Granular Flow in a Rough Annular Shear: Validating DEM Simulations with Experiments
(Part 1)

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Sponsor: NETL/DOE

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Outline

• Who are we?

• “R2R”: Relevance to Roadmap

• Abbreviated Historical Review

• Granular shear cell: experimental setup

• Digital particle tracking velocimetry (DPTV)

• Granular shear cell experiments

• Single particle coefficient of restitution tests
The Particle Flow & Tribology Laboratory at Carnegie Mellon University...

We have 3 core competencies...

• Granular Flow

One of the most difficult areas of tribology relates to the multi-physics behavior of particulate materials—large or small. They can wear and damage relatively sliding materials, or they can be used to protect materials.

What is tribology?

Tribology is the study of interacting surfaces and the resulting friction, wear, and lubrication
Relevance to the 2006 Multiphase Technology Roadmap…

Pursuant to the 2006 *Report of the Workshop on Multiphase Flow*, this effort is to:

- Conduct experiments specifically designed to test different aspects (e.g., *boundary/wall effects*) of granular theory;
- Enable DEM modeling experts to collaboratively participate in the development of granular validation experiments;
- Develop experiments with well-defined single particle experiments which may provide insight into DEM modeling;
- Define relevant material properties for couette granular flow system.

D. Physical and Computational Experiments

- Measurements of near wall phenomena to establish wall boundary conditions.
- Small-scale experiments to provide data to improve and check sub-models; e.g., solid velocities (slip).
Review of Particulate flows in Sliding Contacts: Cohesive vs. Cohesionless

### Historical Review

**Granular shear cell: experimental setup**

**Digital particle tracking velocimetry (DPTV)**

**Granular shear cell experiments**

**Single particle tests**

**Conclusion**

### Particulate flows

#### Cohesive particulates

**Theory**
- Godec (1986) [63]
- Mathis & Louise (1986) [13]
- Hesmat et al. (1989) [119]
- Hesmat (1991) [12]
- Allam (1991) [12]
- Hesmat & Brewe (1991) [42]
- Hesmat (1993) [83, 139]
- Hesmat & Walton (1993) [17]
- Tardos (1995) [96]
- Diez & Breed (1997) [140]
- Klauser et al. (2000) [96]
- Hesmat (2000) [141]
- Massoudi & Mehrabadi (2001) [57]
- Bouquet et al. (2001) [80]
- Chen et al. (2002) [81]
- Jordanoff et al. (2002) [60, 69]
- Tardos et al. (2003) [63]
- Wornyo & Higgs (2005) [71]

**Experiment**
- Ogston & Lancaster (1967) [124]
- Hesmat et al. (1989) [119]
- Berdiev (1990) [65]
- Hesmat & Brewe (1991) [42]
- Hesmat (1993) [20, 83, 143]
- Hesmat & Walton (1993) [17]
- Higgin (1999) [77]
- Klauser et al. (2000) [96]
- Hesmat (2000) [141, 144]
- Kaur et al. (2001) [10]
- Boquet et al. (2001) [80]
- Chen et al. (2002) [81]
- Jordanoff et al. (2002) [60, 69]
- Kaur & Hesmat (2002) [9]
- Tardos et al. (2003) [63]

**Numerical Sim.**
- Mei et al. (2000) [56]
- Pillot et al. (2005) [70]

#### Cohesionless particulates

**Theory**
- Godec (1986) [13]
- Ristema (1990) [14]
- Edwards (1990) [145]
- Yu et al. (1994) [13]
- Higgin (1999) [77]
- Khorsani (1997) [38]
- Tardos (1996) [82]
- Bernis-Cazenave et al. (1999) [146]
- Zhou & Khorsani (2000) [87]
- Yu & Tichy (2001) [22]
- Massoudi & Mehrabadi (2001) [37]
- Zhou & Khorsani (2000) [87]
- Yu & Tichy (2001) [22]
- Massoudi & Mehrabadi (2001) [37]
- Zhou & Khorsani (2000) [87]
- Yu & Tichy (2001) [22]
- Massoudi & Mehrabadi (2001) [37]

**Experiment**
- Yu et al. (1994) [13]
- Savage & Jeffrey (1996) [14]
- Tardos et al. (1998) [82]
- Sawyer & Tichy (2001) [22]
- Massoudi & Mehrabadi (2001) [37]
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Annular Shear Cells - Background

Historical Review

Granular shear cell: experimental setup

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Single particle tests

Conclusion

- **Tardos et al. (1998)**
  - Measured only global torque

- **Veje et al. (1999)**
  - Measured velocity & spin using particle tracking technique

- **Mueth et al. (2000)**
  - Measured local properties in 3D using MRI, x-ray tomography and particle tracking techniques

Very slow linear speeds

- Both surfaces rotate
- Flow is entirely in kinetic region

Roughness is not quantified
Granular Shear Cell (GSC) Setup

- **P = 1/16 HP motor**
- **ω = 50 to 280 RPM**
- **U = 0.51 m/s to 2.9 m/s**
- **U/H = 8 s⁻¹ to 45.6 s⁻¹**

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Granular Shear Cell Working

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Merits of the Experimental Setup

- Measures local granular flow properties
- Quantifies imposed parameters
- 2-D transparent setup

Contact vs. Kinetic Regime

Grain Inertia Region or Granular Kinetic Region:
Instantaneous Collisions

Macro-Viscous Region or Granular Contact Region:
Long Lasting Collisions
Digital Particle Tracking Velocimetry (DPTV)

Autonomous Hi-Speed Video

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<table>
<thead>
<tr>
<th>Camera Settings</th>
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<td>Resolution</td>
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### Historical Review

Granular shear cell: experimental setup

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### Frame 1

<table>
<thead>
<tr>
<th>Journal Properties</th>
<th>Granule Properties</th>
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<td>Material</td>
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<td>Quantity</td>
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Image Processing Module

Historical Review

Granular shear cell: experimental setup

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Grey Scale

\[ \{0 \rightarrow 256\} \]

Threshold

Black and White

\[ \{0,1\} \]
Identifying Centroids

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- Processed region
- Region of Interest
- Clustering Pixels to get particles
- Identifying Centriods
Velocimetry

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Global Filtering
• Distance Criteria
• Velocity Criteria

Local Filtering
• Average Velocity
• 5 trials for each Setting

• Error bars are one standard deviation of 5 trials

• Each trial analyses 450 sets of frames

• Sets are chosen at equal intervals over 3000 frames
### Calculations

<table>
<thead>
<tr>
<th></th>
<th>Solid Fraction</th>
<th>Tangential Velocity</th>
<th>Slip Velocity</th>
<th>Granular Temperature</th>
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</thead>
<tbody>
<tr>
<td><strong>Calculations</strong></td>
<td></td>
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<tr>
<td><strong>Solid Fraction</strong></td>
<td>$v_i = \frac{N_i \pi r^2}{A_i}$</td>
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<tr>
<td><strong>Tangential Velocity</strong></td>
<td>$V_{T,i} = \frac{1}{N_i} \sum_{j=1}^{N_i} v_{T,j}$</td>
<td></td>
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<tr>
<td><strong>Slip Velocity</strong></td>
<td>$S = V_{T,w} - V_{T,1}$</td>
<td></td>
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</tr>
<tr>
<td><strong>Granular Temperature</strong></td>
<td>$T_i = \frac{1}{N_i} \sum_{j=1}^{N_i} \frac{1}{3} \left( (v_{T,j} - V_{T,i})^2 + (v_{R,j} - V_{R,i})^2 \right)$</td>
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</table>

**Abbreviations:**
- $N$: Number of granules
- $r$: Granule radius
- $i$: Bin number
- $T$: Tangential
- $R$: Radial
- $A$: Area

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GSC Results: A Representative Case

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Parametric Study on Roughness

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Parametric Study on Wheel RPM

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Parametric Study on Global Solid Fraction

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Coefficient of Restitution Drop Tests

Historical Review

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Marinack, M., and Higgs, C.F., In preparation for publication, 2009
Coefficient of Restitution Results

Brass Granule on Brass Plate

\[ y = -0.8774x^4 + 0.1602x^3 - 35.646x^2 + 81.23x - 38.586 \]

Coefficient of Restitution Results

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Coefficient of Restitution Results

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Steel Granule on Steel Plate

\[ y = -0.0636x^4 + 0.7622x^3 - 2.487x^2 + 3.3389x - 0.7773 \]

2 2.2 2.4 2.6 2.8 3 3.2

Velocity (m/s)

Coefficient of Restitution

Coefficient of Restitution Results

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Marinack, M., and Higgs, C.F., In preparation for publication, 2009
Coefficient of Restitution Results

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Chrome Steel Granule on Steel Plate

\[ y = -0.9389x^4 + 10.025x^3 - 39.97x^2 + 70.449x - 45.594 \]

Coefficient of Restitution Results

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<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of Elasticity E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bronze</td>
<td>41.0 - 125 GPa</td>
</tr>
<tr>
<td>Steel</td>
<td>68.9 - 317 GPa</td>
</tr>
<tr>
<td>Chrome Steel</td>
<td>193 - 234 GPa</td>
</tr>
<tr>
<td>Tungsten Carbide (WC)</td>
<td>669 - 696 GPa</td>
</tr>
</tbody>
</table>

Conclusion

• Local flow properties were measured using DPTV

• Roughness was quantified

• Parametric studies were conducted on wheel roughness, wheel rotation rate and global solid fraction

• Single particle coefficient of restitution tests
Future Work

1. Conduct experiments with different materials (more CFB relevant), particles types, and shapes
2. Measure wall shear stresses in shear cell and CFBs
3. Quantify friction and surface roughness of particles and walls
4. Parallelize and generalize DPTV method
5. Evaluate continuum and DEM against experiments
Acknowledgements

- Other PFTL students who have contributed to this work
  - Brian Chin
  - Young Choi

- Sponsor
  - National Energy Technology Laboratory (NETL/DOE)
Thank you!!
Coefficient of Restitution Results

Various Granule - Plate Combinations

- Brass on Steel
- Tungsten Carbide on Steel
- Chrome Steel on Steel
- Steel on Steel
- Brass on Brass
- Chrome Steel on Stainless Steel