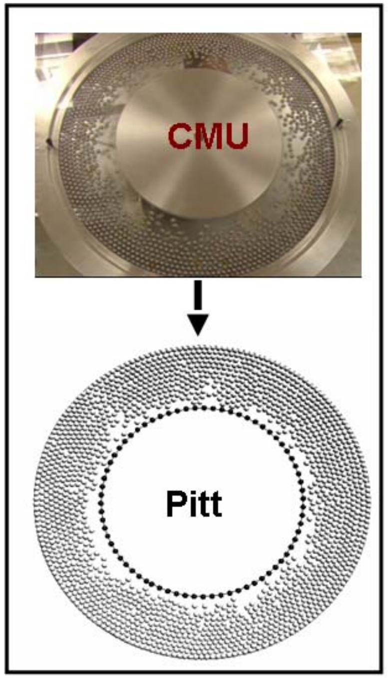
Granular Flow in a Rough Annular Shear: Validating DEM Simulations with Experiments

(Part 1)

C. Fred Higgs III
***PhD Students*: Venkata Jasti*, Martin Marinack, Jr.**
Particle Flow and Tribology Lab
Mechanical Engineering Department
Carnegie Mellon University (*CMU*)

Collaborator: Joe McCarthy *(See Part 2)*
University of Pittsburgh (*Pitt*)
Chemical & Petroleum Engineering Department



Sponsor: NETL/DOE

NETL 2009 Workshop on Multiphase Flow Science
Morgantown, WV
April 23, 2009

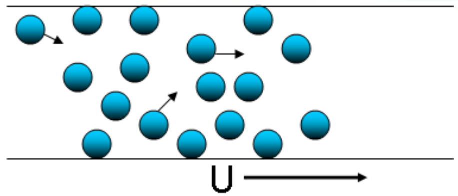
Outline

- 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

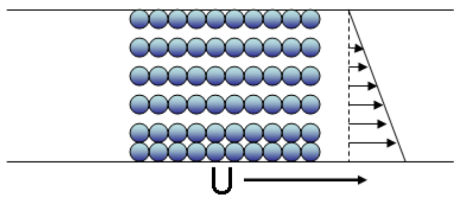
The **Particle Flow & Tribology Laboratory** at Carnegie Mellon University…

We have 3 core competencies…

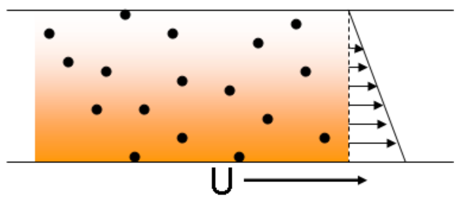
- Granular Flow



- Powder Flow



- Slurry Flow



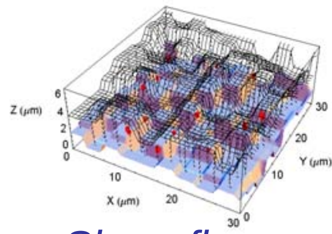
One of the most difficult areas of tribology relates to the multi-physics behavior of particulate materials– large or small. They can wear and damage relatively sliding materials, or they can be used to protect materials.

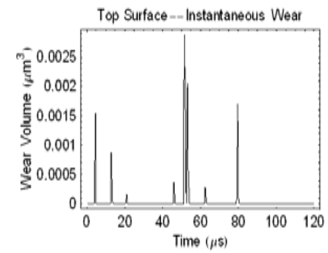
What is tribology?

Tribology is the study of interacting surfaces and the resulting friction, wear, and lubrication

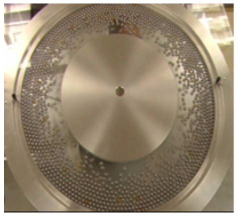
Our strength is that we conduct:

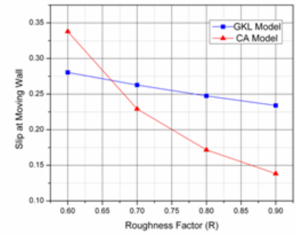
Experiments | Model/Simulations | Predictions



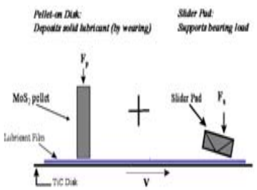


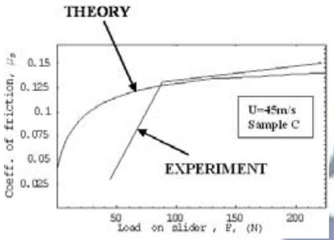
Slurry flows





Granular flows





Powder flows

Relevance to the 2006 Multiphase Technology Roadmap…

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).

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.

PFTL

Review of Particulate flows in Sliding Contacts: Cohesive vs. Cohesionless

Particulate flows

- **Cohesive particulates**
  - **Theory**
    - Godet (1984) [65]
    - Mathia & Louis (1984)[135]
    - Molerus & Nywlt (1984)[136]
    - Heshmat et al. (1989) [137]
    - Heshmat (1991)[15]
    - Allam (1991)[138]
    - Heshmat & Brewe (1991)[42]
    - Heshmat (1993)[83, 139]
    - Heshmat & Walton (1993) [17]
    - Tardos (1997)[95]
    - Diss & Brendle' (1997)[140]
    - Klausner et al. (2000)[96]
    - Heshmat (2000)[141]
    - Massoudi &Mehrabadi (2001)[57]
    - Bocquet et al. (2001)[80]
    - Chen et al. (2002)[81]
    - Iordanoff et al. (2002)[60, 69]
    - Tardos et al. (2003)[63]
    - Wornyoh & Higgs (2005)[71]
  - **Experiment**
    - Grattan & Lancaster (1967)[142]
    - Molerus & Nywlt (1984)[136]
    - Heshmat et al. (1989)[137]
    - Berthier (1990)[66]
    - Heshmat & Brewe (1991)[42]
    - Heshmat (1991)[2, 109]
    - Heshmat (1993)[20, 83, 143]
    - Heshmat & Walton (1993)[17]
    - Higgs et al. (1999)[7]
    - Klausner et al. (2000)[96]
    - Heshmat (2000)[141, 144]
    - Kaur et al. (2001)[10]
    - Bocquet et al. (2001)[80]
    - Chen et al. (2002) [81]
    - Iordanoff et al. (2002)[60, 69]
    - Kaur & Heshmat (2002)[9]
    - Tardos et al. (2003)[63]
  - **Numerical Sim.**
    - Mei et al. (2000)[56]
    - Fillot et al. (2005)[70]
- **Cohesionless particulates**
  - **Theory**
    - Savage & Jeffrey (1981)[89]
    - Godet (1984) [65]
    - Rietema (1984)[45]
    - Edwards (1990)[145]
    - Yu et al. (1994)[13]
    - Khonsari (1997)[38]
    - Tardos et al. (1998)[82]
    - Barois-Cazenave et al. (1999)[146]
    - Zhou & Khonsari (2000)[87]
    - 4& Tichy (2001)[22]
    - Massoudi & Mehrabadi (2001)[57]
    - Tsai & Jeng (2002)[77]
    - Mohan et al. (2002)[92]
    - Pappur & Khonsari (2003)[88]
    - Iordanoff & Khonsari (2004)[34]
    - MiDi (2004)[144]
    - Higgs & Tichy (2004)[33]
    - Massoudi & Phouc (2005)[29]
  - **Experiment**
    - Yu et al. (1994)[13]
    - Yu and Tichy (1996)[14]
    - Tardos et al. (1998)[82]
    - Sawyer & Tichy (2001)[22]
    - Massoudi & Mehrabadi (2001)[57]
    - Shen (2002)[147]
    - Higgs & Tichy (2004)[33]
    - MiDi (2004)[144]
  - **Numerical Sim.**
    - Savage & Jeffrey (1981)[89]
    - Zhou & Khonsari (2000)[87]
    - Sawyer & Tichy (2001)[22]
    - Pappur & Khonsari (2003)[88]
    - Higgs & Tichy (2004)[33]
    - Iordanoff & Khonsari (2004)[34]
    - Fillot et al. (2005)[70]
    - Massoudi & Phouc (2005)[29]
    - Jasti & Higgs (2006) [103]

Wornyoh, E., Jasti V. & Higgs, C.F., Journal of Tribology, 129, 438 (2007)

Annular Shear Cells - Background

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

Elliot *et al. (1998)*
Measured
local properties
using
imaging technique

•Both surfaces rotate

•Flow is entirely in kinetic region

Roughness is not quantified

Granular Shear Cell (GSC) Setup

Historical Review

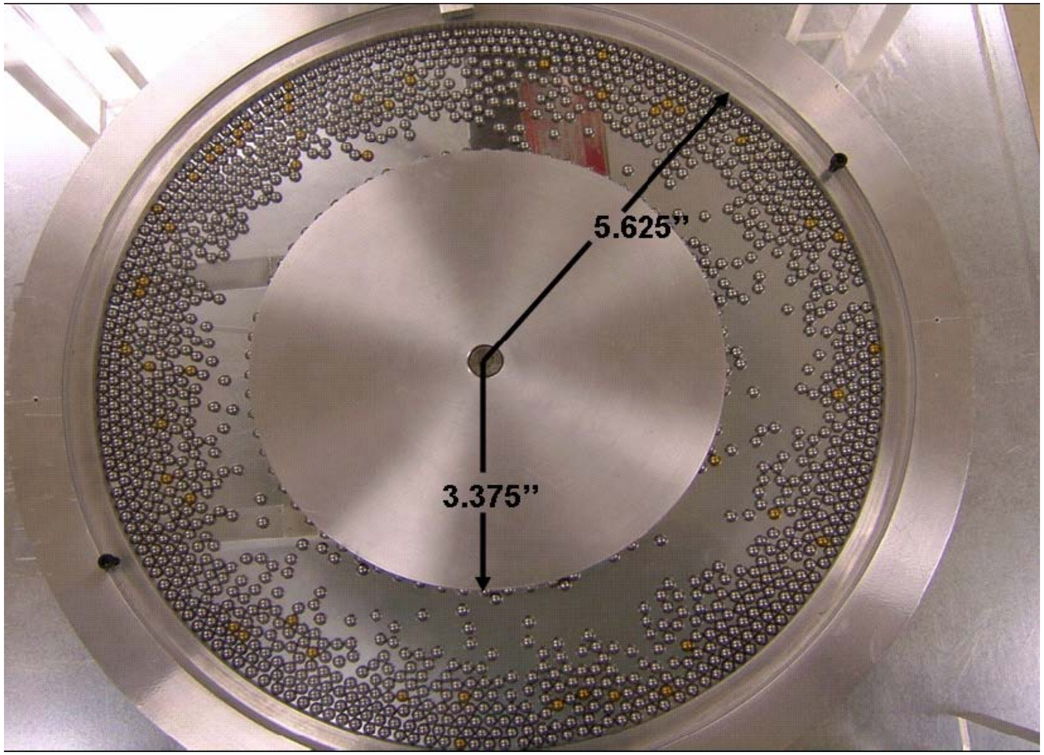
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



P = 1/16 HP motor

ω = 50 to 280 RPM

U = 0.51m/s to 2.9m/s

U/H = 8 s^{-1} to 45.6 s^{-1}

Granular Shear Cell Working

Historical Review

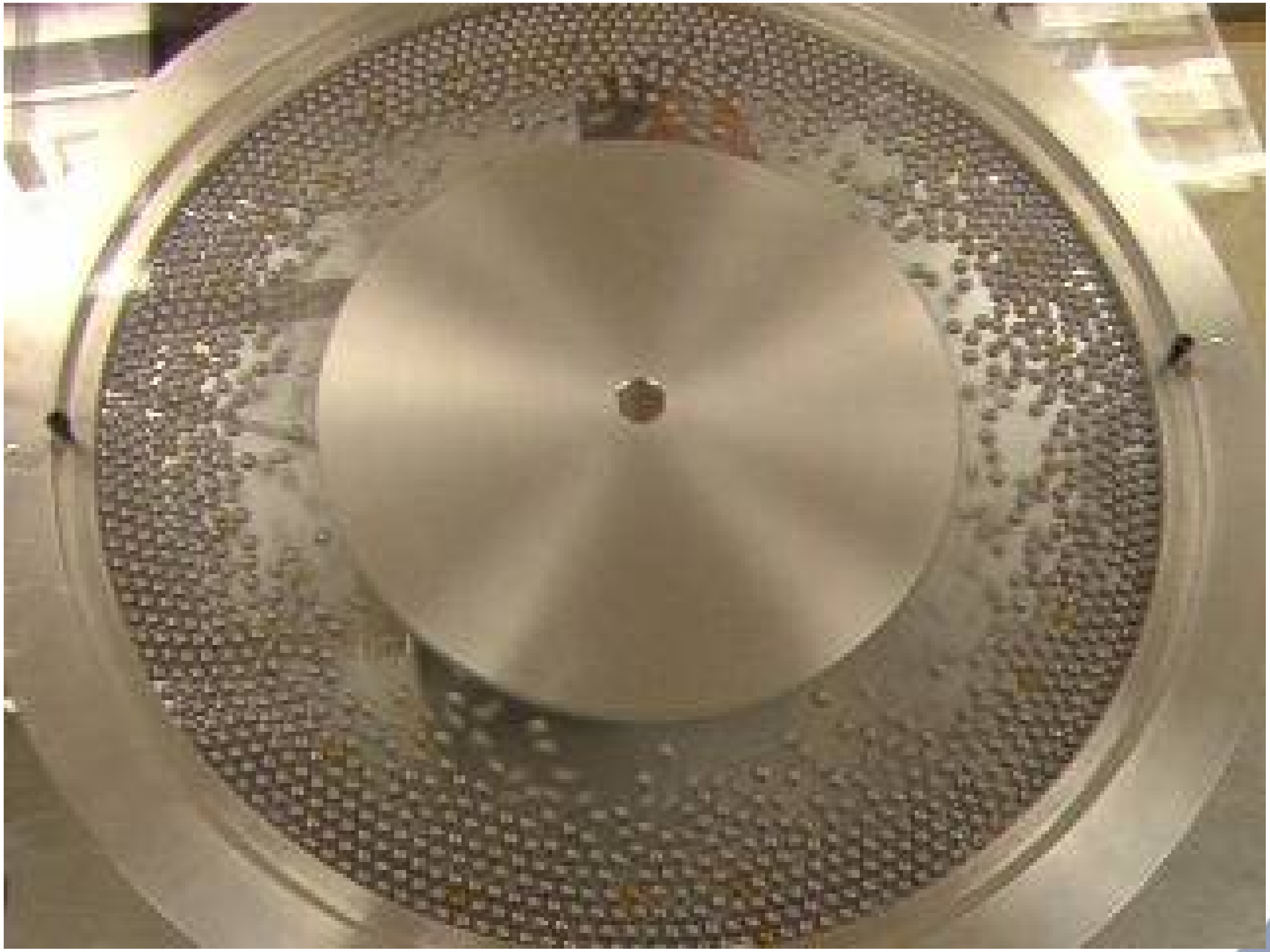
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Merits of the Experimental Setup

Historical Review

Granular shear cell: experimental setup

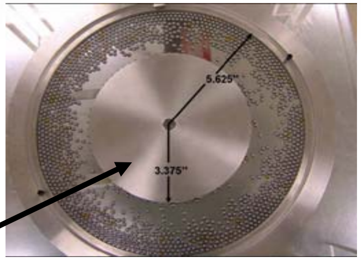
Digital particle tracking velocimetry (DPTV)

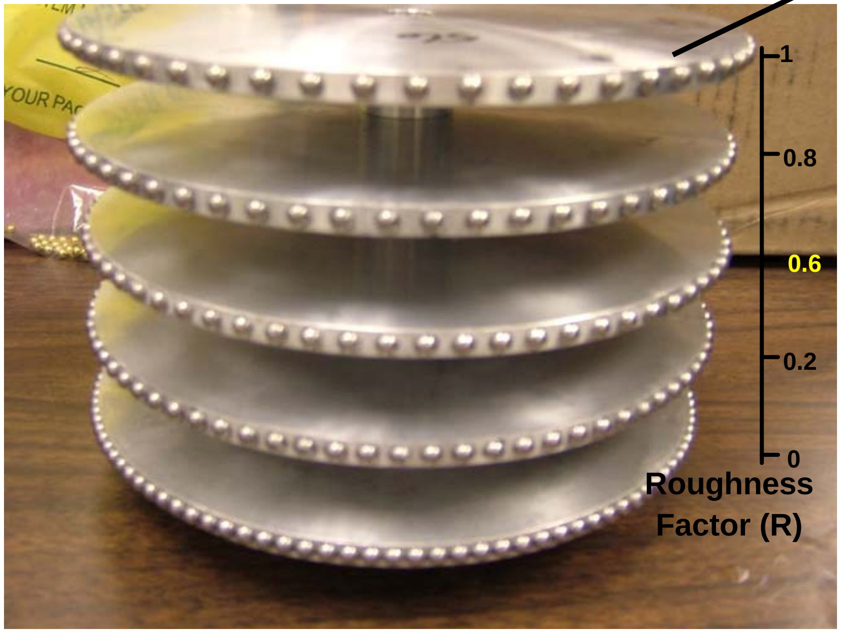
Granular shear cell experiments

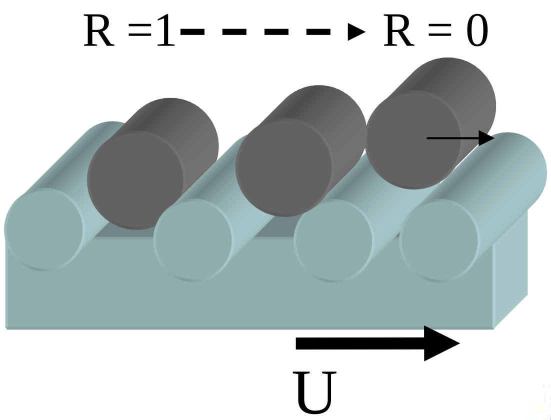
Single particle tests

Conclusion

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







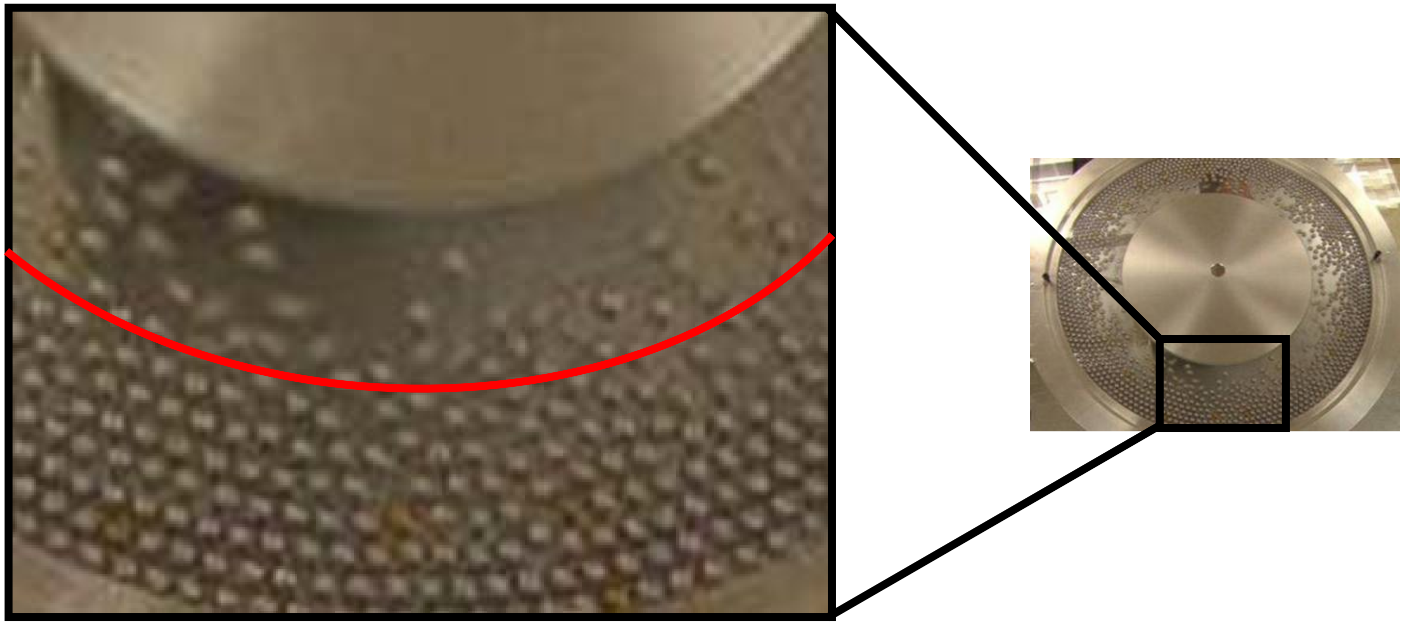
Varying wall roughness

Motivated by: Jenkins, J. and M. Richman, Journal of Fluid Mechanics, 1986. **171**: p. 53.

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*

Historical Review

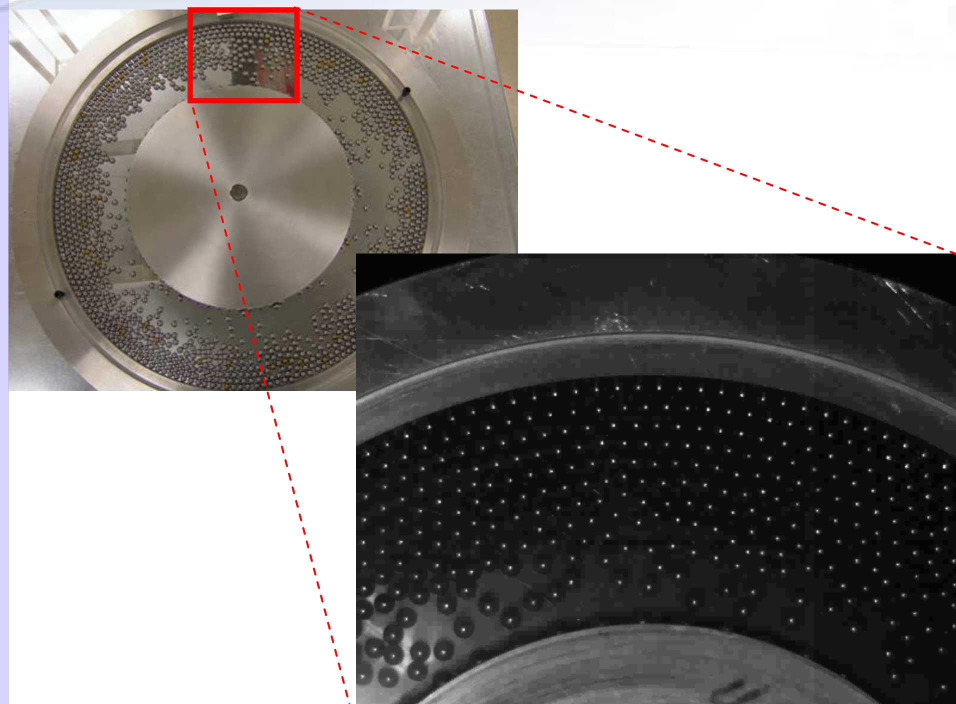
Granular shear cell: experimental setup

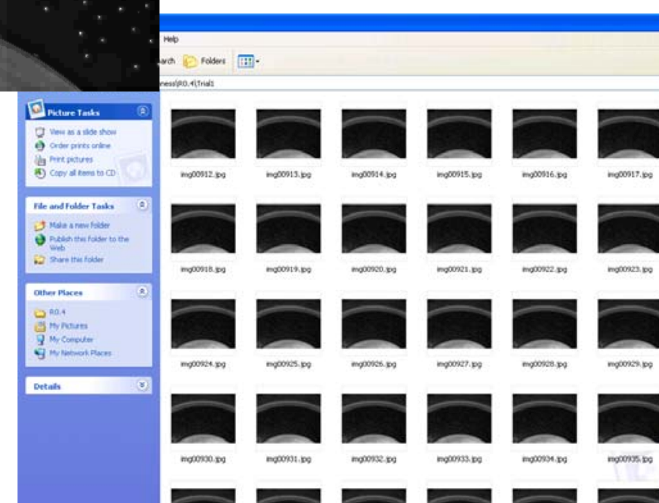
Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion





Camera Settings	
Resolution	512X384
FPS	1000-3000

Historical Review

Granular shear cell: experimental setup

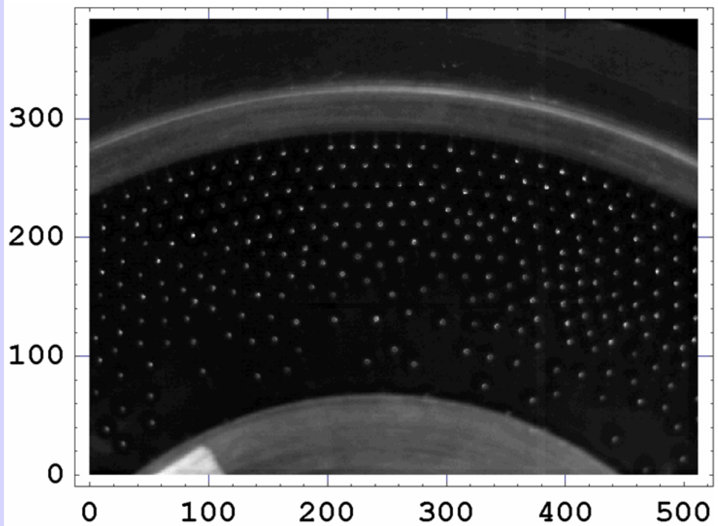
Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

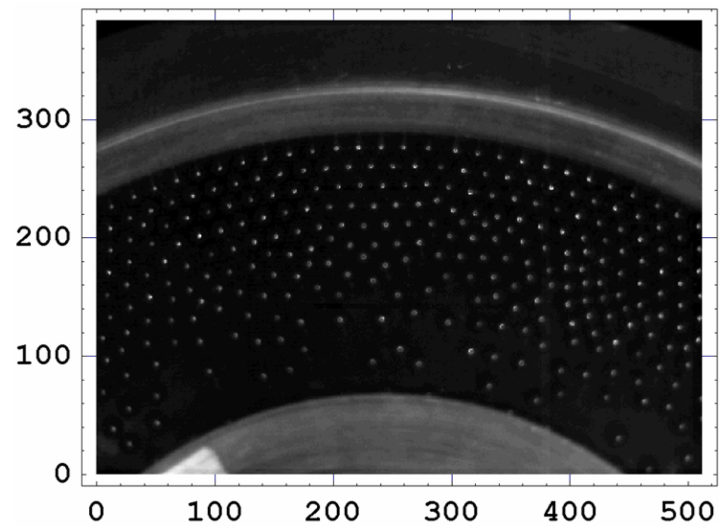
Single particle tests

Conclusion

Video Image Frames



Frame 1



Frame 2

Journal Properties		Granule Properties	
Material	Steel (1995T11)	Material	Steel (1995T11)
Roughness	0.8	Size	3/16in
RPM	240	Quantity	1633

Historical Review

Granular shear cell: experimental setup

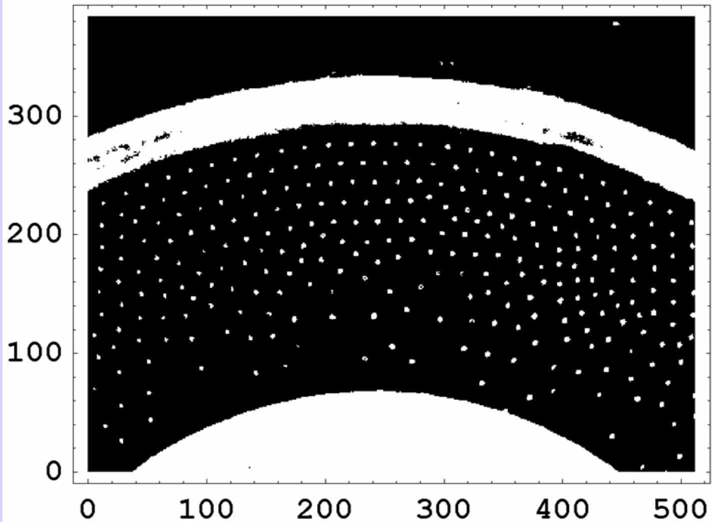
Digital particle tracking velocimetry (DPTV)

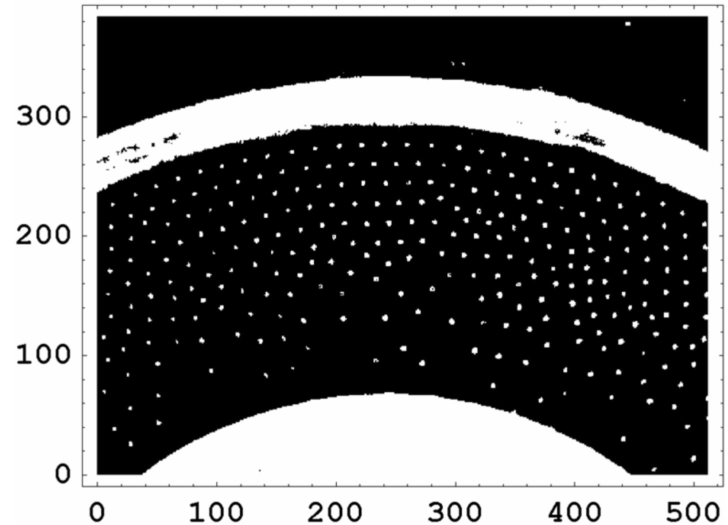
Granular shear cell experiments

Single particle tests

Conclusion

Image Processing Module



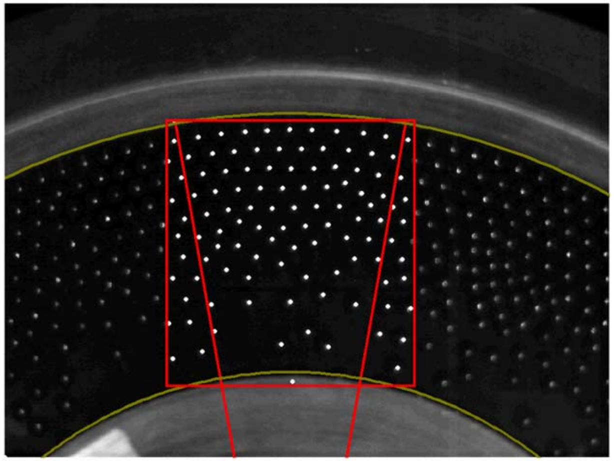


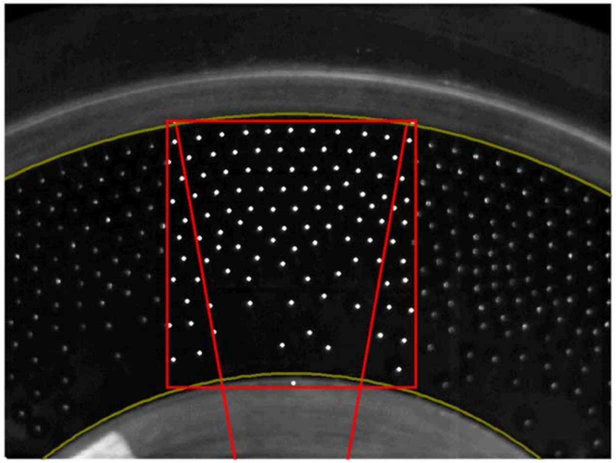
Threshold

Grey Scale → Black and White

{0 → 256} {0,1}

Identifying Centroids





$$\left\{\begin{matrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{matrix}\right\}$$

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

Historical Review

Granular shear cell: experimental setup

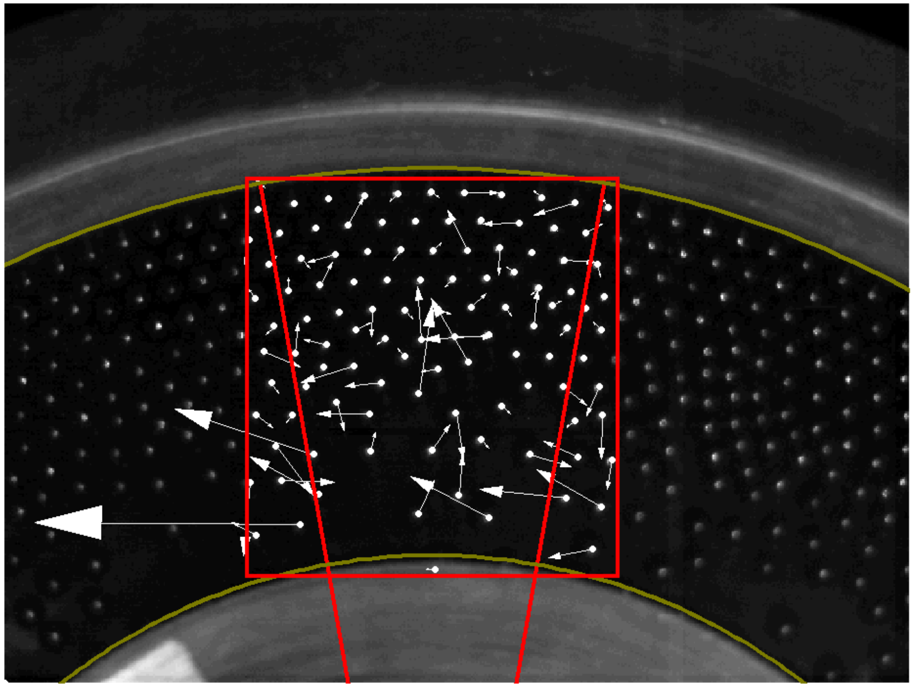
Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion

Velocimetry



Global Filtering

- Distance Criteria
- Velocity Criteria

Local Filtering

- Average Velocity

PFTL

Data Integration

Historical Review

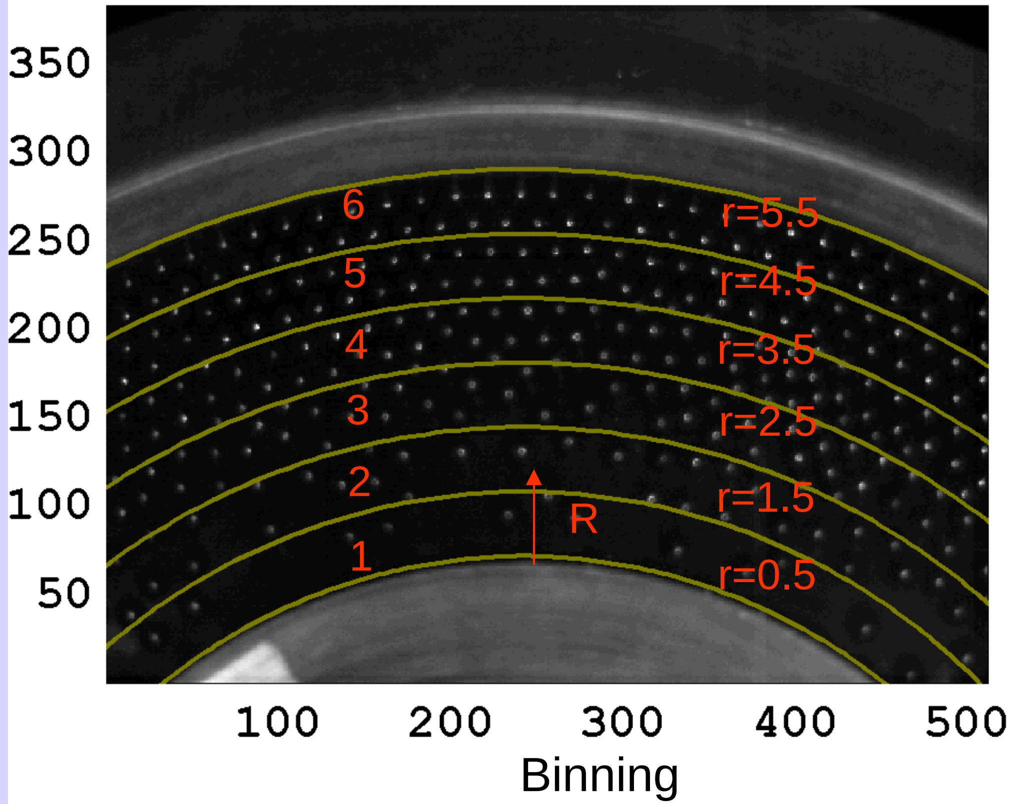
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



- 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

Historical Review

Granular shear cell: experimental setup

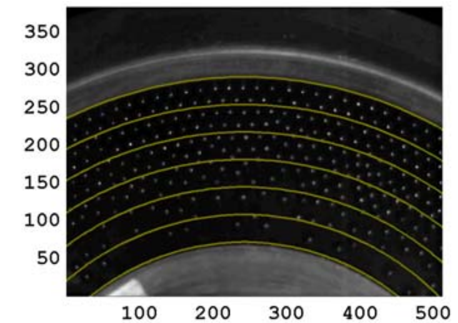
Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion

Calculations

$$\nu_i = \frac{N_i * \pi r^2}{A_i}$$	**Solid Fraction**	***N*: Number of granules** ***r*: Granule radius** ***i*: Bin number** ***T*: Tangential** ***R*: Radial** ***A*: Area** 
$$V_{T,i} = \frac{1}{N_i}\sum_{j=1}^{N_i} v_{T,j}$$	**Tangential Velocity**	
$$S = V_{T,w} - V_{T,1}$$	**Slip Velocity**	
$$T_i = \frac{1}{N_i}\sum_{j=1}^{N_i}\frac{1}{3}((v_{T,j} - V_{T,i})^2 + (v_{R,j} - V_{R,i})^2)$$		**Granular Temperature**

GSC Results: *A Representative Case*

Historical Review

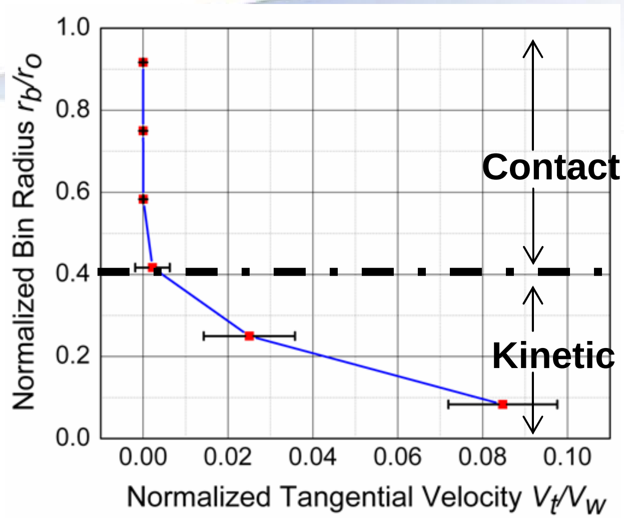
Granular shear cell: experimental setup

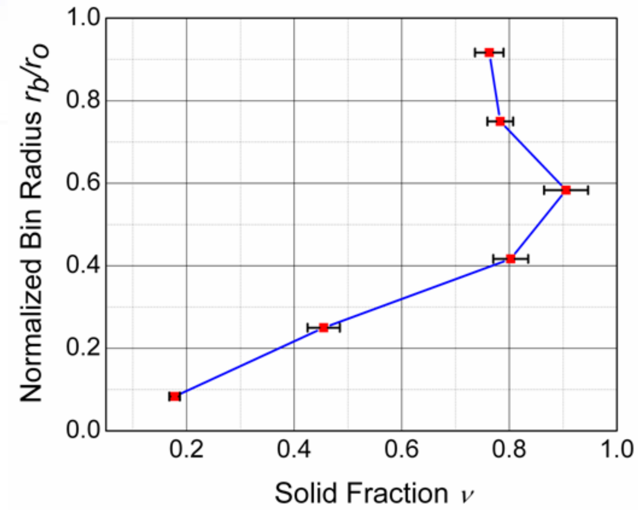
Digital particle tracking velocimetry (DPTV)

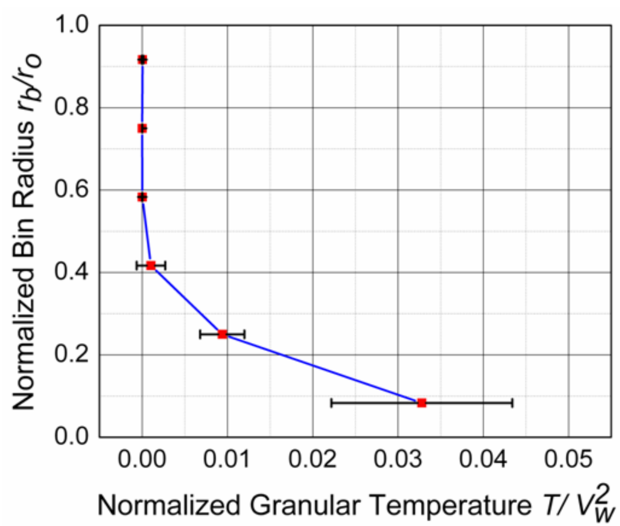
Granular shear cell experiments

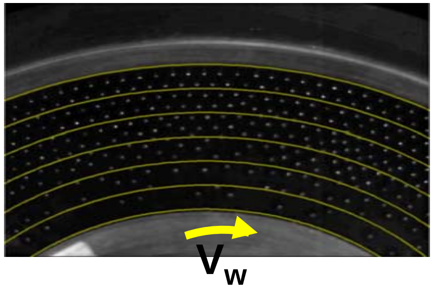
Single particle tests

Conclusion







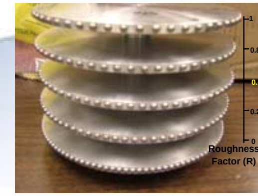


Journal Properties		Granule Properties	
Material	Steel	Material	Steel
Roughness	0.8	Size	3/16in
RPM	240	Quantity	1633

Jasti, V., and Higgs, C.F., *Physical Review E*, 2009

PFTL

Parametric Study on Roughness



Journal Properties		Granule Properties	
Material	Steel (1995T11)	Material	Steel (1995T11)
RPM	240	Size	3/16in
		Quantity	1633

Historical Review

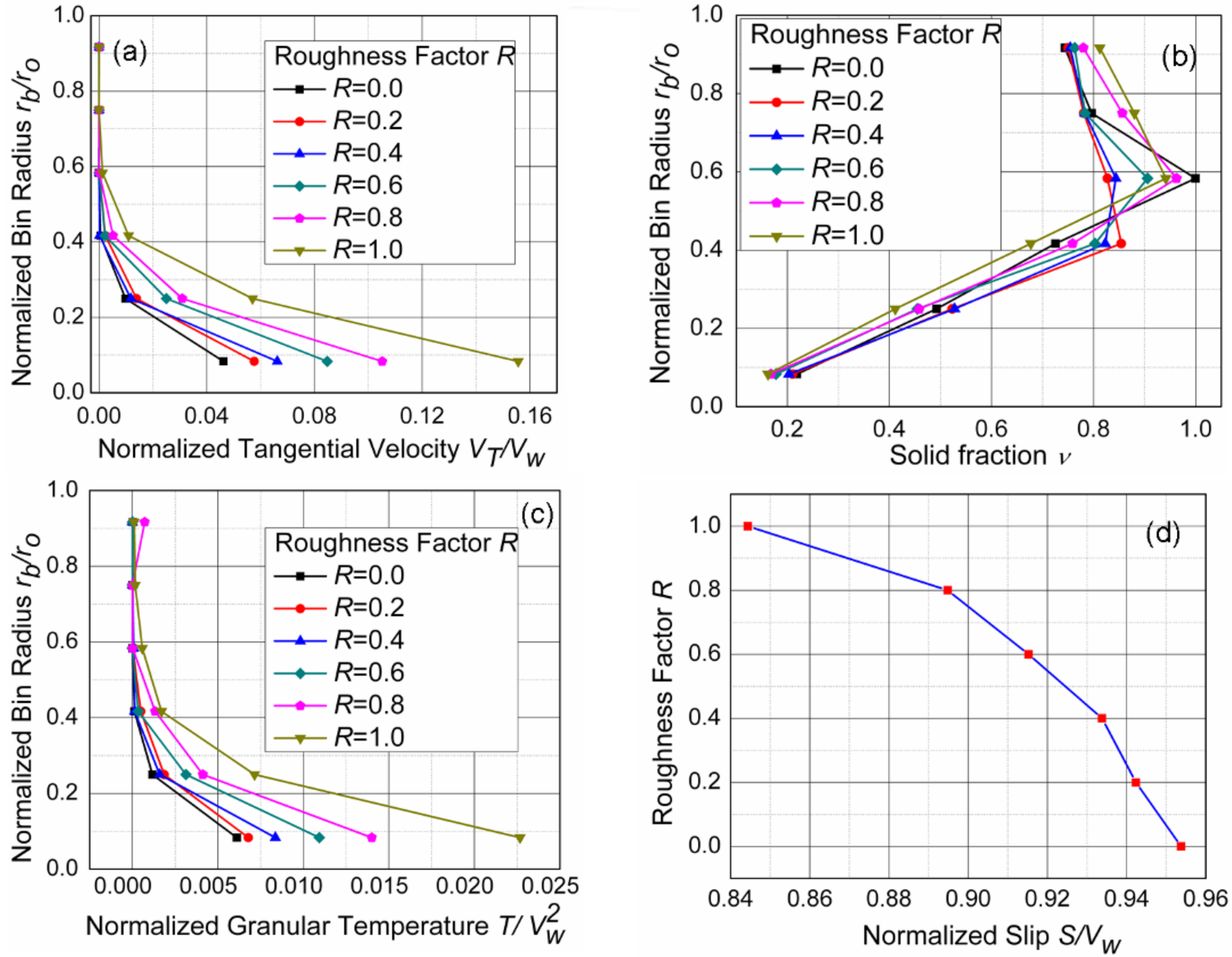
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

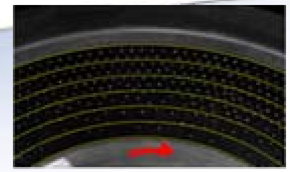
Single particle tests

Conclusion



Jasti, V., and Higgs, C.F., *Physical Review E*, 2009

Parametric Study on Wheel RPM



Journal Properties		Granule Properties	
Material	Steel (1995T11)	Material	Steel (1995T11)
Roughness	0.6	Size	3/16in
		Quantity	1633

Historical Review

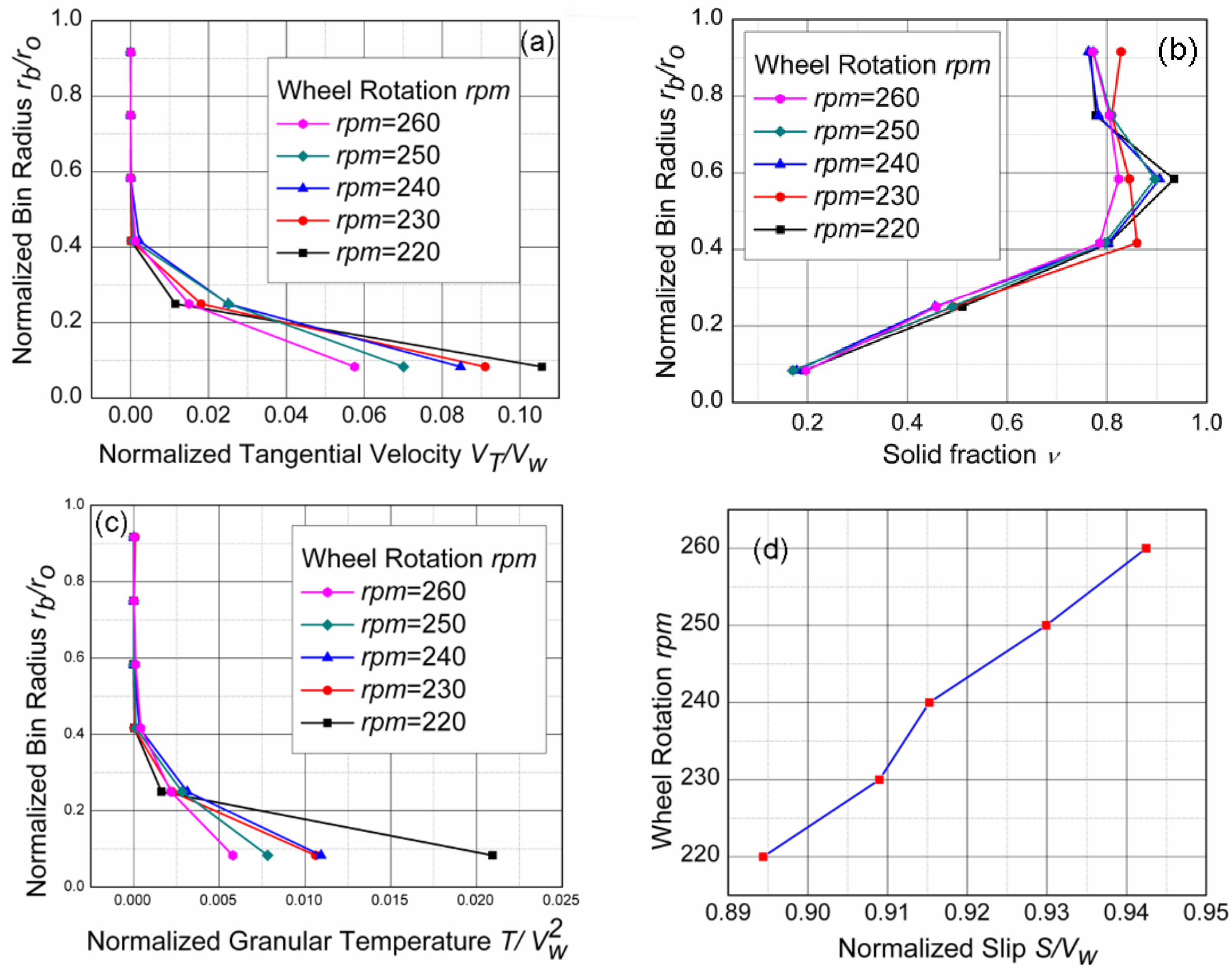
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Jasti, V., and Higgs, C.F., *Physical Review E*, 2009

Parametric Study on Global Solid Fraction

Journal Properties		Granule Properties	
Material	Steel (1995T11)	Material	Steel (1995T11)
Roughness	0.6	Size	3/16in
RPM	260		

Historical Review

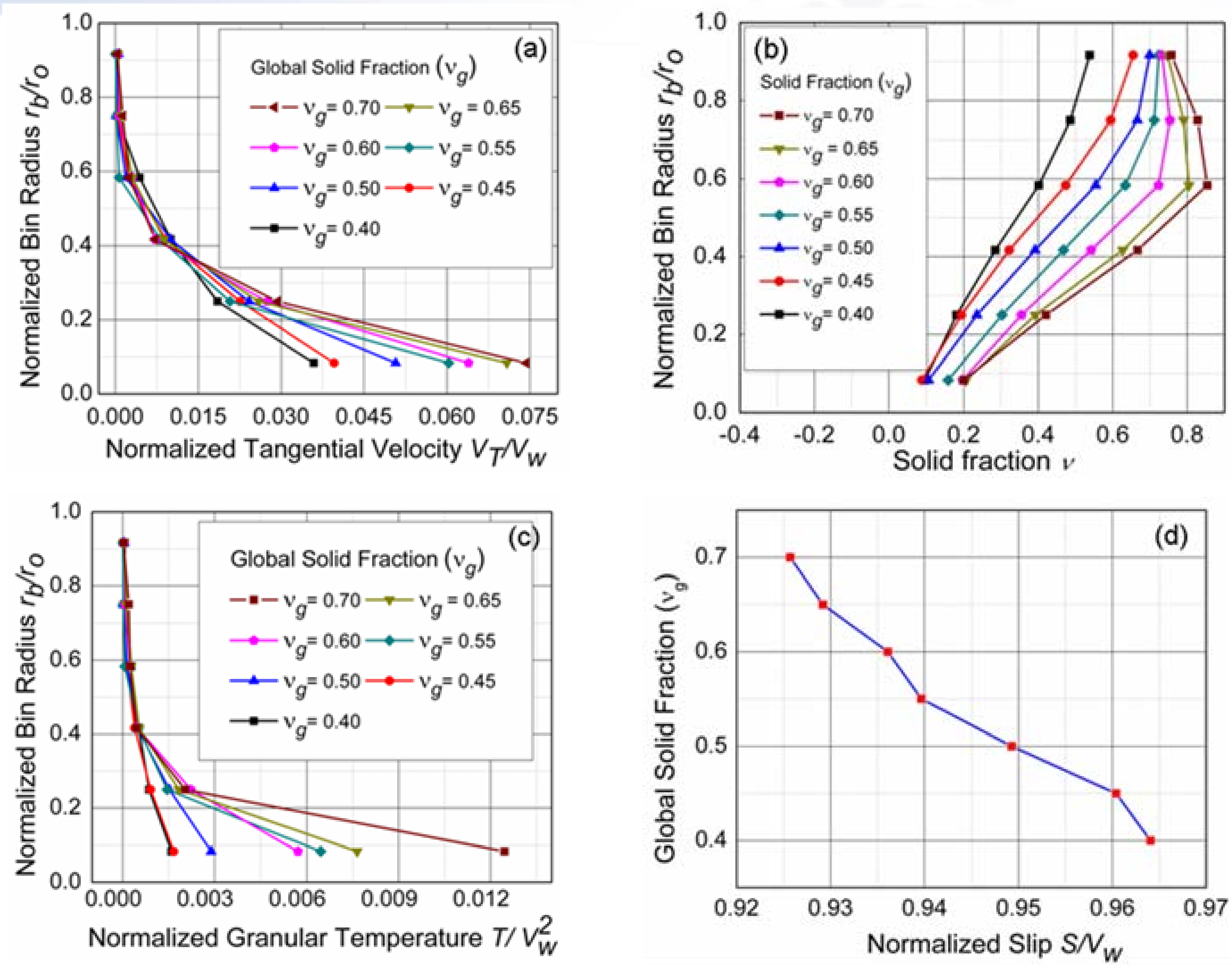
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Marinack, M., and Higgs, C.F., *In preparation for publication*, 2009

Coefficient of Restitution Drop Tests

Historical Review

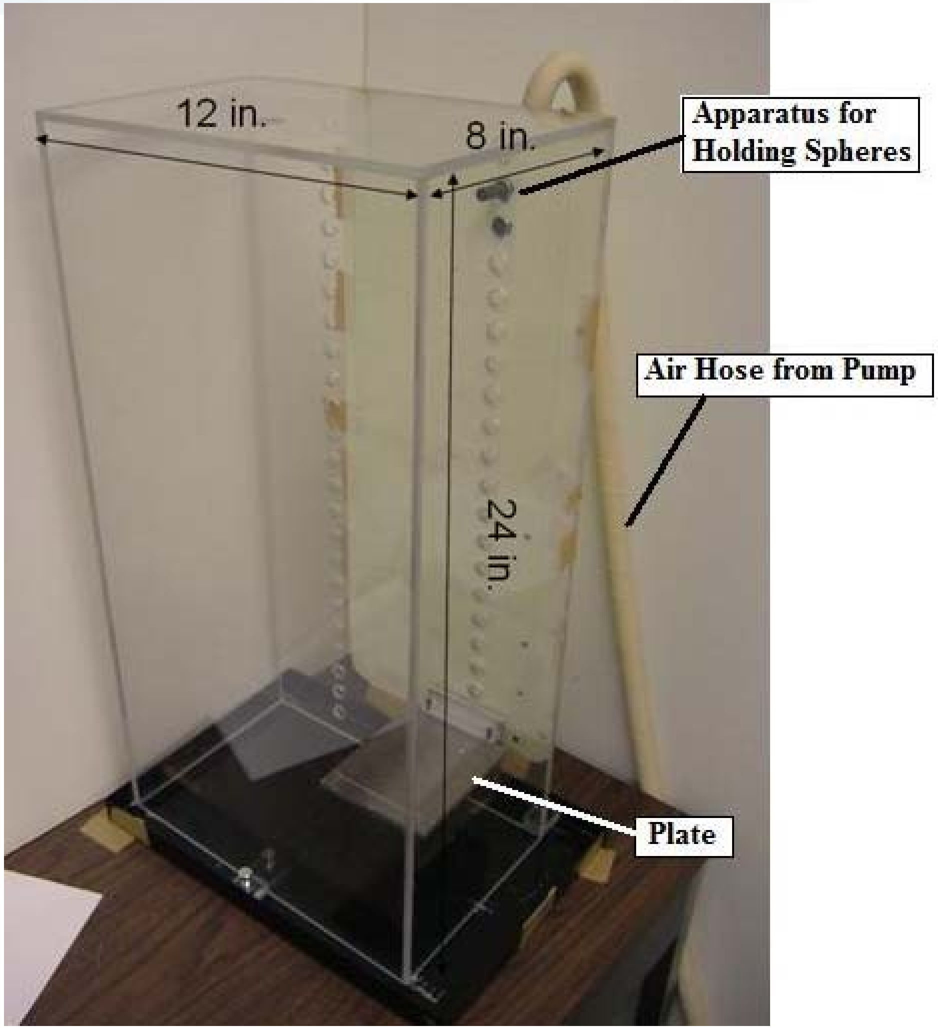
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Marinack, M., and Higgs, C.F., *In preparation for publication*, *2009*

Coefficient of Restitution Results

Historical Review

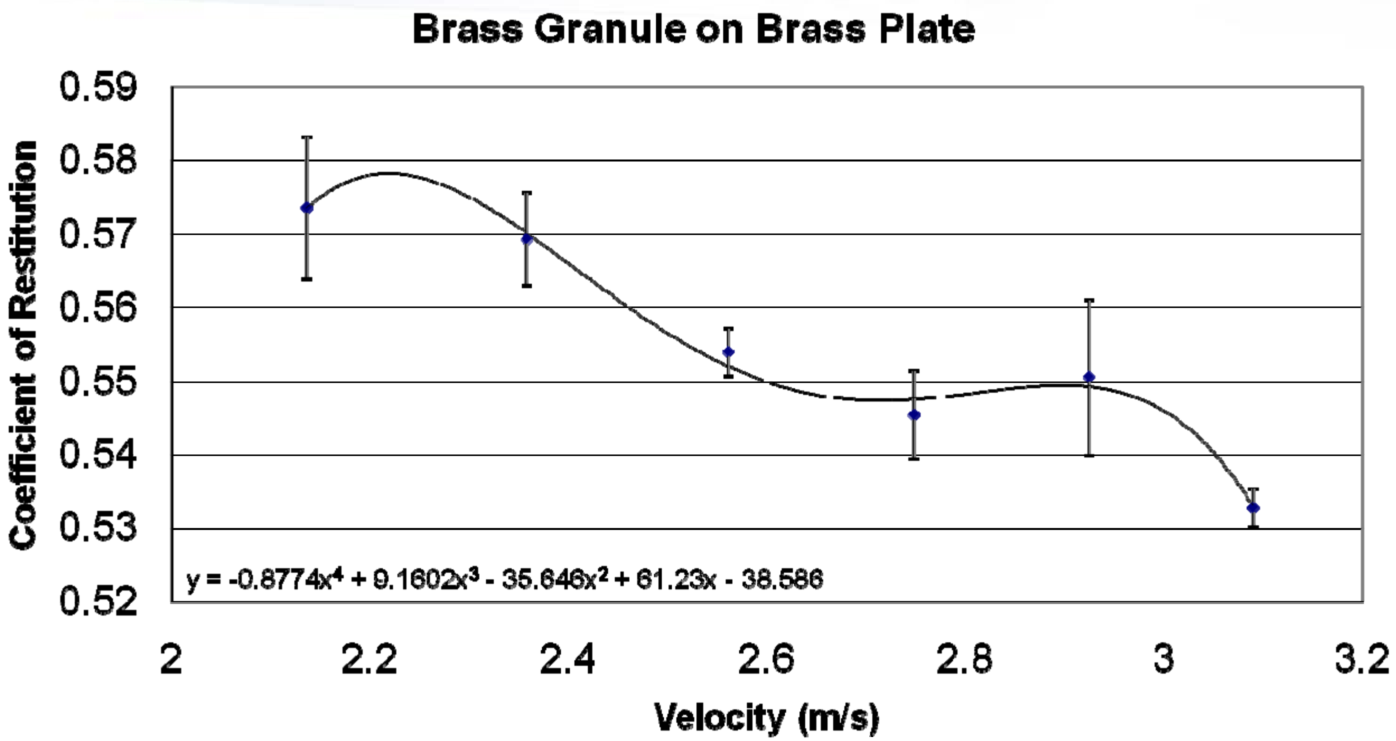
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Marinack, M., and Higgs, C.F., *In preparation for publication*, 2009

Coefficient of Restitution Results

Historical Review

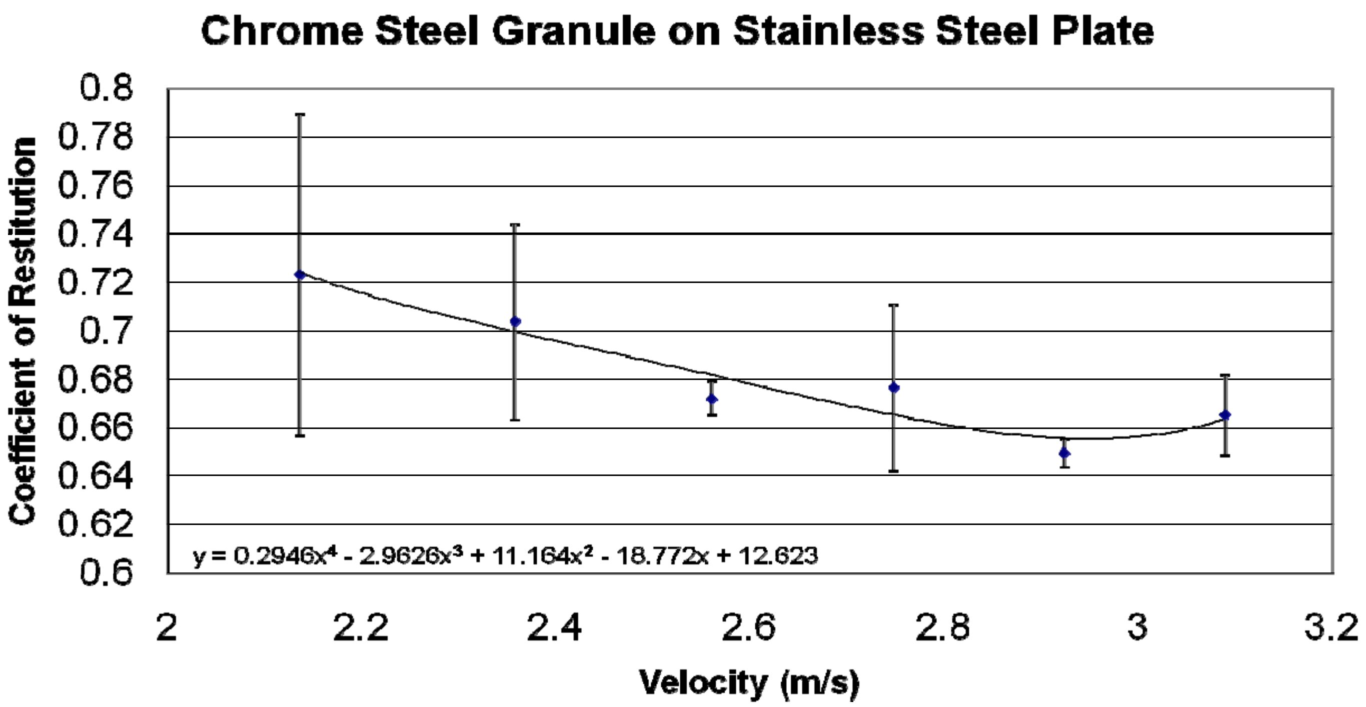
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Marinack, M., and Higgs, C.F., *In preparation for publication*, *2009*

Coefficient of Restitution Results

Historical Review

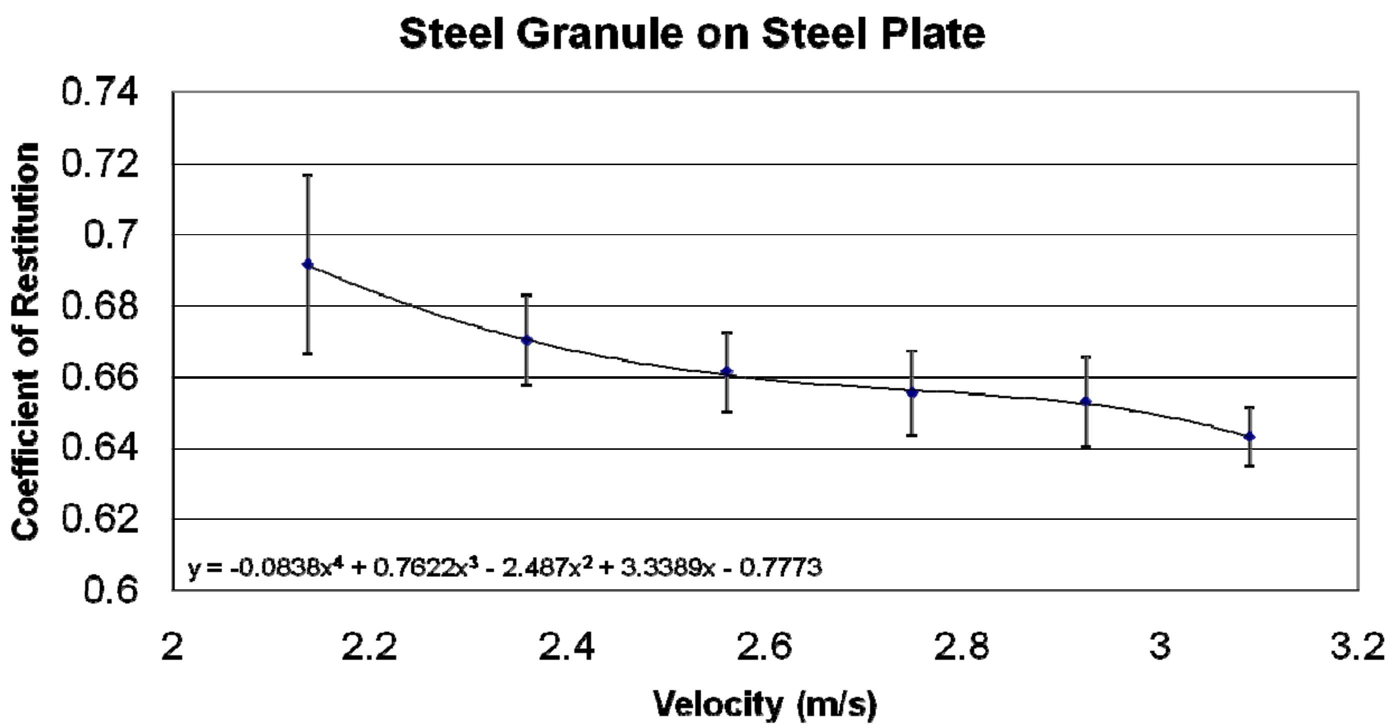
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Marinack, M., and Higgs, C.F., *In preparation for publication*, *2009*

Coefficient of Restitution Results

Historical Review

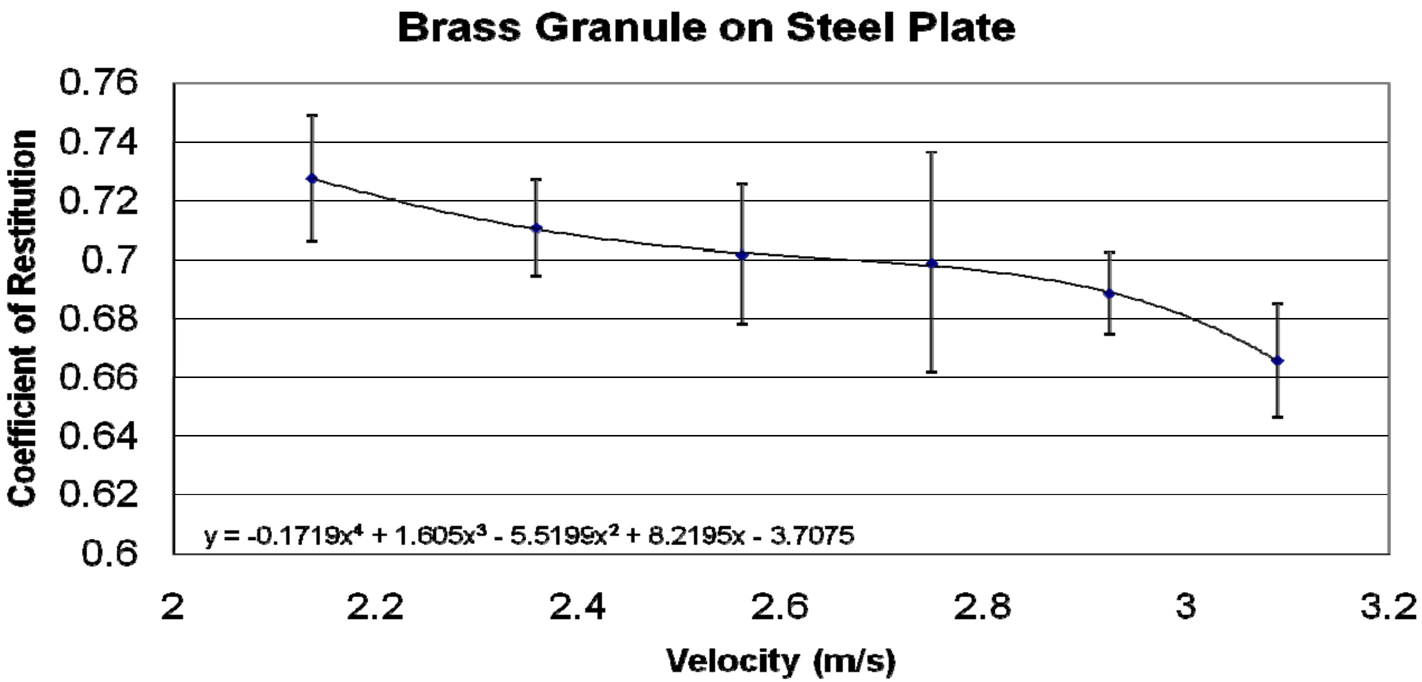
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Marinack, M., and Higgs, C.F., *In preparation for publication*, *2009*

Coefficient of Restitution Results

Historical Review

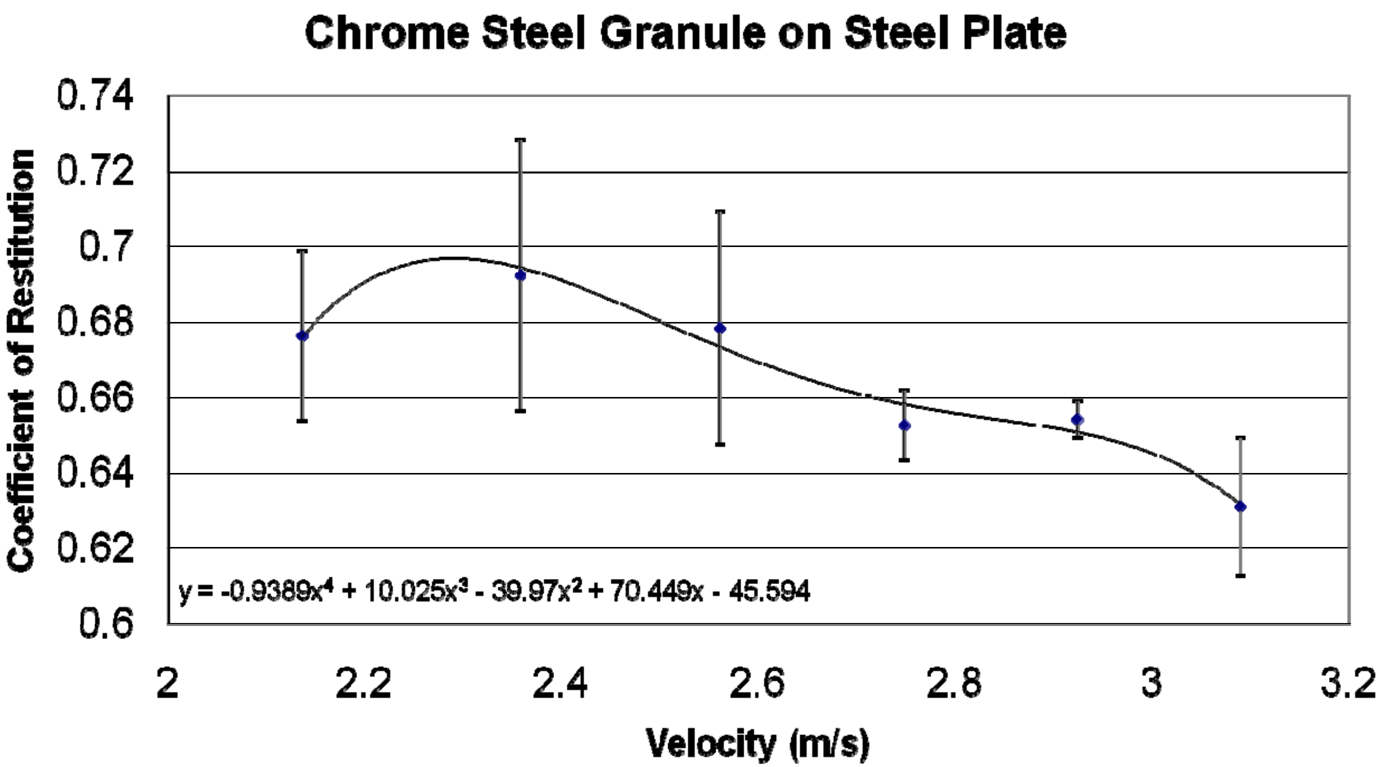
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Marinack, M., and Higgs, C.F., *In preparation for publication*, *2009*

Coefficient of Restitution Results

Historical Review

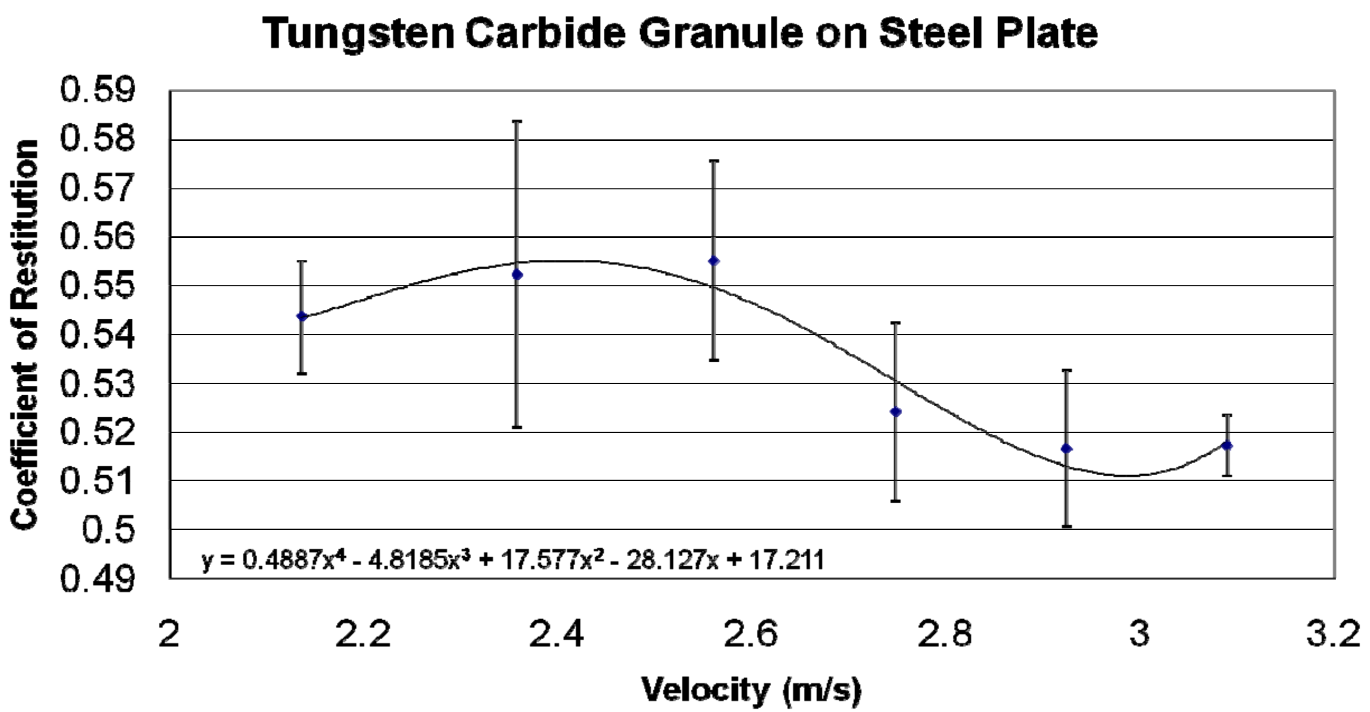
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Marinack, M., and Higgs, C.F., _In preparation for publication_, *2009*

PFTL

Coefficient of Restitution Results

Historical Review

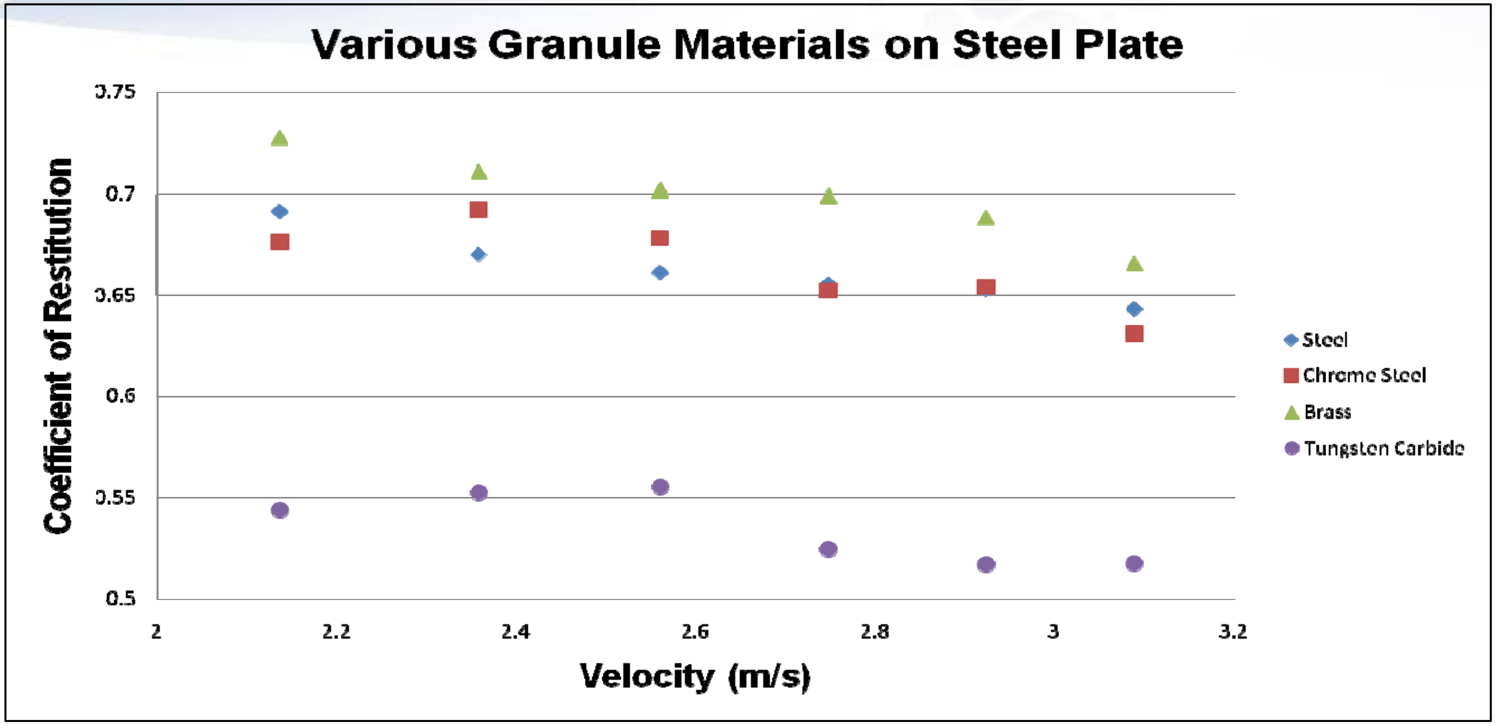
Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion



Material	Modulus of Elasticity E
Bronze	41.0 - 125 GPa
Steel	68.9 - 317 GPa
Chrome Steel	193 - 234 GPa
Tungsten Carbide (WC)	669 - 696 GPa

Marinack, M., and Higgs, C.F., *In preparation for publication*, *2009*

Conclusion

Historical Review

Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

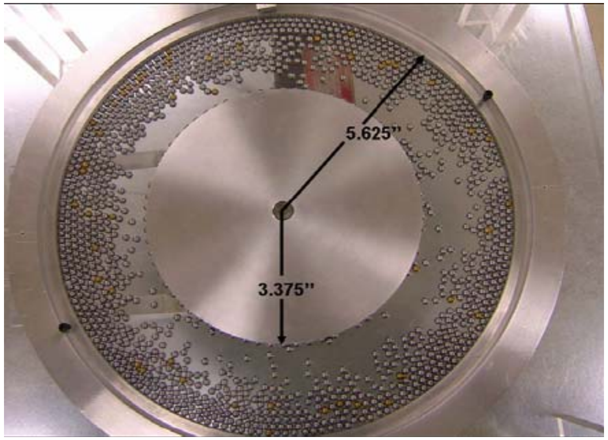
Conclusion

- 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

PFTL

Acknowledgements

Historical Review

Granular shear cell: experimental setup

Digital particle tracking velocimetry (DPTV)

Granular shear cell experiments

Single particle tests

Conclusion

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

- **Sponsor**
  - National Energy Technology Laboratory (NETL/DOE)

Thank you!!

PFTL

Coefficient of Restitution Results