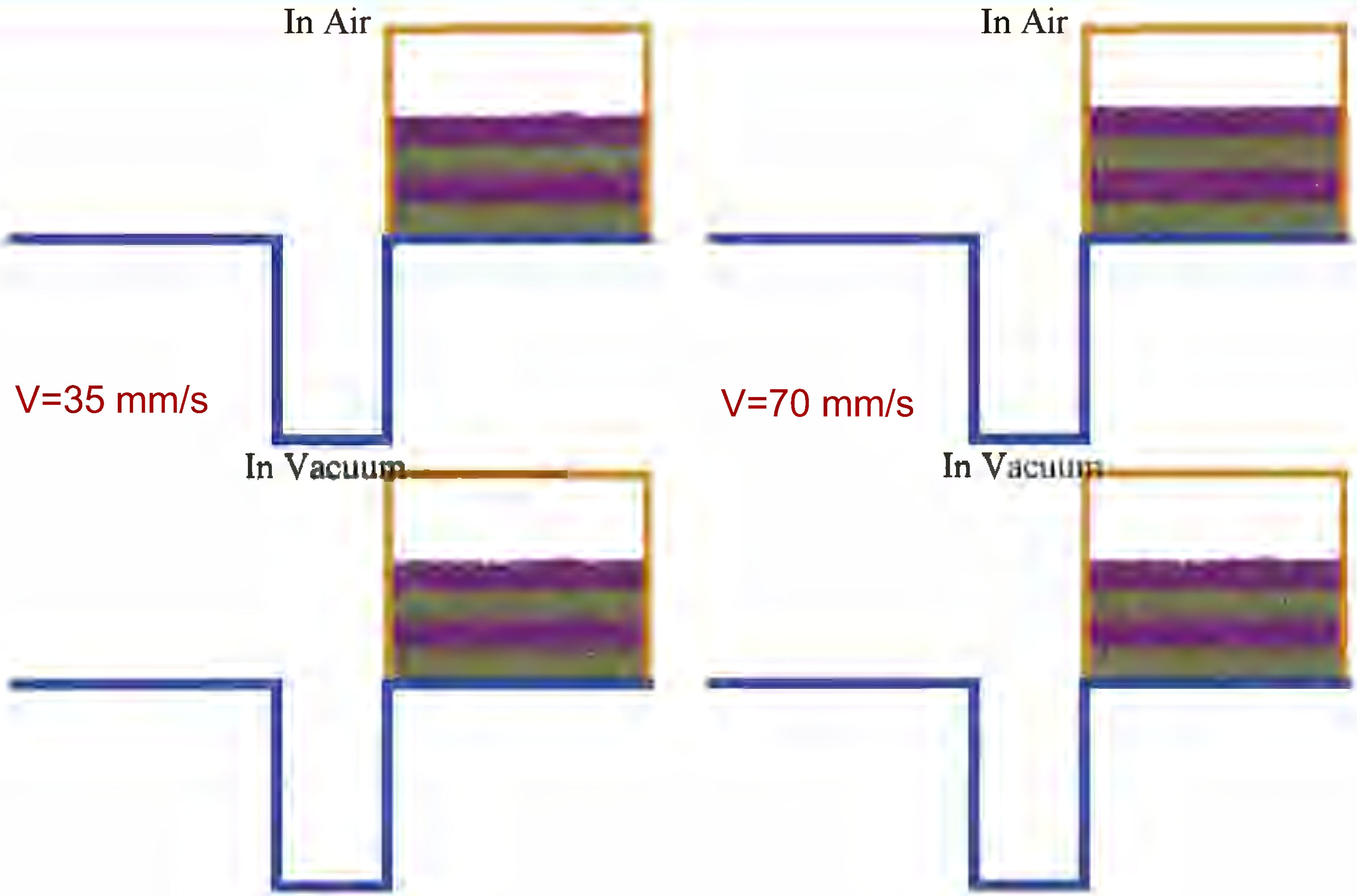
Flow from a moving feeder

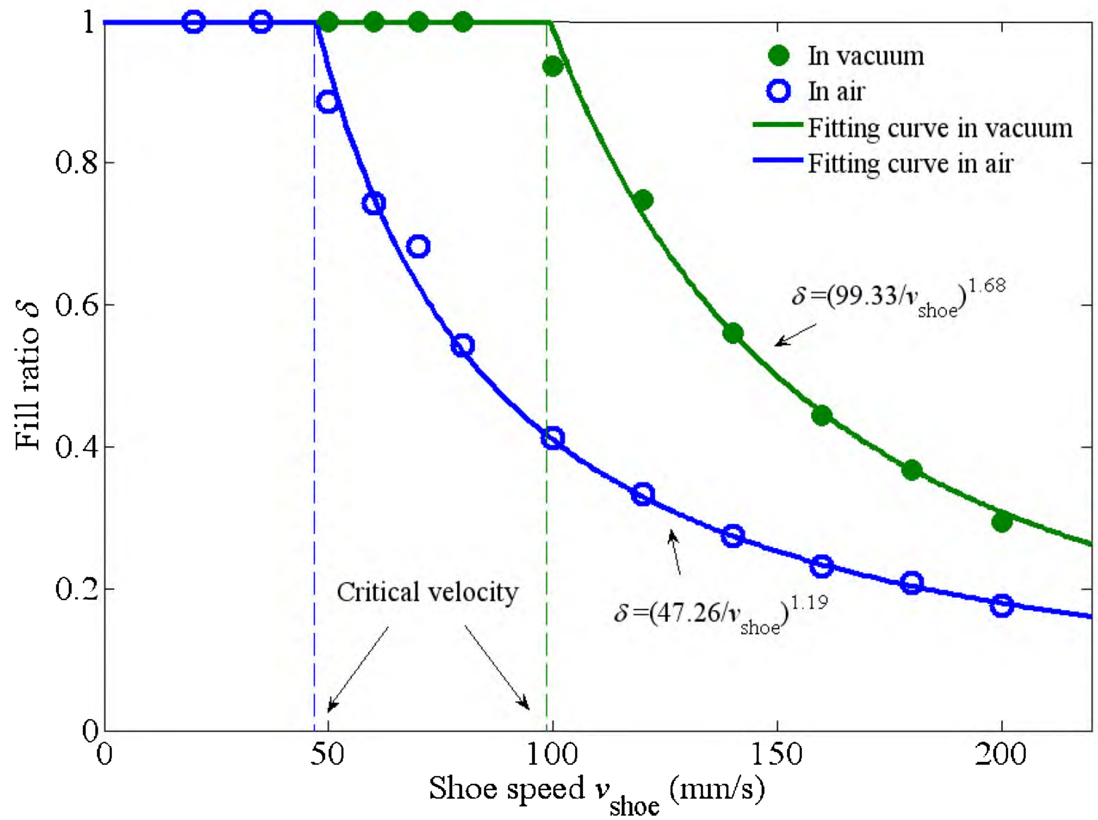
(Fine sand, V_{shoe}=300 mm/s)

(MCC, V_{shoe}=50 mm/s)

Flow from a moving feeder

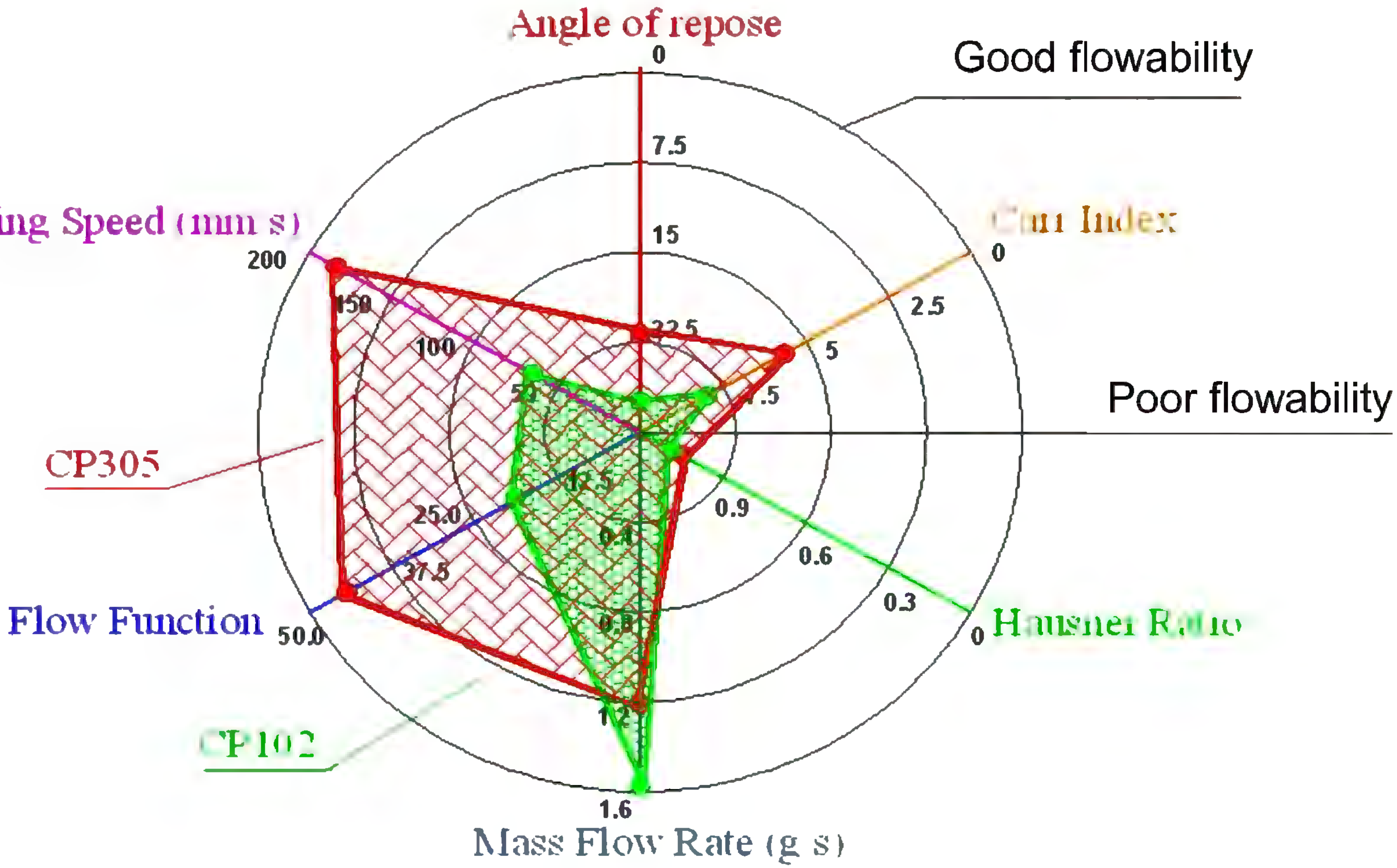


Flow from a moving feeder

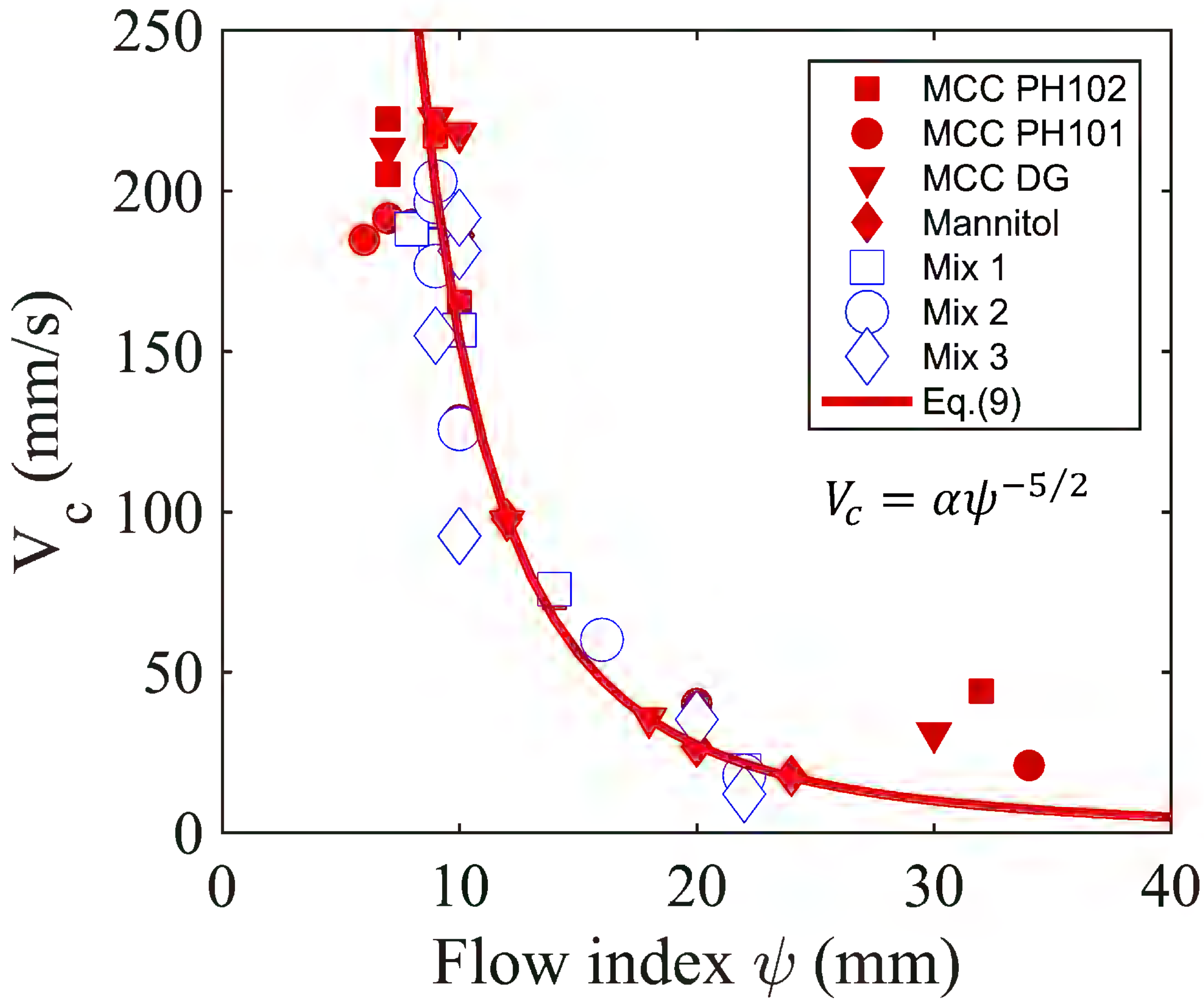


- There is a critical filling speed during die filling, above which the die cannot be completely filled.
- The critical filling speed is a function of powder properties, and process system parameters
- For a given process system, the critical filling speed is dominated by powder properties. This can also be used to assess powder flowability.

Flow from a moving feeder



Flow from a moving feeder



A Mathematical Model for Die Filling

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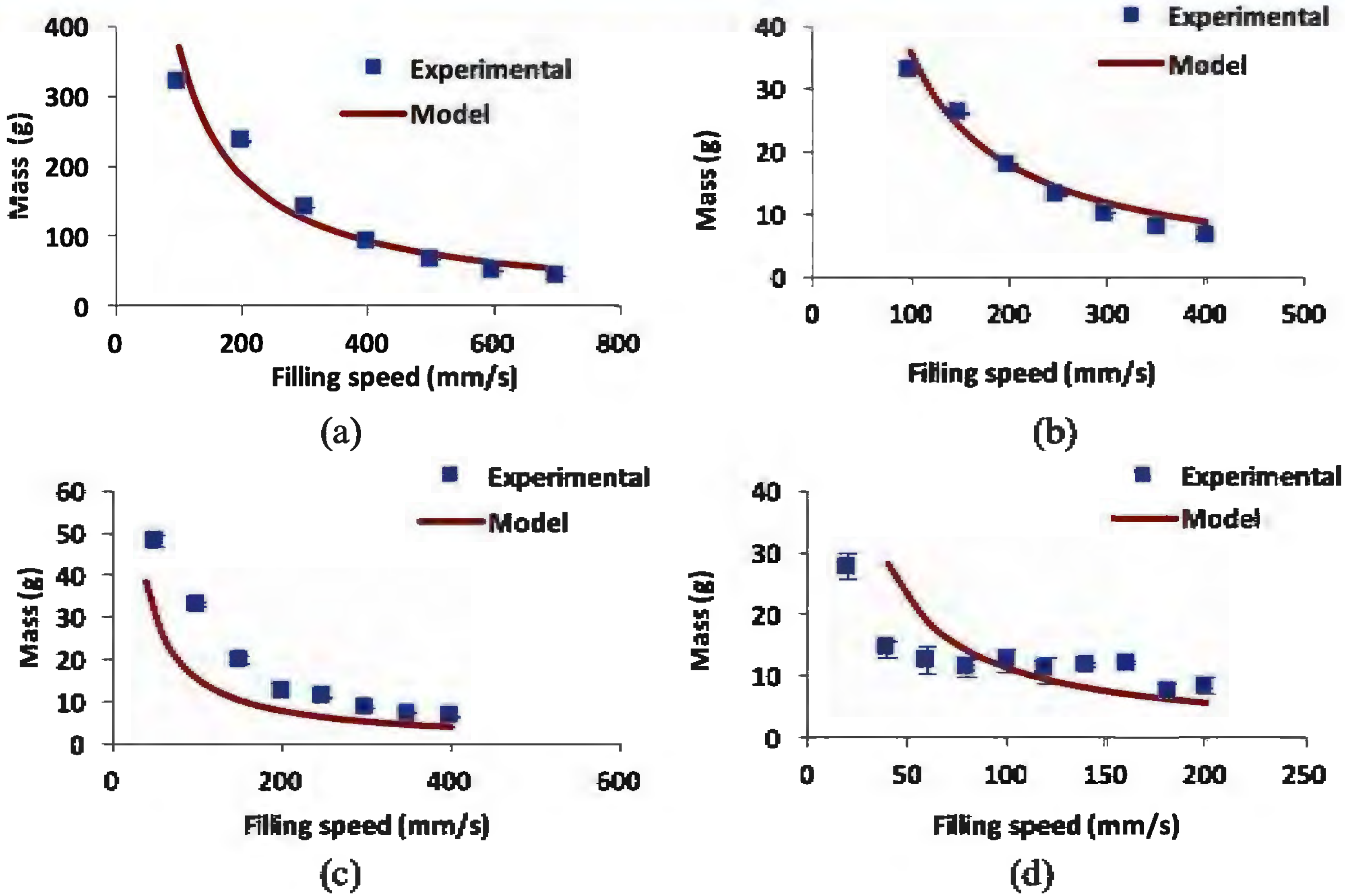

The variation of the ***deposited mass*** *with the filling speeds for a) Silibeads 300; b) Cenopheres 500; c) Mannitol and d) Alumina 4.*

A Mathematical Model for Die Filling

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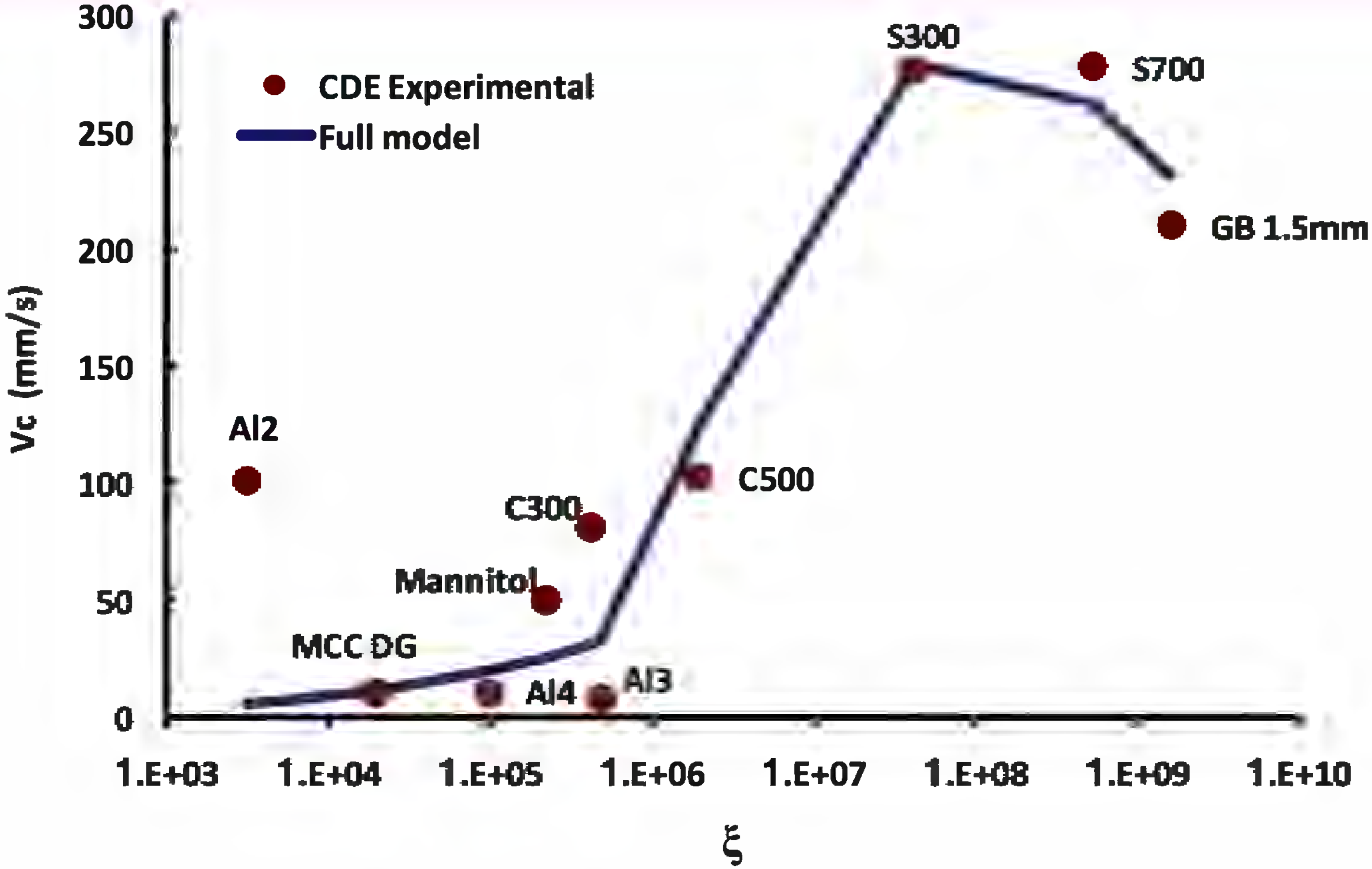
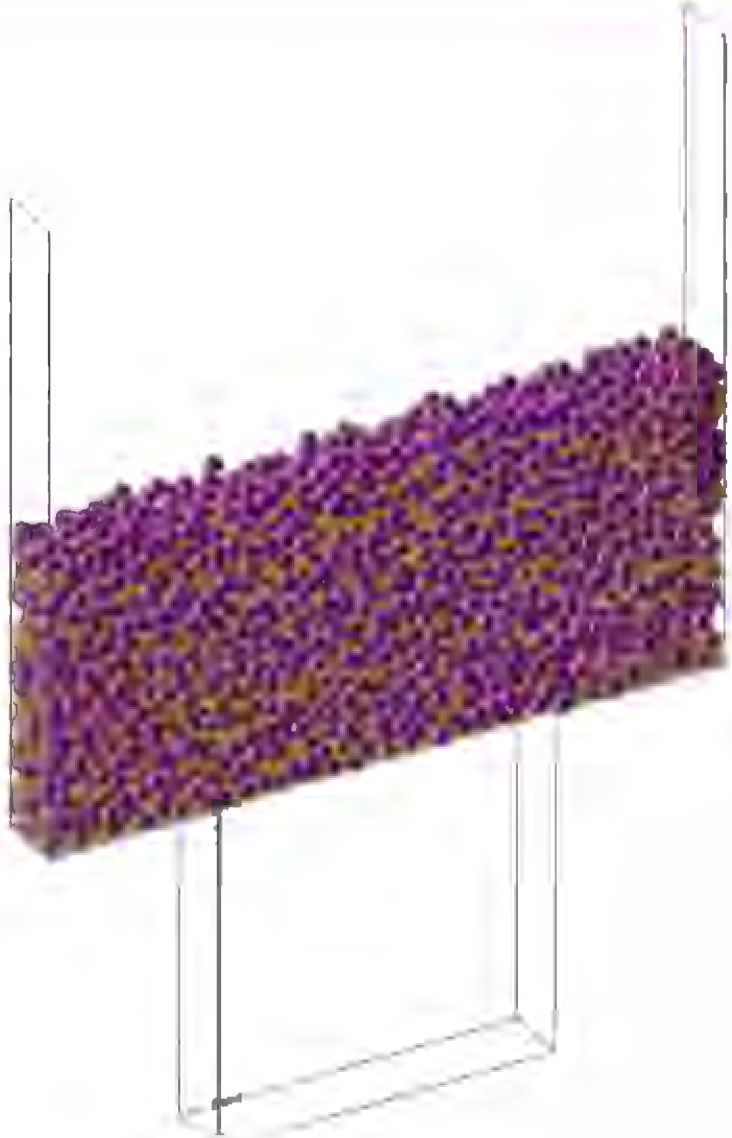


*The **critical filling speed** obtained in the closed die experiments as a function of* ξ $(=Ar.\phi)$

$$Ar = \frac{\rho_a \rho_s g d_p^3}{\eta^2} \qquad \Phi = \frac{\rho_p}{\rho_a}$$

Conclusions

- Powder into a confined space depends upon powder properties, die geometry and filling conditions.
- The influence of air presence can be significant.
- DEM-CFD is capable of capturing the major features during die filling.
- Critical filling speed could be used to characterise powder flowability.
- Based on air sensitivity classification obtained by Guo et al. (2010), a model was developed to predict the deposited mass and the critical filling speed.



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