

An abridged survey of IFPRI work in particle flow.

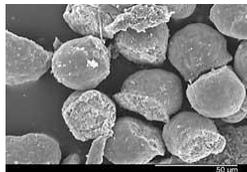
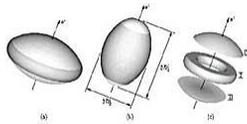
Paul Mort
Procter & Gamble Company
Member of International Fine Particle
Research Institute (IFPRI)

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1

IFPRI



The International Fine Particles Research Institute, www.ifpri.net, is a unique global network of companies and academics with active research programs in particle science and technology. It is a non-profit organization.

IFPRI membership represents some of the world's largest manufacturing industries: bulk and specialty chemicals, pharmaceuticals, minerals, construction, coatings, detergents and foods. The industry members work alongside some of the finest academic researchers in the world in particle science and technology, and other allied areas.

Since its inception in 1979, IFPRI has explored the whole range of particle science and technology including the formation, modification, mixing, dispersion, handling and transport of particles. The particles can range in size from nanometres to millimeters. Dispersions of particles in gases, liquids and pastes are also studied.

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2

My Background:

- Ceramic Science and Engineering
- Started at P&G in 1993, focus on detergent.
 - Involved w/ IFPRI through P&G.

Ceramics...

- Aluminosilicate powder
- Add a little surfactant/polymer as a process aid,
- Forming process...



Saint Gobain Ceramics

Detergent...

- Surfactant active
- Add a little aluminosilicate as a process aid,
- Granulation process...

**Industrial issue...**

Products with high organic compositions may be softer, stickier and more susceptible to fouling in processes that require granular flow:

- Mixing,
- Milling,
- Agglomeration,
- Drying,
- Conveying...



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3

Motivation – optimizing processes that handle particulates either as intermediates or end products

- We desire efficient processes:
 - Maximize production throughput
 - Minimize the spent energy.
- Two aspects in this optimization:
 1. Process equipment and its integration within a system; and
 2. Properties of the particulate material that are relevant to the processing conditions, specifically the material's response to flow and stress fields that are imposed by the process equipment.
- Industrially-relevant materials have a complex coupling among:
 - imposed flow field and boundary conditions,
 - constitutive properties of the material function of shear rate, packing density...
 - resultant stress & energy consumption.
- Optimization requires understanding of flow and stress fields.

Dense flows are of interest

Optimize the use of energy to achieve desired product transformation

$$\int \frac{\text{stress} \cdot \text{flow}}{\text{mass}} = \text{specific energy}$$

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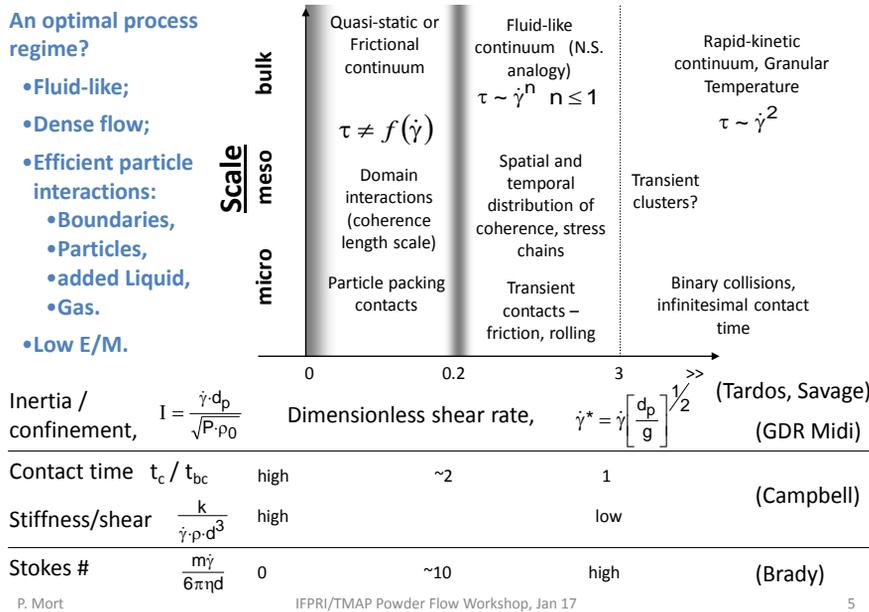
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4

Multi-scale Approach to Particulate Flow – A Regime Map

An optimal process regime?

- Fluid-like;
- Dense flow;
- Efficient particle interactions:
 - Boundaries,
 - Particles,
 - added Liquid,
 - Gas.
- Low E/M.



IFPRI's support of powder flow research since 1985

- **Aerated Powder Flow**; Nedderman, Rathbone (Cambridge) 1985.
- Estimation of Powder Yield Locus & its Application to Design; Makino (Akita) 1985.
- **Method of Characterizing the Flow of Aerated Powders**; Lloyd, Webb, (Loughborough), 1986.
- Unification of Wet, Intermediate and Dry Granular Flow – A Theoretical Approach; Buggisch (Karlsruhe), 1988.
- **Characterization and Prediction of Powder Flow**; Geldart, Woodcock (Bradford), 1989.
- Granular Shear Flows: Fluid/Solid Interfaces, Impact strengths and Self-Diffusion; Campbell, Zhang (USC), 1992
- **Rapid Shear of Fine Powders**; Jackson (Princeton) 1992.
- **The Discharge of Fine Powders from Conical Hoppers**; Nedderman (Cambridge) 1993.
- **Turbulent Gas-Particle Flow in Vertical Risers**; Jackson, Sundaresan, Dasgupta (Princeton) 1995.
- **Bubble and Elutriation Control in Fluidized Beds with Electric Fields**; Colver et al. (Iowa) 1997.
- A Review of Instrumentation for Dense Gas-Solid Flows; Louge (Cornell) 1997.
- Mixing and Segregation in Industrial Processes; de Silva (Telemark) 1997.
- Measurement of Fluidization Dynamics in a Fluidized Bed using Capacitance Tomography; Beck, Dykowski, Yang (UMIST) 1998
- **Discrete Particle Simulation of Gas-Solid Flow - Effect of Inter-Particle Collision**; Tsuji, Tanaka et al. (Osaka) 1998.
- **Experimental Rapid Shear Flow**; Louge (Cornell) 1998.
- **Rapid Shear Flow of Granular Materials**; Sundaresan (Princeton) 1998.
- Test Methods for Measuring Flow Properties of Bulk Solids, Schwedes (Braunschweig) 1999.
- Suspension Paste and Powder Flow - Prospects of a Unified Approach; Melrose (Cambridge) 1999.
- Characterisation of the Rheo-Mechanical Properties of Wet-Mass Powders; Tomas (Magdeburg) 2001.
- Biaxial shear cell; Scarlett, Janssen (Delft) 2000.
- **Powder Mixing and Segregation**; Muzzio et al (Rutgers) 2001.
- **Study on Fundamentals of Mixing of Powders with Emphasis on Cohesive Systems**; Sommer (Munich) 2002.
- **Inter-particle Forces in Powder Flow**; Pollock & Jones (Lancaster) and Geldart & Verlinden (Bradford) 2002.
- Granular flows in the intermediate regime; Tardos (CUNY) 2002.
- Studies of the fundamental interactions between a gas and agitated particles; Louge et al. (Cornell) 2002.
- From Wet to Dry; Brady (Caltech) 2003.
- **Workshop – Powder flow in the intermediate regime** (Bremen) 2003.
- **IFPRI Powder Flow Working Group**. Behringer (Duke), Louge (Cornell), McElwaine (Cambridge), Pfeffer (NJIT), Sundaresan (Princeton), Schwedes (TU Braunschweig); Jacob (Dow), Halsey (Exxon), Michaels (Merck), Mort (P&G); Place (IFPRI); Mountziaris (NSF) 2005.
- Mixing of powders and granular materials by mechanical means; Bridgwater (Cambridge) 2008.
- **Constitutive characterization of dense flows in the intermediate regime**; Tardos (CUNY), 2010.
- **Dynamics and Rheology of Cohesive and Deformable Granular materials**; Behringer (Duke), 2013.
- Flowability assessment of weakly consolidated particles, Colin Hare (Surrey)
- Die filling of aerated powders, Charley Wu (Surrey)
- Dry Powder Rheology, Karen Daniels (NC State)

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Handling of Fine Powder

Flow and handling of fine powder is a consistent challenge to industry. Early IFPRI projects focused on problems of aerated powder, including discharge from silos and avoidance of flooding.

- The Flow of Aerated Powders (1985), Nedderman et al, Cambridge Univ
 - Flooding is associated with aerated powders; for example, finely-powdered materials that may become aerated as a result of rapid filling or the collapse of an arch or rat-hole. To the extent that powders remain aerated, they present flooding hazards. It is important to either avoid handling that causes aeration, and/or adopt operating strategies to promote effective de-aeration. Models relating to de-aeration kinetics are available; however, they are least accurate for fine powders (e.g., Geldart type "C") that are most susceptible to the problem of flooding.
- The Discharge of Fine Powders from Conical Hoppers (1993), Nedderman et al, Cambridge
 - While the flow rate of free-flowing coarse granules (i.e., $> \sim 500 \mu\text{m}$) is well described by the Beverloo correlation, it over-predicts the flow rate of finer particles. This project tested the hypothesis that retarded flow of fine powder is caused by air drag resulting from the dilation of the material as it approaches the orifice. Measurement of the flow rates confirmed the validity of the Beverloo correlation for coarse materials and the existence of related flow for finer materials. Direct measurement of the interstitial pressure profile showed that the immediate cause of retardation was the existence of adverse pressure gradients near the orifice. Direct confirmation of dilation above the orifice was obtained using gamma-ray tomography. In addition, this study tested the effect of hopper half-angle and particles' size (down to $150 \mu\text{m}$) on the flow rate through a range of orifice sizes; while data showed a general trend with the Beverloo relation, with flow coefficient "C" being a function of half-angle and particle size, scatter was considerable. Scatter was attributed to inconsistent surface conditions in the test device; i.e., the boundary conditions were not well controlled in the experiments.

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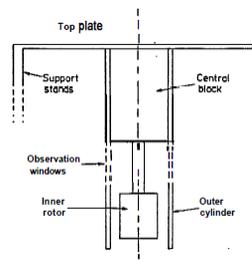
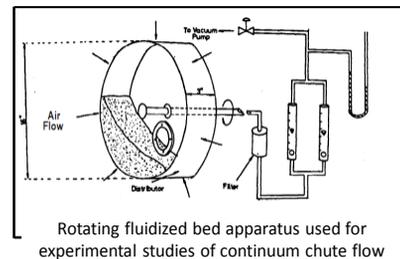
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7

Rheology of Aerated Powder

Toward fundamental understanding of powder flow...

- Characterization and Prediction of Powder Flow (1989), Geldart et al, Bradford Univ
 - Using experiments and simulations for model systems, a framework was proposed for constitutive rheology amenable to parameterization and use of dimensionless scaling law equations. Challenges in compression/ dilation (i.e., concentration gradients) and distributed characteristics (size, shape...)
- Development of a Method of Characterizing the Flow of Aerated Powders (1986), Lloyd & Webb, Loughborough Univ.
 - Developed a shear cell to investigate importance of aeration on the properties of powders, so that the phenomenon of flooding can be explored. Two principle effects of aeration have been found. At low velocities in the shear plane, the effect is to reduce the transmitted shear. The powder continues to behave as a powder but its strength is reduced by the aeration. The powder will then be less likely to arch and will flow more easily. The second effect is that above a 'critical' velocity the transmitted shear increases with increasing velocity. The powder now behaves as a liquid.



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8

Rheology of Aerated Powder, cont.

From Lloyd & Webb...

- Results on industrial powder (Alcoa Alumina: "bad" sample flooded, "good" did not) demonstrated how important is the particle size distribution in determining the properties of a powder. In the bulk handling of a free flowing powder it is very unlikely that the powder can ever be considered to be homogeneous in particle size. It is important therefore to investigate how sensitive the powder properties are to changes in particle size distribution. Measurement of the transmitted shear stress as a function of aeration and velocity in the shear plane shows that for some particle size distributions a little entrainment can have a large effect on the powder properties.

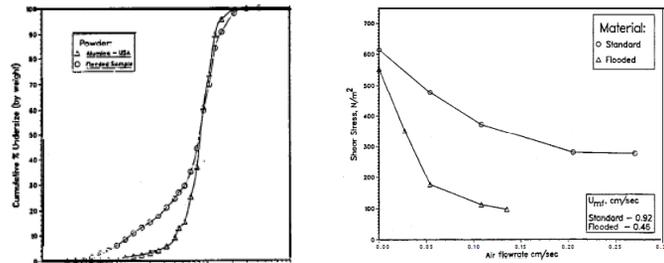


Figure 5.12: Effect of Aeration — Alcoa Alumina
Comparison between Standard & Flooded Materials
Rotational Speed (ω) = 0.131 r/s

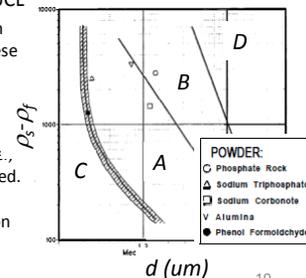
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9

Gas-Particle Flows in Reactors

- Rapid Shear Flow of Fine Powders (1992), R. Jackson et al, Princeton University
 - Industrial interest in fluidization of catalyst powders for chemical production, e.g., FCC, was a primary driver of a series of projects in riser flows and other aspects of fluidization. In cases where the gas comprises the product, the primary objective is to be able to predict and control the flow of gas as it interacts with particulate (e.g., catalyst) materials. The multiphase flow of gas and solid particulate material can be through a fluidized bed or duct of arbitrary size and inclination, where particles may be distributed in a non-uniform way, making it difficult to predict the holdup of solid material, pressure drop, and the distribution of residence times of gas and particles.
- The Role of Interparticle Forces in the Gas Fluidization of Fine Powders (1994), Geldart & Xie, Bradford University
 - Of special industrial interest, type "A" powders exhibit a uniform fluidization as part of a bed expansion prior to the onset of bubbling. Uniform fluidization of fine powder in a gas-solid reactor is desired for its high gas-solid interfacial area and avoidance of gas bypassing via bubbling.
- Fluidization at Elevated Temperature and Pressure (1994), Yates, UCL
 - Yates suggested further work on circulating fluidized beds, citing gaps in understanding, disagreement about types of flow regime existing in these systems, and reliable scaling rules.
- Agglomeration in Fluidized Beds (1985), Tardos et al, CUNY
 - Fluidized beds of fine particles are used extensively in the chemical industry; their large contacting area between gas and solid, heat transfe., and low pressure drop are desirable as long as stable operation is assured. The presence of liquids (molten material) and/or high temperatures, in fluidized bed reactors can produce uncontrollable particle agglomeration and subsequent loss of fluidization.



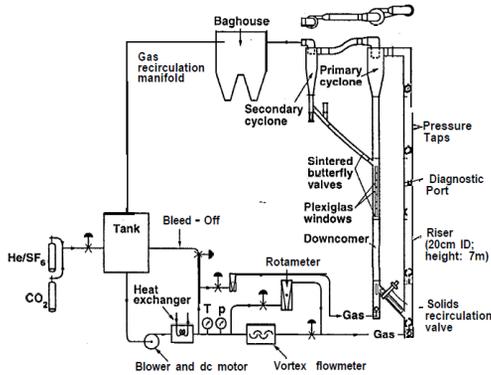
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10

Particle flow in Fluidized Reactors

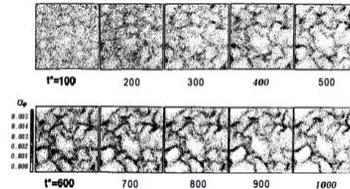
- Experimental Rapid Shear (1998), Circulating Fluidization (2002), Studies of the fundamental interactions between a gas and agitated particles (2002), M. Louge, Cornell University (1998)
- Discrete Particle Simulation of Gas- Solid Flow - Effect of Inter-Particle Collision (1998), Tsuji et al, Osaka University
- Turbulent Gas-Particle Flow in Vertical Risers (1995), Rapid shear flow of granular materials (1998), Jackson, Sundaresan et al, Princeton University
- Bubble and Elutriation Control in Fluidized Beds with Electric Fields (1997), G. Colver, Iowa State



Circulating fluidized reactor at Cornell

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Simulations of cluster formation, Tsuji et al

Inter-particle forces in powder flow (2002)

Collaboration of:

- Physicists (H Pollock & R Jones, Lancaster Univ) and
- Chemical Engineers (D Geldart & A Verlinden, Bradford Univ)

Particle-scale measurements were done with an AFM

- Pull-off profile can discriminate cohesive effects of fine powder exposed to moisture.
- Friction measured using relatively slow lateral speeds (i.e., well within QS regime).
- Surface roughness characterized; fractal scaling observed.

Shear cell used for bulk measurements.

Results:

- Best correspondence between bulk and single-particle cohesion obtained with relatively small particles (2-6 μm) and low consolidation loads, suggesting single-asperity contacts.
- Other scaling arguments based on single-particle cohesion fail; this implies aggregation of small particles and multiple-asperity contacts of larger particles.

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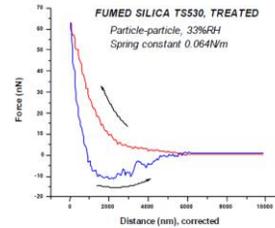
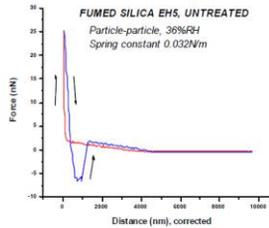
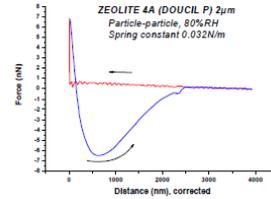
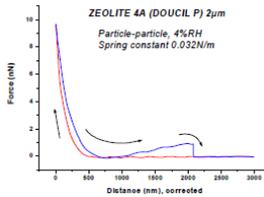
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12

Inter-particle forces in powder flow (cont)

AFM hysteresis profile can discriminate:

- Cohesive effects of fine powder exposed to moisture.
 - Zeolite (1-2 μm) is cohesive. Aggregates attach to the cantilever; single particles could not be isolated.
- Effect of surface treatment
 - Untreated fumed silica shows some RH dependence.
 - The treated material can show ultra- long range effects, particularly at low RHs.



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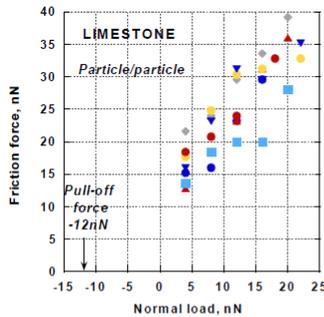
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13

Inter-particle forces in powder flow (cont)

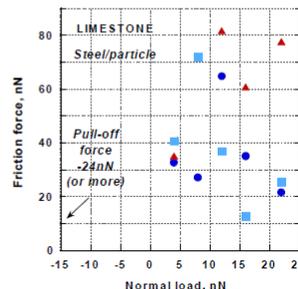
Lateral friction:

- Limestone & titania show linear load dependence with relatively high inter-particle friction coefficients and good extrapolation to pull-off values on negative load axis.
- Ballotini show non-linear load dependence with relatively high friction and slip-stick character; poor pull-off extrapolation.



Clear load dependent friction for particle-particle contacts, linear data (?) with high $\mu \sim 1.0$ extrapolating to pull-off force. Single or multiple-asperity contacts? No significant humidity dependence of adhesion or friction in the range 10-90%RH, consistent with bulk observations. Stick-slip behaviour, but less obvious than for glass ballotini.

Enormous scatter of data with no significant load dependence for particle-wall contacts. Pull-off force is also large and variable, suggesting large local variations due to wall adhesion or roughness, but no significant variations due to RH.



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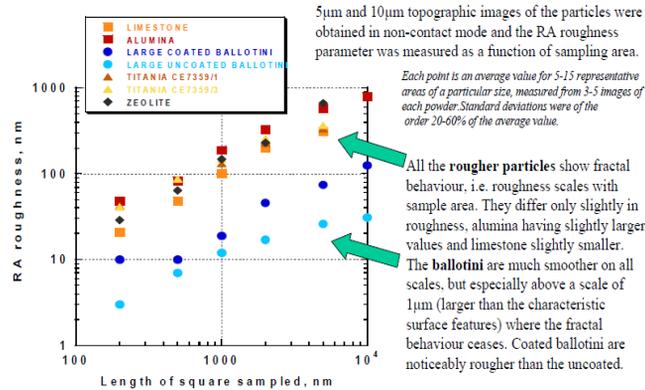
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14

Inter-particle forces in powder flow (cont, Pollock et al)

Surface roughness:

- Smoother ballottini surfaces are clearly consistent with the idea of single-asperity contacts suggested from friction-load plots and stick-slip behavior.
- However, roughness parameters are difficult to relate to adhesion and friction in a useful way, i.e., alumina has a surface as rough as the other powders and yet appears to show much lower friction, so a satisfactory relationship between roughness and friction remains to be found.



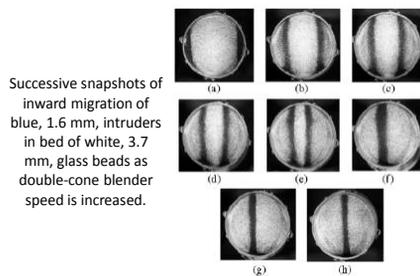
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15

Mixing, Segregation

- Powder Mixing and Segregation (2001), Muzzio et al, Rutgers Univ
 - Developed predictive modeling capabilities and quantitative characterization methods for mixing and segregation in practical blending devices (V-blenders, double cone...), showing a robust and reproducible set of segregation patterns that can occur across a wide range of blender sizes and geometries and across a range of particle sizes. Cited need to improve constitutive modeling of flow and stress in powdered and granular materials, along with mixing responses.
- Study on Fundamentals of Mixing of Powders with Emphasis on Cohesive Systems (2002), K. Sommer, TU Munich.
 - Extensive pilot capability with emphasis toward sampling and on-line measurement (NIR) for mixing studies. Analysis of mixing used the Fokker-Planck Equation was successful in overall trends, but could not deduce the relative importance in mixing mechanisms, i.e., convective versus dispersive contributions.



Industrial pilot plant at TU Munich



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16

Powder Flow Workshop July 4-5, 2003 Bremen, Germany

The workshop was interactive, with invited academic experts and industrial practitioners representing different disciplines and backgrounds, including expertise in modeling, theory, and experimental approaches across a range of relevant scales of scrutiny.

Key Questions and Objectives

- Can fundamental understanding of intermediate and/or transitional flow behavior can be developed to the extent that industry can design, predict and optimize flow behavior of real materials in industrial scale equipment?
- What are the critical physics across a range of scales, for example, micro-scale interactions on a particle level to meso-scale structural aspects and bulk continuum or quasi-continuum models?
- Identify facilities, resources and linkages available or in need of development.

Industrial Needs

- Fundamental understanding of powder and granular flows is important for most member companies' activities, including unit operations, process, storage, transport:
 - Consistent performance & optimization
 - Loss avoidance
- Principal challenges include:
 - Mixing and segregation in materials having distributed size and shape characteristics
 - Balancing Flowability versus Cohesion

Debates

- Is a Couette-flow device suitable to study flow and stress field relations; is a fluid-like analogy a useful approach? If so, how to control packing fraction?
- Is the problem defined sufficiently for IFPRI to move forward with a research program?

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17

Report of the IFPRI Powder Flow Working Group (2005)[†]

R. Behringer, M. Louge, J. McElwaine, P. Mort, R. Pfeffer, S. Sundaresan

The report is a summary of salient questions on inter-particle forces, bulk behavior, constitutive relations, scaling relations, and numerical modeling in powder and granular flows:

- Inter-particle forces in powder flow systems
- Bulk properties: compressibility and cohesion
- Stress and Flow Fields in Particulate Flows
- Scaling in Cohesive Flows
- Different Regimes in Granular Flows
- Flows down inclines
 - Dense inclined flow (e.g., chute) of mono-disperse spherical particles is an example in which the physics is simple enough to reconcile experiments, numerical simulations and theory.
- The effect of interstitial fluid

IFPRI used the report as a starting strategy for further research in powder flows (Tardos, Behringer) and as a foundation for a collaborative grant proposal to the NSF.

[†] IFPRI SAR 30-08, <http://www.ifpri.net/publications/report-ifpri-powder-flow-working-group>

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18

IFPRI Projects following Working Group's Report

- Toward a Grand Challenge in Powder Flows: The effect of material properties, boundary conditions and shear rate on fluctuations and stress fields in flowing powders (2010), Tardos et al, CUNY.
 - Instrumented Couette with axial flow.
- Dynamics and Rheology of Hopper Flow: Two and Three Dimensions, Effects of Particle Shape and Cohesion (2013), Behringer, Duke Univ.
 - Flow and stress fields visualized using photoelastic particles

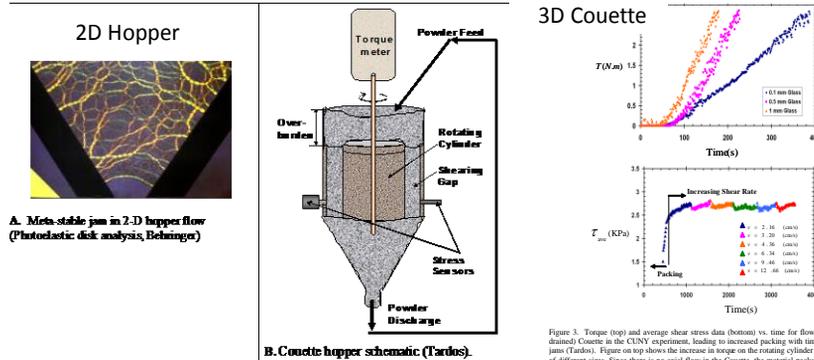


Figure 1. Left (A): Photo-elastic image from Duke experiments showing force chains. Data are generally obtained with high speed video, and this image is one frame of such a video. Right (B): Schematic representation of CUNY apparatus, including information on transducers that measure key properties such as stress, torque on the inner cylinder, etc.

Figure 3. Torque (top) and average shear stress data (bottom) vs. time for flow in the batch (on a diametric Couette) in the CUNY experiment, leading to increased packing with time and metastable jams (Tardos). Figure on top shows the increase in torque on the rotating cylinder for three particles of different sizes. Since there is no axial flow in the Couette, the material packs (increase in solid fraction), different slopes show the rate of packing due to size and shape differences. The first part of the figure on the bottom (denoted "packing") represents the same data for 0.1 mm glass chips while the RHS shows that the shear stress remains practically constant for any surface velocity "v" from 2-12 cm/sec of the rotating cylinder. The implication of the data is that under batch conditions in the Couette, the material packs in time and the shear stress is practically independent of shear rate (average shear rate is obtained by dividing the velocity "v" by the gap, approximately 5 cm).

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19

IFPRI-NSF Collaboratory on Dense Particle Flow (2010-2012)

NSF grant awarded to IFPRI, 1+1 year duration, \$97,500 total amount disbursed to US collaborators. No IFPRI overhead or other indirect costs

Academic leaders in granular modeling invited to simulate 2D Hopper and/or 3D Axial Couette of Behringer and Tardos projects. IFPRI provides detailed data sets.

Goal: enable broader community of industrial and academic researchers, modelers and engineers to define and understand relevant regimes of dense particulate flow, the underlying physics therein, and the effect of boundary conditions, material properties and particle characteristics.

Several key challenges were foreseen, including:

- Reconciling current experimental practices in material property measurement and particle characterization with the properties required for current modeling and simulation programs.
- Reconciling the statistical aspects of stress and flow measures (i.e., fluctuations and error bars) between experiments, models and theory.
- Reconciling multi-scale aspects of the challenge – from particle characteristics and material properties, to stress chain characteristics and statistics, to bulk rheology.

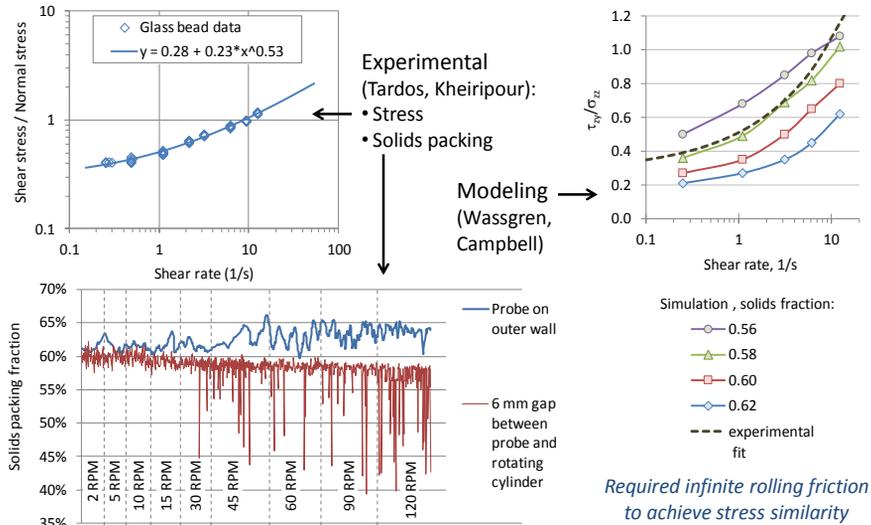
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20

Collaboratory results, 3D Axial Couette

Compare stress field as function of solids packing fraction



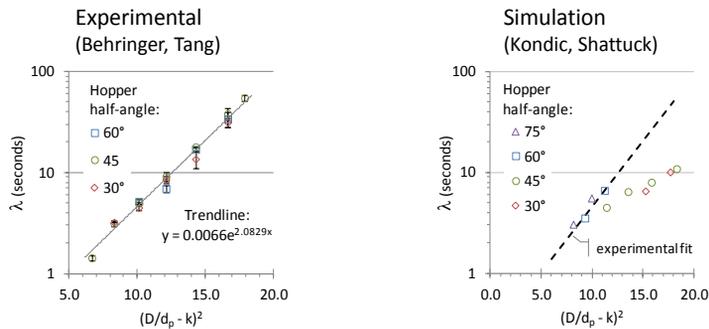
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21

Collaboratory results, 2D Hopper

Compare time between jamming events at hopper outlet –
 statistical character of stress chains and flow fabric in a converging flow
 (hopper half angle from vertical)



Required static friction, $\mu_s \sim 0.8$,
 to achieve jamming

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22

Collaboratory conclusions

- The IFPRI program in rheology of dense particulate flows brought focus to intermediate regime flows, having particle packing and flow rates of relevance to many industrial unit operations.
- Linking the physics of intermediate flows across the 2D and 3D datasets required transitions between static and dynamic particle interactions.
 - 2D Hopper flow simulations required static friction to match the experimental emptying times over the range of hopper angles tested.
 - 3D Couette flow simulations required impeding rolling friction as a means to transmit stress through the granular medium.
- Findings support the concept of inter-particle contact networks (i.e., force chains) having static-like behavior capable of localized jamming and transmission of stress over finite intervals (temporal & spatial), where the ability of the system to dynamically form and break such networks on a scale that is comparable to a shear rate characteristic of an intermediate regime.
- Fluctuating stress fields in dense flows remain a challenge for both modeling and experimental measurement (multiple sensors in 3D Couette are not directly coherent on a local spatial or temporal scale).

IFPRI-NSF Collaboratory Results: Issues and Suggestions

- Scope of the Collaboratory Challenge (Rapid Dense Granular Flow) exceeds its level of funding.
- Collaboration on this scope requires better integration of experimentalists and modelers; it is recommended to include modelers in early stages of the project, especially to:
 - Guide selection of model materials;
 - Specify details of boundary conditions in the experiments;
 - Develop simpler experiments (i.e., having a single flow regime) that can elucidate important modeling parameters including:
 - Contact mechanics in dense flows, normal and tangential;
 - Transition between static and kinetic friction;
 - Effect of particle shape, especially in relation to contact mechanics;
 - How to approach packing fraction – input control or measured output?
- Industrially relevant materials comprise an even more challenging range of properties (complex modulus, cohesion...) and characteristics (shape and size distributions).
- A wider range of modeling techniques (regime mapping, quasi-continuum modeling) could help.
- In spite of the difficulties in modeling the flows within the 3D Axial Couette, its usefulness as an experimental probe of dense-phase rheology makes it relevant for future modeling work.
- On the whole, the Workshop was useful in bringing participants together face-to-face to discuss modeling approaches and results; however, the interaction was very concentrated and did not allow for productive iteration of the models themselves. For a challenge of this scope, a series of meetings could have been more productive, for example to involve modelers earlier in the experimental program, and to promote more cross-fertilization of approaches and results.

Active IFPRI projects in powder flow

- Flowability assessment of weakly consolidated particles, Colin Hare (Surrey)
- Die filling of aerated powders, Charley Wu (Surrey)
- Dry Powder Rheology, Karen Daniels (NC State)
- Segregation, Joe McCarthy (Pittsburgh)

Powder Flow Round Tables

2015: Industrial Practice with Shear Testing focused on incipient flow.

2016: Expand discussion to driven and dynamic flows, including:

1. Process. Catalog industrial perspectives on relevance of powder and granular flows in unit operations, e.g., feeders, conveyors, mixers, filling operations, roll or tablet presses, classifiers, reactors using particles as catalyst carriers, etc. Describe the types (i.e., regimes) of driven flows within each.
2. Materials. Gain industrial perspective on the types of powder/granular characterization methods that are used to predict performance in unit operations, and resultant product quality. Specifically, what measurements are done to inform models that link material characteristics that are relevant to flow (multi-scale: particle/meso/bulk), the materials' flow in unit operations or regimes of flow, and resultant process efficiency and/or product quality.
3. Modeling, relating measurable material properties and characteristics to flow behavior in industrially-relevant unit operations and process systems.

2017 Workshop...

Do granular mechanics apply to fine powder flow? Micro-rheology, Compression & Dilation