3D Imaging of Segregation in Granular Shear Flows

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Refractive Index Matched Scanning (RIMS)


Split-bottom shear cell
Flythrough
Parameters:

• Quasi-static shear rate $\Omega = 0.001$ rad/s (Dijksman, et al, *PRE* 2010)
• Shear is performed in 2° (0.035 radian) steps
• $R_s = 45$ mm, $L = 150$ mm
• 1 voxel $\approx 200$ µm x 200 µm x 200 µm

Procedure:

• Capture images after each shear increment
• Convolution kernel gives 3D particle center locations (Tsai and Gollub, *PRE* 2004)
• Particle center resolution of $\sim 100$ µm
Segregation: definition and examples

**Segregation** is the separation of granular mixtures by physical property (e.g., size, density) under a driving force.


Knight, et al, *PRL* 1993

Fan & Hill, *PRE* 2010

H. A. Makse
What we don’t (and would like to) know

Consistent, robust predictive model for shear-driven segregation of a dense 3D granular material

What do we need?

• Account for seemingly inconsistent experimental results
• Absolute particle size effects – segregation length scale?
• Particle-scale dynamics?
• Internal dynamics/flows?
Bidisperse setup

- PMMA (acrylic) spheres: Refractive index $n = 1.49$
  
  $D_S = 1/8$ inch (3.2 mm) and $D_L = 3/16$ inch (4.8 mm)
  
  $3D_S = 2D_L$

- Index-matched fluid: Triton X-100 with Nile Blue 690 Perchlorate

- Twin laser sheets with $\lambda = 635$ nm

- $27M_S = 16M_L \leftrightarrow N_S = 2N_L$

- $H = 46$ mm $\approx 10D_L \approx R_S$
Steady shear at $z = 3.8 \text{ cm (} 8 D_L \text{)}$
Segregation under steady shear
Global and local phenomenon

Volume fraction -- **GLOBAL**  Average coordination number -- **LOCAL**

\[ \phi = \frac{V_{\text{parts}}}{V_{\text{space}}} \]

\[ \langle C \rangle = \text{Average number of large/small contacts} \]
$10^\circ$ cyclic shear at $z = 3.8 \text{ cm}$ ($8 \, D_L$)
Segregation under cyclic shear?

There appears to be a segregation transition between 10° and 40° cyclic shear.
Similar trends for $D_L$ monodisperse system (Slotterback, et al, PRE 2012)
Secondary flows – steady shear

Convection of large grains
Net downward flux of small grains
Secondary flows \(-\theta_r = 10^\circ\)

Very diminished magnitude of flows
Secondary flows – $\theta_r = 40^\circ$

Convection starts to develop
Downward drift of small grains near disk
Summary

• Critical strain amplitude for segregation under cyclic shear
  – Continuum gradient-based models are not enough!
• Bulk segregation concurrent with microscale irreversibility
• Amplitude-dependent secondary flows:
  – Convection of large grains
  – Downward drift of small grains
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