Influence of Interparticle Forces on Powder Behaviour

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RSC Meeting

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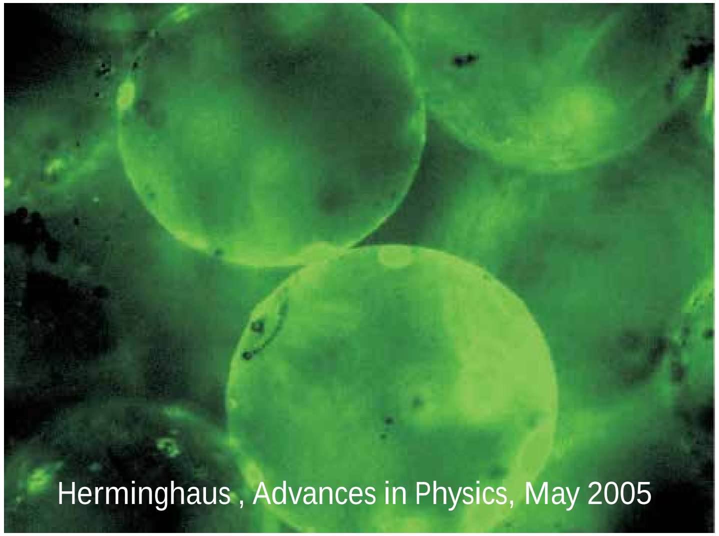
Interparticle Forces



Capillary Forces

Due the presence of liquid →liquid bridges
Capillary condensation from a vapour,
Or by addition of non-volatile liquid.

Static component by Kelvin and Laplace-Young equations

Roughness scale rather than particle size may dictate the capillary forces.

Also a dynamic component important in some cases.

Interparticle Forces

Van der Waals Forces

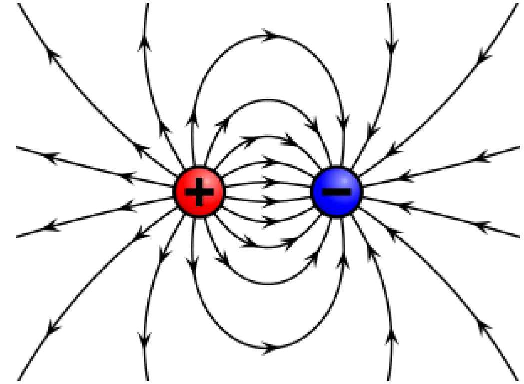
§ Forces arising between molecules
§ Always present
§ Decay as separation squared

Inter-sphere Van der Waals force $$F_{vdw} = \frac{AR}{12a^2}$$

R depends on surface roughness rather than particle diameter

Hamaker constant , *A*, dependent on the material

Interparticle Forces



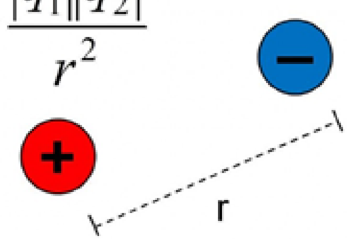
Electrostatic Forces

§ Tribo-electric charging of the particle surface
§ Repulsion between like charges
§ Attraction between opposite charges
§ Both can change powder behaviour

In mixtures of sizes, smaller particles gain opposite charge to larger particles

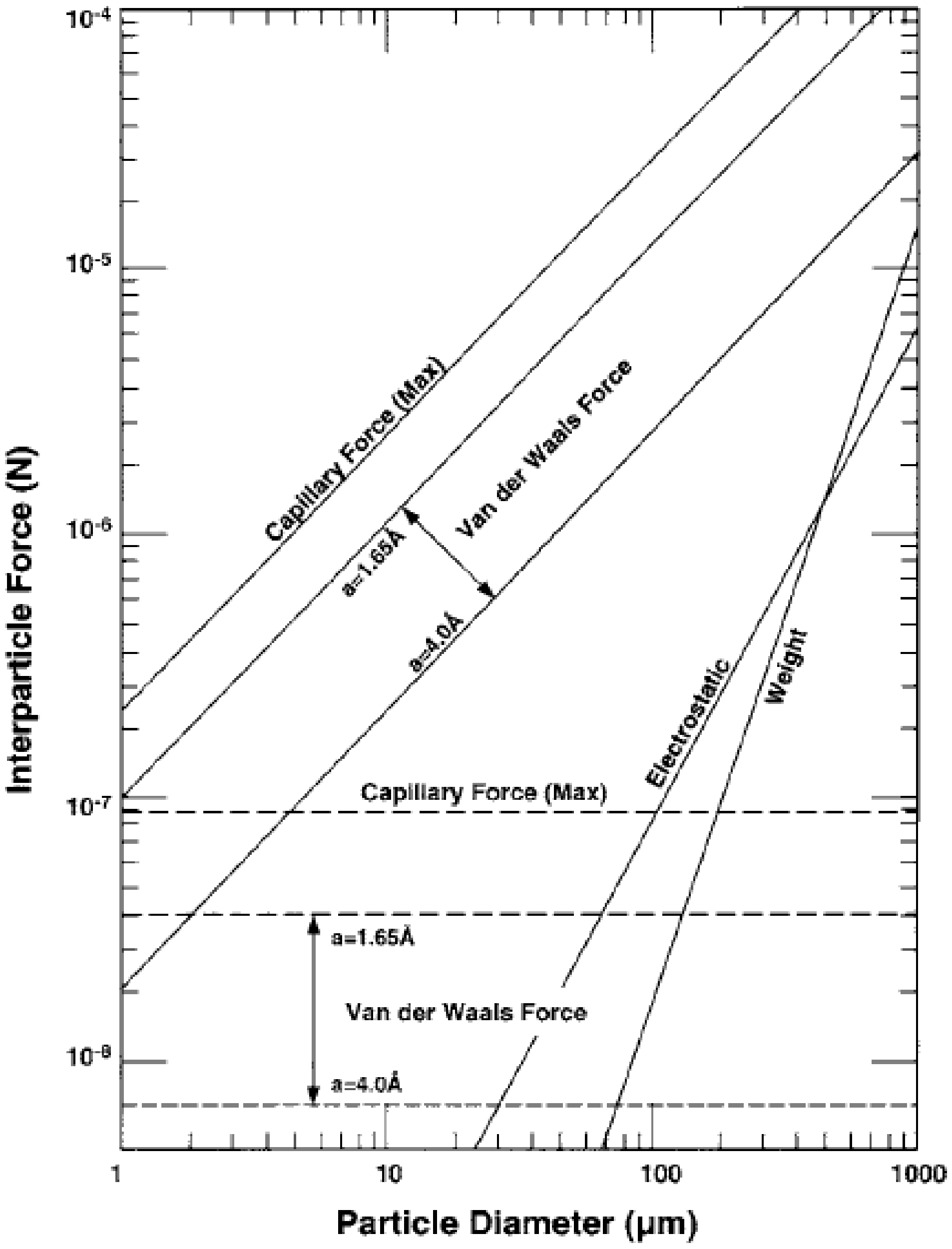
Important at low humidities with non-conducting particles

$$F_e = k\frac{|q_1||q_2|}{r^2}$$



Interparticle Forces

Relative magnitudes



Seville, JPK, Chapter 22 Fluidisation of cohesive particles, Granulation, 2007, Vol.11, p.1041-1069

Other forces considered here

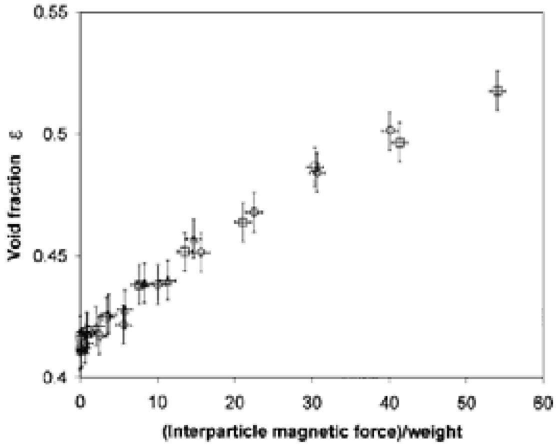
Magnetic Forces

Here concerned with iron or iron containing particles in an externally imposed magnetic field.
Field in different directions. Key features: dipoles, dominant direction, potential for chain formation, cancelling effect occurs

Friction Forces

Note that recent findings show that increase in cohesive force causes increased friction and reduces relative motion of particles.

Porosity of Randomly Packed Spheres



Forsyth et al, 2001:

§ Experiments with iron particles in a magnetic field

§ Calculation of van der Waals forces

Porosity:

§ Increases with increasing interparticle force (IPF)

§ Governed by IPF/particle wt. (Bond number Bo)

Yu et al, 2003:

§ Confirmed this result for van der Waals forces and capillary forces

§ Added an empirical expression for porosity:

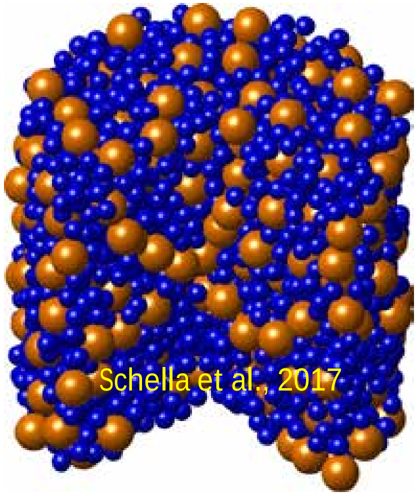
$$\varepsilon = \varepsilon_0 + (1 - \varepsilon_0) exp(-m B_o^{-n})$$

Porosity with zero IPF

A.F. Forsyth, S. Hutton, M.J. Rhodes and C.F. Osborne, 2001, Physical Review Letters, Vol. 87, 24.

A.B. Yu, C.L. Feng, R.P. Zou, R.Y. Yang, Powder Technology, 2003, 130 (1-3).

Porosity of Randomly Packed Spheres



Lumay et al, 2009:

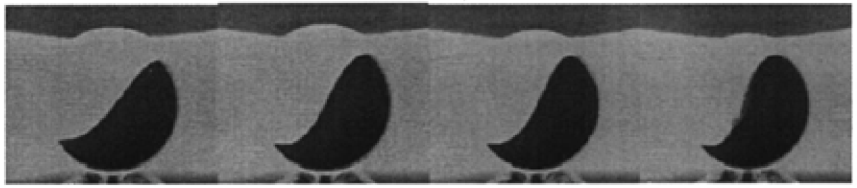
- § Iron particles in a magnetic field:
- § Confirmed porosity is a function of Bond Number

Schella et al, 2017:

- § Using controlled electrostatic forces with PTFE spheres:
- § Confirmed the trend of porosity increase with increasing Bond No.

G. Lumay, N. Vandewalle, M. Nakagawa, S. Luding, AIP conference proceedings, 2009, Vol. 1145.
A. Schella, S. Weis, M. Schröter, 2017, Physical Review E, Vol. 95, 6.

Angle of Repose



Forsyth et al, 2001:
Rotating drum with iron spheres in a variable magnetic field

Showed **static and dynamic** angle of repose (AOR) increase linearly with Bo

Lumay and Vandewalle, 2010:
Confirmed AOR results by experiments (magnetised particles)

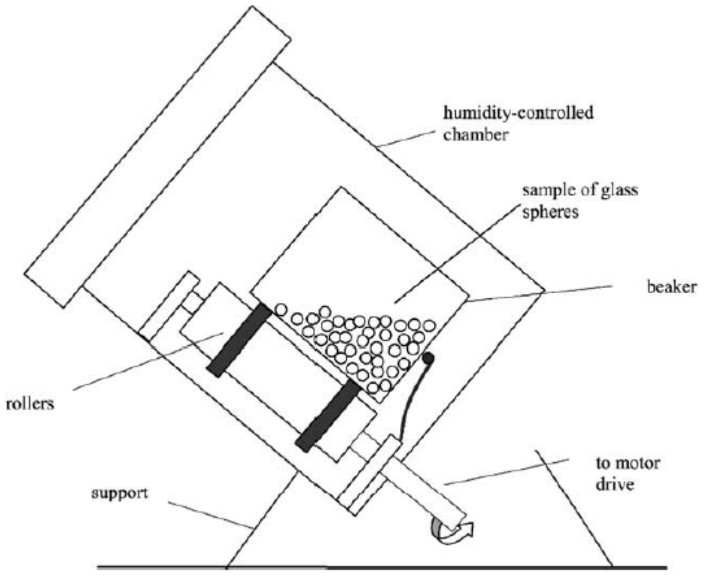
Fasekas et al. 2005:
Confirmed AOR results by simulation of magnetised particles

Taylor et al. 2008:
Explained why, for magnetic systems, this effect is much less than as expected (magnetic cancelling effect)

Forsyth, et al., 2001, Physics Review E, Vol. 63, 3
Lumay and Vandewalle, Physical Review E, 2010, Vol.82 (4).

Fazekas et al., Physical Review E, 2005, Vol.71(6)
Taylor et al., Phys. Rev. E, 2008, 78.

Angle of Repose – Flow Behaviour



Forsyth et al, 2002:
Using two systems:
§ glass spheres in humidity-controlled air
§ iron spheres within a magnetic field

showed that the transition from free-flowing to stick–slip behaviour occurs at a critical ratio of IPF/particle weight (Bo)

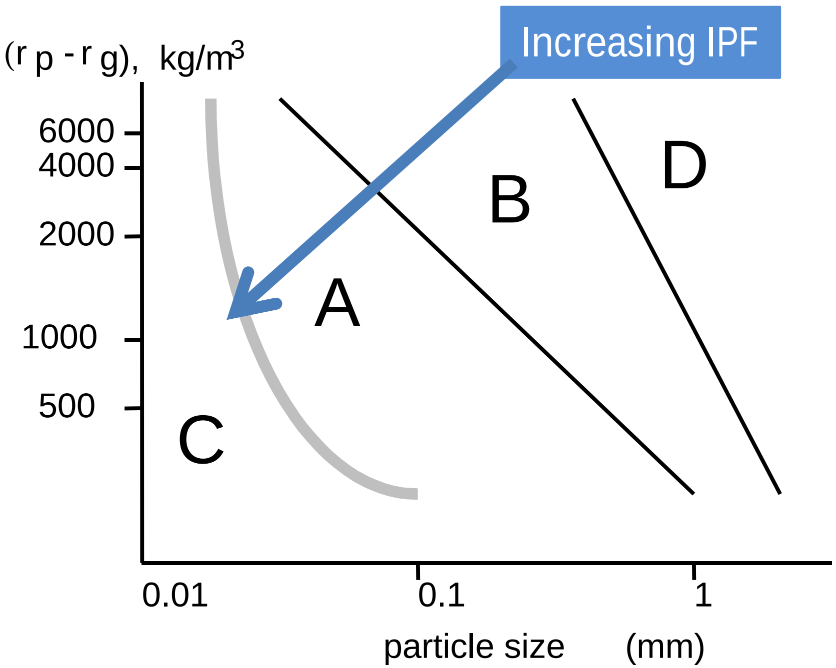
AFM measurements showed force increased monotonically.

Xiang-Yun Lu et al., 2017:
Dry powder inhaler study:
Optimal relative humidity for promoting powder flow and dispersion dependent on the <u>balance between the electrostatic force and the capillary force.</u>

Forsyth, A.F., S. Hutton and M.J. Rhodes, Powder Technology, 2002, 126.
Xiang-Yun Lu,Lan Chen, Chuan-Yu Wu, Hak-Kim Chan, and Tim Freeman, Materials (Basel), 2017, 10(6): 592.

Fluidization

General trend:

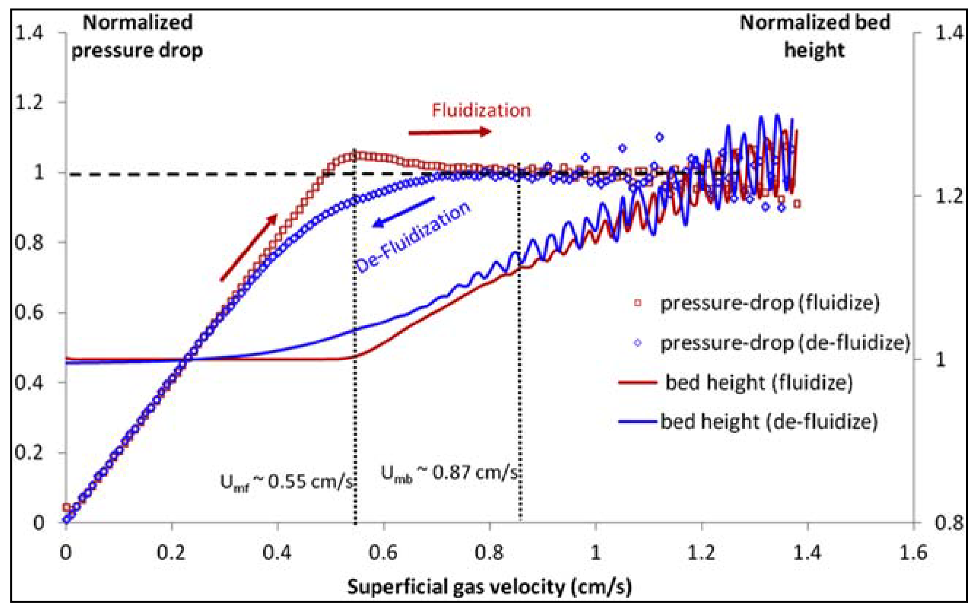


Geldart's classification of powders

B: Bubbling only

A: Non-bubbling range (U_{mf} to U_{mb})

C: Channelling, ΔP<buoyant weight



Evidenced by capillary forces, magnetic forces, van der Waals forces

Fluidization

Molerus, 1982:
Suggested ratio of IPF/wt determines the BA and AC boundaries in Geldart's classification:

This result supported by many others, but values at boundaries vary.

Examples:

System	**IPF/wt at BA**
van der Waals estimation (particle radius)	6
van der Waals estimation (asperity radius)	0.3-0.5
DEM simulation	1.0
Added non-volatile liquid	0.02-0.06
Magnetic	2.5

Molerus, O., 1982,. Powder Technology, 33, 81.
Seville, JPK, 2007 Granulation, Vol.11.
McLaughlin, et al., 20021 Powder Technology, 114
Rhodes et al. 2001, Chem. Eng. Sci., Vol. 56, 1; and 56, 18

Fluidization

AC Boundary

Values of Bond number vary considerably (0.43 to 47) depending on the system and researchers

However, main conclusion:
Both BA and AC boundaries seem to be governed by critical Bond number.

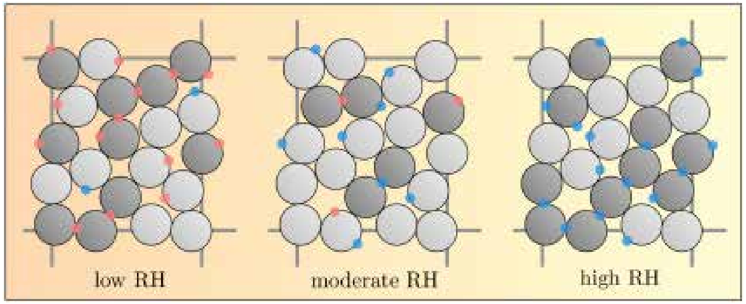
Although:
Simulations suggest that A behaviour can occur in the absence of imposed IPF (Pandit et al., Galvin et al., Rhodes et al.)

Support for Foscolo and Gibilaro theory (1984, transition based on hydrodynamics alone)

P.U. Foscolo, L.G. Gibilaro, Chem. Eng. Sci. 39 (1984) 1667.
Galvin et al., AIChEJ, 2014, Vol.60(2).
Pandit et al., Powder Technology, Vol. 160, 1
Rhodes et al. 2001, Chem. Eng. Sci., Vol. 56, 1

Surprising Effect of Interparticle Forces

Hornbaker et al., Nature, 1997:
Static angle of repose in **0.8mm** glass beads changes linearly from 25 to 35 degrees with oil layer thickness changing from **5nm to 30nm**

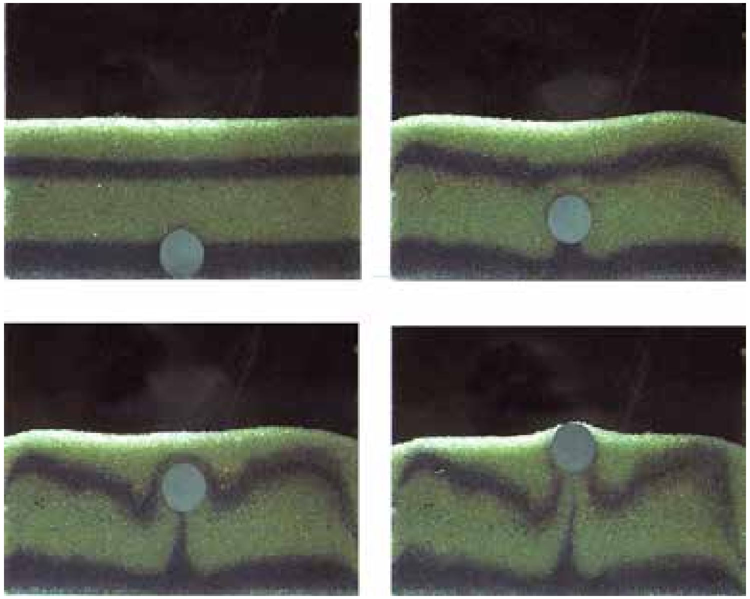


Vandewalle et al., 2012:
Packing fraction of **1mm** particles affected by relative humidity (RH).
"A remarkable result ...."

Mobility of particles changes with humidity - low for very low and very high RH - highest around 45% RH.

Vandewalle et al, Phys. Rev. E, 2012, Vol.85(3).
Hornbaker et al., Nature, 1997, 387 765

Surprising Effect of Interparticle Forces



Yang, 2006, Brazil Nut Effect:
DEM simulation with simplified liquid bridge forces.
Found that small addition of liquid causes large change in rise rate of intruder.

Rhodes et al, 2003, Brazil Nut Effect:
Order of magnitude change in rise speed of **25mm steel intruder** in a bed of **1mm** glass beads as RH changed.

High RH (capillary condensation) and high electrostatic charge (at low RH) each had the effect of slowing the rise rate. Maximum rise rate at 55% RH.

Rhodes et al, Granular Matter, 2003, 5, 107-114.
Yang, Chem. Eng. Sci, 2006, Vol.61(18), p.6180-6188.

Conclusions

Ratio of interparticle force to particle weight (Bo) important in factor in determining powder behaviour.

Changes in behaviour often governed by critical values of Bo.

These critical values of Bo not associated with step changes in the nature of the forces.

Humidity plays an important and surprising role in influencing behaviour of granular systems:

Low humidity → electrostatic forces
High humidity → capillary forces
Optimum humidity for good flow, dispersion etc: 50-60%

Deserving of much further research