

# IFPRI Workshop on “Dynamic Powder Flow”

## Meeting Summary

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## Introduction

We had around 60 industrial and academic participants (in addition to 15 TMAPP students and postdocs) at the workshop. Attachment 1 is the agenda and Attachment 2 lists the participants (attachments can be found at the end of this document). The participants were divided into parallel "syndicates" to facilitate idea generation and capture. Prior to the workshop, a questionnaire was sent to each of the participants (except for the TMAPP students and postdocs) to collect their interests and background. This facilitated the assembly of syndicates with balanced sets of experience, knowledge and interest. Each syndicate had a designated leader with the responsibility of managing the session and collecting the ideas generated. The ideas were then shared amongst the rest of the participants in the workshop. Attachment 3 lists the participants for all the six syndicates (syndicate leaders have ‘\*\*\*’ next to their names). It was decided to have all the TMAPP students and postdocs in one syndicate led by TMAPP academics.

Each syndicate was asked to address the following questions in three sequential sessions:

1. Characterize the state of the art in powder flow
2. Confront the "grand challenge" to relate particle properties, microstructure, and bulk flow behavior.
3. Define three scientific questions that IFPRI and other funding sources should promote.

Both the raw results from the syndicates (as posted during the meeting) (Appendix 1) and subsequent summary comments (Appendix 2) are appended. At a conclusion to the workshop, a panel discussion was held with some of the syndicate leaders as the panelists. Notes on that discussion are included in Appendix 1. Email dialog from immediately after the workshop is shown in Appendix 3. Appendix 4 is a quick, but thoughtful summary by Michel Louge of the implications of the workshop. (Note: the emails were edited slightly for brevity, and to remove addresses).

## **Reflections for Future Workshops**

The original intention was to have this workshop in the summer of 2017, in conjunction with the IFPRI AGM. This arrangement is typical, and minimizes travel costs. However, we learned that the "Powders and Grains" conference was going to be held at nearly the same time, which would make it difficult to attract some of the desired academic guests. The timing and location was therefore moved to that of the 2017 IFPRI winter meeting. It was then determined that the T-mapp consortia was going to have a meeting that included some of the same people in the same geographic region at roughly the same time. It was decided to combine the two meetings, with independent portions of the T-mapp event taking place both before and after the IFPRI workshop.

The pairing of IFPRI and T-mapp provided opportunities and challenges. The two groups had different objectives for their meetings. Some of the participant travel was paid for by T-mapp instead of individual delegates' employers. This provided additional participants for the IFPRI program. However, it increased the overall size of the group, causing some strain on the resources.

IFPRI's practice is to have roughly a 50/50 split of academics and industrial delegates at workshops. When the number of industrial delegates is relatively small, adding an equal number of academic guests results in a total that is both manageable in size and affordable to fund. Due to the number of T-mapp and IFPRI industrial delegates many academic guests would be required to achieve a 50/50 balance. This was not practical, and we settled for 10 invited IFPRI academics, 7-8 T-mapp academics and two IFPRI consultants.

We felt that most of the invited IFPRI academics should be offered a chance to give a presentation. Ultimately, we had eight such presentations, which made the workshop agenda quite full. In hindsight, we probably did not need to do this. However, it provided some diverse perspectives and gave IFPRI a useful opportunity to see some previously-unknown academics in action. We used a laptop-based digital timer display to monitor speaker times, and a dedicated time-keeping person to help maintain the schedule. This was quite successful.

The optimum size for syndicate groups is thought by some to be 7-8 people. However, with our large group, several extra syndicates would be needed to make each group that small. Each group would require report-out time, which would lengthen the program and likely lead to repetition. Consequently, we made the syndicate groups somewhat larger (up to 12 each). This arrangement worked adequately if the syndicate chair was mindful of the need to draw out opinions from everyone.

# Appendix 1 – Text from individual Post-It Notes presented at each session [clarifying comments in brackets]

## Session 1. Characterize the State of the Art in Powder Flow

### 1.1 Characterization

- We have adequate or reliable characterization and understanding of
  - flow/no-flow
  - Mass or funnel flow limits
- We know how to make some basic measurements of particles and bulk properties
- We have particle & powder characterization methods that are sometimes useful but additional characterization approaches are needed (e.g. for low stress and dynamic cases)
- We have a poor understanding of how to characterize and predict flow that are cohesive and unconsolidated.
- Bulk characterization is mostly static [i.e., the onset of flow], but new tools are emerging in the realm of powder dynamics / rheology
- Wide range of pragmatic testing, but can lack consistent reliability of predictions
- Measurement and analysis depends on flow regime and driving force: shear, air, etc.
- We can characterize particle-scale properties above a certain size, but not often used in practice
- Morphology and shape
- No single test device is suitable for all processes
- Many testers integrate physical effects – be careful
- Characterization data is not shared within a company or cross companies
- Work is being done to refine and extend models and characterization to allow them to make predictions for real world industrial applications (which tend to be very complex)

### 1.2 Discrete Element Method (DEM)

- DEM is useful at the moment for dry, spherical, cohesionless, non-deformable particles
- DEM needs
  - Unified calibration approaches
  - Validation at different scales
  - To address deformable particles
- DEM is developing and currently incomplete, viz.
  - Simple contact models, more understanding of physics
  - Model inputs / calibration needs work

- Computation limitations
- But DEM can give insight into powder processes and in some cases quantitative predictions
- We can make model predictions for many systems involving idealized particles that are
  - Narrowly distributed , Spheres, Relatively dense packings
- Well calibrated and validated DEM and continuum approaches are useful on simple enough problems (cohesionless particles) but extension to more complex systems is emerging.
- DEM has issues limiting industrial uptake [utilization] (e.g. system size)
- DEM is not consistently used in industry:
  - Best in rapid flow under low consolidation
  - Ok with very large particles in soil mechanics
  - Inadequate validation
  - More useful for flow fields than forces

### 1.3 Scale Bridging (from micro to bulk)

- Particle to bulk behavior connections through a stepwise approach
  - Particle to small bulk to large bulk
  - Maybe don't need it for all problems
  - For some problems you do need to build the connection. DEM is key here
- Measurements from particle level is insufficient to predict bulk scale powder flow at units ops, process, and plant scales.
- True multiscale modeling is emerging but limited to academia
- Lack of constitutive equations

### 1.4 Two-Phase Flow

- Fluidization → no general equations to predict at the large scale: hydrodynamics / mixing / segregation
  - Link microscopic particle properties to predict Geldart chart
  - Link meso to macro
- There is a considerable, largely empirical, knowledge of fluidized beds
- Interaction of particle assembly and interstitial gas phase
  - High velocity (packaging, filling)
  - N2 blankets
  - Deaeration (die filling)
  - Gas leakage flow – such as rotary valve – (delta P works against flow and gravity)

## 1.5 Knowledge Gaps

- Electrostatics
- Caking / consolidation
- Friction
- Gaps in general unifications
- Lack of empirical equations
- Dimensionless numbers
- Consistency of Flow
  - Flow rate / variations
  - Intermittent flow
  - Jamming dynamics

## 1.6 Continuum Models

- Ok for:
  - Rapid granular flow
  - PSD
  - Cohesionless
  - Not too soft
- To do:
  - Constitutive relationships for stresses and drag
  - Particle rotation
  - Meso-scale drag, Reynolds stresses [possibly referring to particle stress fluctuations caused by turbulence in the continuum fluid]

## 1.7 Other Topics

- Powders confined by flexible walls [such as bulk bags]
  - Powder-wall interaction
  - Stress state
  - Caked material
    - Moisture mitigation
    - Disintegration
    - Forced flow
- Vibration effects not known (Juergen Tomas work)
- Cohesion
  - Help flow / hinder flow
  - What is actually flowing length scale? Clusters? Shear banding?

- We need to be very explicit about the heterogeneities in a flow system
- Considerable efforts spent firefighting powder processing problems in existing equipment
- Properties needed to characterize additive manufacturing [3D printing] materials.
- Education in particle technology is limited especially in undergraduate and management levels. Improving undergrad education would likely improve education in management roles.
- Powder equipment is designed and operated using mostly (semi-) empirical approaches, which are largely propriety
- We've created some of the confusion. Not all flows are the same – incipient, quasi-static, intermediate, rapid etc. Be explicit about where you are. Micro-meso-macro transitions and the terminologies to define those are not clear or consistent in the literature

## Session 2. Confront the "Grand Challenge" to Relate Particle Properties, Microstructure, and Bulk Flow Behavior

### 2.1 Length Scale

- Need to describe material flow at the coffee cup / toaster length scale → would help “average out” single particle behavior
- Meso scale unknown in realistic systems
  - Use advanced DEM + penetrating imaging techniques (or other advanced measurement techniques) to connect micro-structure to bulk flow behavior
- Direct measurement and/or quantifying of coherence length scale in:
  - Granular / dense → e.g. idealized systems such as what Karen Daniels is working on
  - Fine cohesive systems
- Need physical description (e.g. velocity, shear, etc.) for process sized equipment
- System dependency & boundary conditions pertinent to volume + stress limits leading to flow + stress field quantification.
- Need better theories. Look more widely at other scientific communities.

### 2.2 Modeling

- “Involved” models for small, high intensity zones and “average” models for bulk behavior (e.g. think fluid bed)
- Progress in multi-scale / two-scale / homogenization approaches for modeling
- The role of DEM :
  - Explain connection between small bulk behavior & particle/particle/surfaces
  - Need suitable contact mechanics & particle representation
- Challenge of extrapolating academic models to industrial problems

### 2.3 Characterization and Measurements

- What are the parameters we need to measure at the “coffee cup” scale?
- Direct measurement and/or quantification of tensile stress in:
  - Particle-particle
  - Meso/cluster
  - Bulk isostatic systems
- Consider direct and inferential measures.
- Fluctuations matter:
  - Direct measurements, predictions and theories for these fluctuations

- We need data at suitable frequencies
- Statistical basis?
- Stochastic, slip-stick, intermittent phenomena (e.g. fouling, ...)
- Standardization of workflow / process (experiments and simulations)
  - Improve availability and simplicity of experiments

## **2.4 Idealized vs. Real Systems**

- Influence of secondary powders such as
  - Flow aids
  - Anti-flow additives
  - Lubricant
  - Coatings
  - Relative humidity and electrostatics
- Grand challenge is solved for idealized systems, not at all for REAL systems
  - Use tunable particles systematically and isolate physics to help close the gap
- Real systems experience slow temporal changes
  - Some organic systems are inherently unstable and therefore if you leave them long enough they could change. Contacts, for example, will solidify
  - Tim Bell said this may be out of scope for this workshop

## Session 3. Define Three Scientific Questions that IFPRI and Other Funding Sources Should Promote

**Note 1.** The discussion period for the third question was divided into halves. Each syndicate met individually for the first half, but some of the syndicates were paired for the second half. This was done to accelerate the condensation of the ideas generated.

**Note 2.** The number of the syndicate group who had proposed the item is shown in *blue italics*. After all the ideas were presented, an informal, non-binding vote of the invited academics was taken. They were asked which ideas they thought were most likely to advance the field. Those votes are also shown in *blue italics*.

### 3.1 Length Scale (Confronting Clusters with Professor Meso) [*Syndicate 3, 7 votes*]

- Define relevant meso-scale
  - E.g. in terms of length or time scales over which fluctuations decay
- Explore experimentally
  - Tomography
  - Conductivity
  - Light scattering
- Model
  - DEM
  - Continuum
  - Multi-scale
- For
  - Free flowing
  - Fine cohesive powder
    - Consolidated
    - Unconsolidated
- In: multiple flow regimes [Quasi-static, intermediate]

### 3.2 Characterization

- Define & Study new reference powder flow case: [*Syndicate 4 + 5, 0 votes*]
  - Focus on challenges (e.g. free surface or low compaction)
  - State-of-the-art measurement
  - Numerical experiments
  - Boundary conditions are critical

- Direct Characterization of “single” flowable unit, dynamic behavior of cohesive materials in low stress flow [*Syndicate 1 + 2, 0 votes*]
- Characterization of fluctuating flow from small hoppers with cohesive powders: experimental study and predictive models [*Syndicate 1 + 2, 0 votes*]
- Measurement and characterization of “kilogram” sample rheology [*Syndicate 1 + 2, 3 votes*]
  - State of stress
  - Density of sample
  - Shear stress vs. rpm
  - Sample pre-conditioning?

### 3.3 Modeling [*7 votes*]

- Develop true multiscale modeling strategy [*Syndicate 4 + 5*]
  - What is the appropriate strategy @ mesoscale starting from microscale, useful for macroscale
- Multiscale modeling to predict solid-fluid transition [*Syndicate 6*]
- Hybrid modeling of agitated powder flow, to determine flow field and stress on particles
- Unified calibration approach within DEM? [*Syndicate 6*]

### 3.4 Single Particle Properties

- Cohesion United [*Syndicate 3, 8 votes*]
  - Define single particle cohesion
  - Fine particles and compressible
  - Practical measurement of particle-particle cohesion model
    - To inform DEM
  - Collaborate w/ Prof Meso
  - Simple test device to link types of single cohesion [van der Waals, moisture, electrostatic] to system of flow [shear cell, vibratory, impellers/mixer/drum]
- Explore impact of broad PSD/fine additives [*Syndicate 3, 0 votes*]
- Pixie dust as probe
  - Maxwell's pixie\*
  - Tunable flow aids that provide information [used to change fluctuations finger print]
  - Magnetic particles
  - Synergetic systems
  - Humidity and / or electrostatics
  - Motivation:

- Understand dynamics
  - Help or harm meaningful change to system
- Analog to suspension stabilization e.g. in colloids
- How flow aids can be added to prevent flow problems in a controlled way? [\[Syndicate 6, 0 votes\]](#)

\*note, in subsequent communications Paul Mort defined this term (Maxwell's pixie) as follows: "Imagine engineering a flow aide (pixie dust) that could work as a sensor to diagnose a flow. For that matter, the pixie dust could even be a flow inhibitor, or agnostic tracer. Maxwell Demon means the pixie dust has micro-meso frame of reference. What could it be? Some sort of tracer that gives data on collision or force-chain dynamic? Maybe it is two-component (like epoxy), each added separately, with above data deduced from measured interaction"

### 3.5 Other Topics

- Stress state of material in an FIBC/Big Bag during filling, storage, and agitated discharge [\[Syndicate 1 + 2, 0 votes\]](#)
- Explore effect of vibration [\[Syndicate 4 + 5, 0 votes\]](#)
- State of art review: Rheological models in/for powder flow [\[Syndicate 1 + 2, 0 votes\]](#)
- Develop best practice guidelines for powder characterization [\[Syndicate 4 + 5, 0 votes\]](#)

## Panel Discussion

**Panelists:** Karl Jacob (KJ), Olivier Desjardins (OD), John Grace (JG), Herman Feise (HF) (many others also contributed).

**Chair:** Tim Bell (TB)

### Opening Statements

All participants were appreciative of the workshop and its organization.

HF stated that we are dealing with the same questions and issues as we had 20 years ago. The approaches we are taking or thinking are now different. Previously the focus was on shear cell measurements or pneumatic conveying but now the focus is on meso scale and intermediate regime.

**Question** from TB: Based on the industrial perspective lectures there was no indication of major issues in pneumatic conveying. But we know prediction of pressure drop in pneumatic lines is possible only through pilot studies. What is the state-of-the art in the pneumatic conveying? Prediction of pressure drop, or transition between dense or dilute phase? Why this topic was not brought up?

HF: most of the calculations and design are done through suppliers.

KJ: dilute phase is in good shape but still requirements for pilot studies. There are vendors with good experience. Dense phase is a big problem. No work reported in the literature but the dense phase system is very challenging.

**Question** from TB: In the past couple of years DuPont performed an internal survey of DEM application and we got mixed responses. In comparison to CFD, how far DEM is behind the race?

HF: 10 years ago we said we are 20 years behind. We are still 20 years behind!

KJ: 20 to 25 years behind! We do not use DEM that often. We do not use it as a defacto tool.

JG: both CFD and DEM are advancing quickly. CFD only in the past 10 years had enormous advances in terms of reliability and being representative

Prabhu Nott: I think it is an unfair comparison. Baselineing DEM with Molecular Dynamics (MD) would be a better comparison and the conclusions would be different.

**Question** from Filip Francqui: measurement techniques discussed today were focused mainly on the shear cell and consolidated samples. How about angle of repose and dynamic measurements? We did not talk about much about electrostatics.

HF: I agree that the current state of the art in powder flow characterization is focused much on confined measurements e.g. shear cell measurements. You are perfectly right that for dynamic systems we need new methods other than shear cells.

KJ: there are still a lot of tools that we all have that are underutilized.

TB: The only thing we do well is shear testing. The classical techniques such as Carr Index are still relevant but how the results are interpreted is the challenge.

**Question** from TB: We came up with 8 project titles. Please tell us which one you prefer most? (refer to voting on attachments)

KJ: measurement and characterization of KILOGRAM rheology

HF: we need to figure out what are the things that happen in meso scale.

JG: the one in cohesivity. Cohesion makes everything difficult.

OD: true multi-scale modeling is of interest. But I also recognize that if we do not have proper characterization of meso scale and it is essential

Prabhu Nott: micro-meso-continuum multiscale modeling

Rafaella: true multi-scale modeling.

Farhang Radjai: cohesivity

Christine Hreyna: bridging of scales multiscale modeling AND cohesivity

Massimo Poletto: the real core of the regimes we talked about is in the meso scale but it will be difficult to start with that. Therefore I go for measurement and characterization of KILOGRAM rheology.

Stefan Luding: we need DEM and the reason is behind is the number of particles to simulate.

**Question** to the industrial perspective speakers: have we addressed your issues during this workshop?

Judith Bonsall: we addressed the cohesion issues. The irregular flow AND Professor Meso are our greatest interest and I would like to be looked at.

Sean McClure: same comments as JB especially on the cohesivity and meso structures

Hugh Stitt: from practitioner point of view I have issues with characterization of cohesive powder flow and we do not know what we measure. So I vote for COHESIVITY

Paul Mort: From P&G's perspectives I vote for PIXIE DUST but from IFPRI's perspectives I vote both cohesion and meso.

Jin Ooi: cohesion

IFPRI's consultants:

Michel Louge: professor meso.....but cohesivity and multiscale

Mojtaba Ghadiri: multiscale is done via the work of Farhang Radjai....we do not understand the single particle to meso scale link.....we are not up to using the state

of the art technology.....I vote for “advanced characterization that enables us quick measurements both temporal and spatial”

## **Appendix 2 – Key Conclusions from Individual Sessions**

### **Session 1 – Characterize the State of the Art in Powder Flow**

In the first session, syndicates evaluated the state-of-the-art in powder flow and summarized their discussion in up to five bullet-points as shown in Appendix 1. The authors of this summary (Bell, Louge, Pasha) grouped those summaries as follows: Characterization, Discrete Element Method (DEM), Scale Bridging, Terminology and Definitions, and Other Topics. Below is a summary for each of these categories.

#### **Characterization**

Characterization of the onset of flow is known primarily in large scale, simple particle environments under consolidation. Hence the need for alternative characterization methods to address flow behavior in the dynamic regime under low consolidation stress.

#### **Discrete Element Method (DEM)**

DEM is more useful for qualitative assessment of flow fields than forces. It is often limited to large and cohesionless particles. Improved physics and computational power are required to model particles with more challenging properties (e.g. having small size, cohesion, odd shape, deformations under stress, etc.) at all scales. More work is needed on “calibration” and “validation”, as well as calibration standards. DEM is not consistently used in industry.

#### **Scale Bridging (from micro to bulk)**

Measurements from the particle level are insufficient to predict bulk behavior at different scales. There is a lack of constitutive equations, understanding, and approaches to link micro to meso to macro. While the most efficient simulations can handle about  $10^6$  particles, even a small system like a shear cell seldom has fewer than  $10^7$ , while a full-fledged industrial system can have more than  $10^{13}$ .

#### **Terminology and Definitions**

Terminology can be confusing or inconsistent in the literature. Because all flows do not behave similarly – incipient, quasi-static, intermediate, rapid etc., it is crucial to define them explicitly first. Micro-meso-macro transitions have particularly inconsistent definitions in the literature.

#### **Other Topics**

Inability to quantify, predict and measure flow inconsistencies, e.g. estimation of cohesive powder flow rate, intermittent flow and cohesive jamming dynamics.

There is not enough work reported on interactions of particle assemblies and an interstitial gas phase, e.g. for high velocity transport in packaging and filling, blanketing of silos with nitrogen, de-aeration during die filling, gas leakage flow in rotary valves in the presence of a pressure differential.

There are few fundamental studies on effects of vibration to promote flow.

Powder-wall interaction and stress state are unknown with flexible walls (e.g. bulk bags)

Education in particle technology (including solids handling) is very limited in university engineering programs, resulting in a low level of understanding both in practicing engineers and their management.

## **Session 2 – Confront the "Grand Challenge" to Relate Particle Properties, Microstructure, and Bulk Flow Behavior**

In the second session, participants discussed the “grand challenge” in powder flow with an eye toward relationships between single particle properties and bulk behavior. All syndicate bullet-points are given in Appendix 1. Findings were grouped as; Length Scale, Modeling, Characterization and Measurements, and Idealized vs. Real Systems. Below is a summary.

### **Length Scale**

We must describe powder flow at a scale larger than micro to “average out” single particle behavior. This scale is unknown in realistic systems without a clear definition and unified terminology (terminologies mentioned during the workshop included: “meso-scale”, “coffee-cup scale”, “toaster length scale”, “flowable units”, “coherence length scale”, “small bulk behavior”).

### **Characterization and Measurements**

With regards to the length scale discussed above, the appropriate parameters to be measured at this “coherence” length scale are not known. Fluctuations in the system must be characterized and measured to reveal dynamic characteristics of the bulk powder. Fundamental studies should move away from ‘idealized’ systems and start investigating real complex particulates.

### **Modeling**

A multi-scale approach should be devised with high intensity zones where DEM would handle individual microscopic interactions directly, while “average” models would then capture bulk behavior on the larger scale. In this context, there is a need to standardize calibration and verification approaches in modeling particulate systems.

## **Session 3 – Define Three Scientific Questions that IFPRI and Other Funding Sources Should Promote**

In the last syndicate session, participants defined three scientific questions that IFPRI and other funding sources should promote on powder flow. All syndicate bullet-points are given in Appendix 1. Findings are grouped as: Length Scale, Characterization, Modeling, Single Particle Properties, and Other Topics. A summary follows.

### **Length Scale**

The most highly-rated question focused on defining the relevant and appropriate length or time scale over which fluctuations decay. This idea was dubbed as “confronting clusters with Professor Meso”.

### **Characterization**

Characterization methods must be applied on a suitable length scale (dubbed as the “Kilogram Sample” or “Coffee Cup Sample”) to measure the dynamic behavior of cohesive powder. In other words, a scale-down strategy should be devised to characterize flows with a test of small size, with an eye toward predicting flows on a higher length scale, such as fluctuating flows from hoppers.

### **Modeling**

Participants echoed comments made in session 2 on this topic.

### **Single Particle Properties**

The question to be addressed is ‘can we predict bulk flow behavior once single particle properties such as cohesion and size distribution are characterized?’

### **Other Topics**

Initiate a state-of-the-art review of rheological models in powder flow.

Explore effects of vibration as a mean of flow promotion.

Stress state of material in Flexible Intermediate Bulk Containers (FIBC, aka bulk bags and Super Sacks®) during filling, storage, and agitated discharge.

## Appendix 3 – Email Dialog the Week After the Workshop (pasted here in the sequence in which it was received).

**From:** James Michaels  
**Sent:** Monday, January 30, 2017 10:45 AM  
**To:** Bell, Timothy A  
**Cc:** 'Michel Louge, Paul Mort  
**Subject:** My Summary of the Workshop

Tim,

First, I want to thank Paul for his humorous and penetrating articulation of his syndicate's ideas for powder flow projects. Professor Meso was particularly helpful for me in unifying the outputs from the workshop.

Professor Meso is the key to understanding weakly confined active flows - aka the intermediate flow regime. We all struggled to define "meso" - which means to me that this is a key unknown in characterizing these flows. More generally, we need to characterize and describe quantitatively the structure of these flows - the spatial and temporal distribution of density, velocity, and stress - if we are ever going to be able to model them. Today, we have some capability to map the 3D velocity field and local density (with PEPT and impedance tomography, for example), but we have no tools for measuring local stress in moving fine, cohesive powders. So, in my understanding, Prof. Meso is an experimental grand challenge to characterize these complex flows. This has an analogy in the characterization of turbulent flows.

The multiscale modeling project ties directly into Prof. Meso, as it is the means of simulating these flows and relating them to material (particle) properties. The critical unknown here is how to describe the constitutive behavior of flowing powders - their rheology. There seemed to be disagreement in the room about how advanced non-local rheological models are (Farhang and Stefan suggested they are "complete" - but most people were unaware of this). I am certainly ignorant of any model that is able to quantitatively describe things like shear banding and fluctuations in agitated powders. It feels like we're in a similar state as the early days of turbulence theory development. There does seem to be a consensus building that DEM is best suited to relate the constitutive parameters in continuum models to particle properties rather than using it for macroscale simulations. I thought Olivier Desjardin's comments about the community's fixation on DEM were interesting - perhaps a warning that we should consider other simulation methods).

Karl Jacob's powder-in-a-coffee-cup project grew out of our group's discussion of characterization of powder at the mesoscale. We couldn't agree what that meant, so the discussion shifted to being able to make meaningful measurements on relatively small amounts of powder. My interpretation of this project is that it is a continuation/expansion of Gaby Tardos' Couette flow project. The grand challenge is to create a well characterized flow (ideally homogeneous and rheometric) from which the constitutive flow parameters of the rheology models can be measured directly. This connects to Rafaella's comments about measuring  $G'$  and  $G''$  in complex fluids.

Finally, I think the Pixie Dust and cohesion projects brings the focus of all of this back to the particles themselves. It is obvious that flow of cohesive particles is qualitatively different than cohesionless ones, but we can't describe this quantitatively. The same goes for adding small amounts of flow aids/lubricants (pixie dust). Perhaps the grand challenge here is simply to stop avoiding studying these things because they are more difficult studying non-cohesive spherical particles?

A long time ago, Roger Place and I initiated a gap analysis process to IFPRI that a began with a simple question: why can't we design or simulate "x" (a particle process) from first principles? As you explore this question, you learn where the major gaps in understanding are. (This is the same concept as the "five whys" in six sigma/lean methodology). I feel that the workshop did a good job of highlighting what are the critical gaps in our understanding of powder flow that prevent us from modeling/predicting them. I hope we can summarize and share these with the community at large so we can start making some progress to close them.

I hope this isn't hopelessly muddled and it's useful.

Jim

**From:** Mort, Paul

**Sent:** Monday, January 30, 2017 11:35 AM

**To:** Bell, Timothy A, James Michaels

**Cc:** Michel Louge

**Subject:** RE: My Summary of the Workshop

I think we are still looking for Prof Meso; perhaps we should modify the title to "Finding Professor Meso", in which case we can have fun with role parodies from the "finding nemo" movie. (Perhaps that can take us to active suspensions.)

Indeed, the interpretation of the meso scale is variable, and can depend on the problem being solved. Stefan Luding made this point in the larger group, and I agree with him to a large extent. However, I think, as a way forward, a more rigorous definition of a meso scale for powder/granular flow is needed, and that rigorous treatment should consider the nature of fluctuations in flow, stress, and packing fraction (compression/dilation), where measurements of such fluctuations are needed over a coherent sampling volume, over some range of scrutiny scaling. Here, the example of Gaby's Couette shows the limit of what can be obtained with discrete sensors, each measuring a different sampling volume location, and each with a different scale of scrutiny.

I'd also like to highlight our syndicate's focus on cohesion. It wasn't obvious at the outset of the discussion (meso and pixie dust being the first two points of discussion), but cohesion was clearly a unanimous choice for the third topic, bringing at least 3 separate perspectives into focus, hence "cGOHESION UNITED". Thanks to Tim for the lower-case "c".

Best,  
Paul

**From:** Michel Louge  
**Sent:** Monday, January 30, 2017 11:50 AM  
**To:** James Michaels  
**Cc:** Bell, Timothy A; PASHA, MASSIH; Paul Mort  
**Subject:** Re: My Summary of the Workshop

Dear Jim,

Thank you for your thoughtful and helpful summary.

The mesoscopic scale is the wild card that nature dealt to us for two-phase systems, in which individual particles immersed in a continuum fluid effectively adopt the volume fraction that they please. The traditional approach to average this scale out, in a similar way that turbulence closures are produced, rarely fulfill its promise.

In this context, it makes sense to encourage thoughtful research deploying all three modern tools of the trade (experiments with modern diagnostics, numerical simulations and models) to understand the role of the mesoscopic scale.

This is what most of our plenary speakers have articulated or recently studied: Nott with recirculating structures in a shear cell; Hrenya with cohesion-induced clusters; Luding with the concept of surrogate "meso-particles"; Daniels with force chain visualization; Radjai with fabric tensor anisotropy; and Ocone with an integrated micro-meso-macro approach.

In my view, studying the mesoscopic scale across regimes of powder flow unifies most discussions at the workshop. From the industrial standpoint, the concepts of "Pixie Dust", cohesion and powder-in-a cup also constitute useful anchors of IFPRI-sponsored projects that would deal with the mesoscale.

In this context, it would be good to look for PIs who are prepared to study the mesoscale in all regimes of powder flow, while considering effects of surface forces and/or particle additives.

Best regards,

Michel

## Appendix 4 – Implications of the Workshop – Email from Michel Louge

**From:** Michel Louge  
**Sent:** Tuesday, March 21, 2017 9:33 AM  
**To:** Bell, Timothy A  
**Cc:** PASHA, MASSIH  
**Subject:** paragraphs for the report

Dear Tim,

I wrote the paragraphs below as a first attempt to summarize implications of the workshop. If you think these words are worthwhile, please feel free to incorporate them in the report.

Thanks!

Best regards,

Michel

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The IFPRI Powder Flow Workshop (PFW) was inspired by presentations from top academic and industrial leaders. Subsequent collective brainstorming of participants was organized around three questions, starting with an acknowledgement of the state-of-the-art, followed by an account of current challenges, and ending with recommendations for further research. The following paragraphs attempt to summarize deliberations and distill a recommendation.

Powder flow arises in crucial industrial equipment such as hoppers, feeders, chutes, mixers or fluidized beds. Since our last 2003 PFW in Bremen, the field has resonated with the enticing prospect of simulating an entire process, thereby avoiding complicated modeling while producing hitherto inaccessible insight. However, although discrete element modeling (DEM) numerical simulations of powder flow keep on growing and improving, they are far from reproducing systems of interest to IFPRI members.

Despite a steady increase in computational power, DEM can only stage particle populations that are smaller than realistic processes by two to seven orders of magnitude. Current researchers meet this challenge in two steps: first, they interrogate DEMs to derive constitutive laws for small "mesoscopic" domains that are behaving collectively, such as clusters or small force networks. They then incorporate these laws in continuum models based on partial differential equations (PDE) to handle larger systems.

Such bottom-up approach, while sounding attractive, is far from trivial to implement, but is promising and worth supporting further. With tongue in cheek, this strategy was dubbed "Finding Professor Meso" (FPM). Here, one discerns a resemblance with the early days of practical turbulence modeling, when the k-epsilon approach, for example, was refined and calibrated against standard flows.

FPM's major challenges include...

(1) ... establishing proper boundary conditions (BC) for PDEs. BCs often play second fiddle to constitutive laws, for example in the  $\mu(I)$  or fluidity paradigms, which ignore BCs altogether.

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(2) ... recognizing the diversity of powder flows. As corollary to (1), powder flows are crucially affected by their confinement and the nature of their boundaries. For example, free surface flows, split bottom cells and extruders have dissimilar contact force networks. Chute flows achieve different mass flow rates on erodible, flat, or rough bases. Therefore, any funded project should produce a taxonomy of generic powder flows, study as many of those as possible, and compare/contrast them for general insight.

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(3) ... running mesoscopic DEMs with measurable and realistic particle properties. For example, DEMs assume particle friction that rarely conforms to realistic values; cohesive forces deriving from collective interactions, such as electrostatics, are too complicated to handle exactly; fine particles can modify flow behavior for good (e.g. fumed silica, more generally nicknamed "pixie dust") or for ill; particle shape or distribution can evolve along the flow; etc. If DEMs cannot handle actual particle features, generic flow standards should specify how to construct effective DEM "particle properties" from characterization equipment that is both widely available and relevant to the confinement and boundaries of the powder flow under consideration.

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(4) ... developing experiments and instrumentation to validate the FPM approach in the generic flows mentioned in (2) and (3). Because DEMs require validation, physical tests remain a crucial component of the "triad" identified at the Bremen 2003 workshop, consisting of experiments, numerical simulations and theoretical modeling, all bonded with particle characterization as a "glue". In this context, the minimum size of an experiment (dubbed "powder in a coffee cup"), is an important down-scaling parameter that funded projects should establish.

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Our plenary speakers, discussion leaders and panel members demonstrated that theory, experiments and numerical simulations have now progressed to the point where a rational mesoscopic approach can be deployed for generic powder flows. While it is clear that DEMs are far from handling an industrial process component in its entirety with realistic particle properties, they continue to offer insight on collective interactions that can guide design and model development at the mesoscopic scale. Meanwhile, academic speakers showcased recent theories that offer great promise for modeling on the large scale, particularly with respect to the handling of force chains and clusters. "Finding Professor Meso" in a range of generic powder flows, with identification of a minimum scale for relevant powder characterization, and with a clear path to informing PDE-based theories, should form the basis of a fruitful academic project with ultimate industrial benefit.

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# Attachments

## Attachment 1



Agenda

## Attachment 2



Participants

## Attachment 3



Syndicates