NMR Studies of Rapid Granular Flows

Chao Huan¹, Xiaoyu Yang¹, Don Candela¹, Ruopeng Wang²,³, Ross W. Mair²,³, Matthew S. Rosen² and Ronald L. Walsworth²

¹ Dept. of Physics, University of Massachusetts, Amherst, MA, 01003, USA
² Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, 02138, USA
³ Dept. of Nuclear Engineering, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA

1. Vibro-Fluidized Granular Media
   - System fluidizes when vibration acceleration exceeds g
   - Energy input: collisions with bottom wall
   - Energy loss via particle-particle collisions
   - Provides system for study of granular hydrodynamics:
     - Is granular hydrodynamic theory ever valid for such a system?
     - It fails for dense, static or quasi-static systems
   - Rapid granular flows - huge temperature gradients

2. Apparatus for Vibro-fluidization
   - Superconducting magnet, 1.7 Tesla
   - Gradient and RF coils
   - Driver (loudspeaker), synchronized with NMR
   - Vacuum pump
   - NMR Method: combine PFG displacement measurements with 1D profile acquisition

3. Time-Resolved Density
   - Mustard seeds shaken at 50 Hz
   - d = 1.8 mm, f = 15 g
   - N = 60 → n* = 3.4, ω* = 4.3
   - Density profile shows impact of container bottom in vibration cycle. Otherwise, it is nearly stationary over vibration cycle.
     - Spin density profile along length of tube, imaged with 1 ms temporal resolution
     - Solid black line shows motion of container bottom
     - Statistical system "heated" from below

4. Time-Resolved Displacement
   - Profiles of vertical (left) and horizontal (right) RMS displacements during Δt = 1.35 ms.
   - Vertical displacements show large effect of impact; horizontal displacements less so.
   - Granular temperature picture appears valid, especially for horizontal displacements

5. Displacement vs. Encode Time
   - RMS vertical (●) and horizontal (○) seed displacements versus observe time, at three different heights (z).
   - PFG technique can reach Ballistic Regime for this system (collision time ~ 5 - 10 ms)
     - Solid lines: displacement = ΔT (ballistic)
     - Dashed lines: displacement = (Δt)^2 (diffusive)
   - Ballistic region displacement distributions give velocity spectrum p(v) → Granular Temperature?

6. Displacement Distributions
   - Distribution of vertical (z) displacements in r = 1.35 ms vs height (z).
   - Distribution of horizontal (x) displacements in r = 1.35 ms vs height (z).
   - Distribution of vertical displacements is highly skewed near vibrating container bottom (small z).
   - Distribution of horizontal displacements is symmetric and roughly Gaussian at all heights

7. Velocity Distribution
   - Velocity Distribution looks like a Gaussian
     - Fit p(v) = exp(-v^2/σ^2), where σ = 0.9 ± 0.1
     - α = 1.4 Gaussian, σ ≈ 0.8 seen in 2D experiments
   - Our 3D experiments give stretching exponent values α between Gaussian and previous 2D results
   - α ≈ Gaussian towards top of granular sample

8. Hydrodynamic Theory Fits
   - Curves show fit to Garzo-Dufty hydrodynamic theory.
   - Ignores pre-collision velocity correlations.
   - Temperature increases linearly with height in low density region, even though heat current is upward.
   - Restitution coefficient = 0.87 for all fits.
     - Dimensionless variable (d/m) = grain diameter, mass)
     - z* = z/d, n* = nd/d, T* = T/μgd

9. Gas Fluidized Granular Media
   - System fluidized by gas passing through from below
   - Fluidized bed column with attached RF coil designed to fit inside horizontal bore magnet
   - Fluidizing gas is laser-polarized Xe
   - Initial study of fluidizing gas behavior by PFG-NMR
     - 50 µm glass beads used as test particles
     - gas flows ~ 20 - 200 cm³/min, with mass flow controller

10. Profiles of Fluidizing Xenon
    - Cross-sectional Profile
    - Longitudinal Profile
    - 1D profiles show regular semi-circular profile in cross-section, for all gas flow rates
    - Longitudinal profile shows mostly uniform magnetization density, but is lower at bottom where particle density is greatest
      - non-slice selective spin echo, gas flow rate 50 cm³/min
      - TE = 7.2 ms, TR = 2 s, FOV = 40 mm (x), 80 mm (y), ns = 8

11. Gas Velocity Distributions
    - Averaged velocity distributions are Gaussian at all fluidizing stages; gas dispersion increases ~ flow rate
      - 100 cm³ - beads bubbling
      - 200 cm³ - random motion

12. Conclusions
    - Hydrodynamic theory can quantitatively describe some real (physical) stationary granular fluids.
    - Garzo-Dufty theory fits well to all temperature and density profiles, for different frequencies and bed depths; except where density is low near vibrating container floor.
    - Temperature inversion (thermal gradient opposite heat current) agrees with hydrodynamic predictions.
    - Xenon gas fluidizing granular media can be imaged
    - Initial gas velocity distributions always Gaussian

References