Experimental and Computational Studies of Fluid-Particle Flow Systems

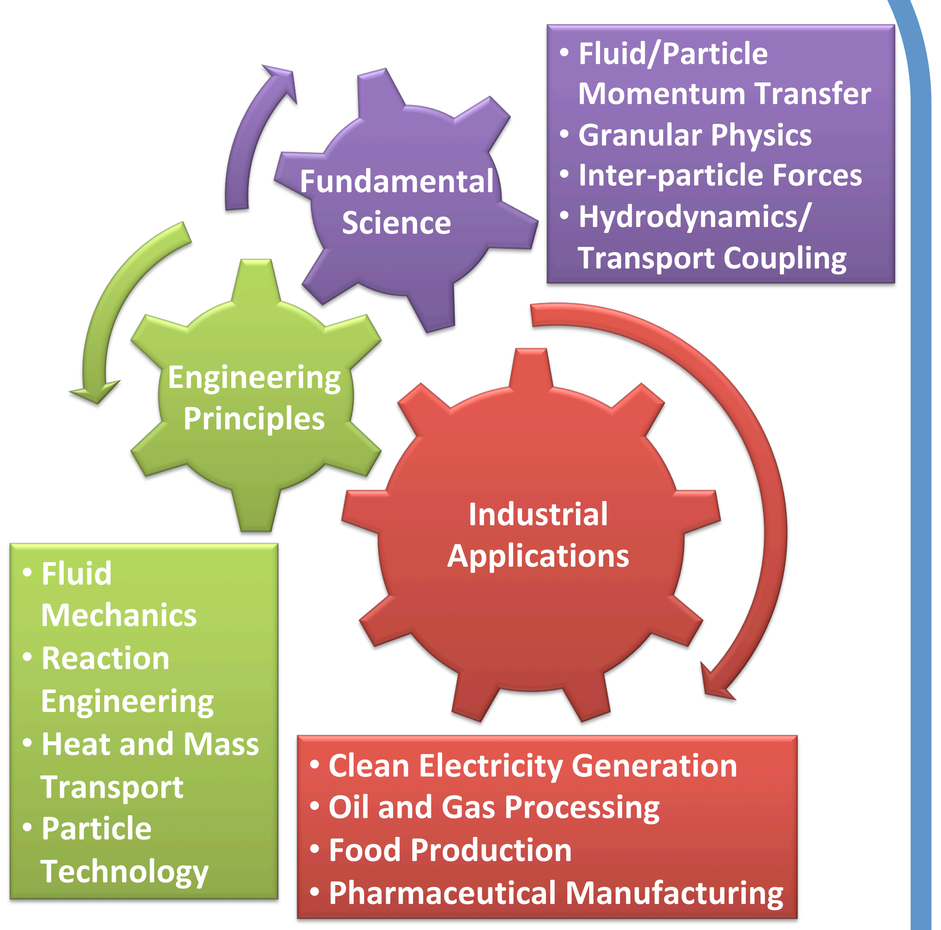
Christopher M. Boyce, Thomas M. Kovar

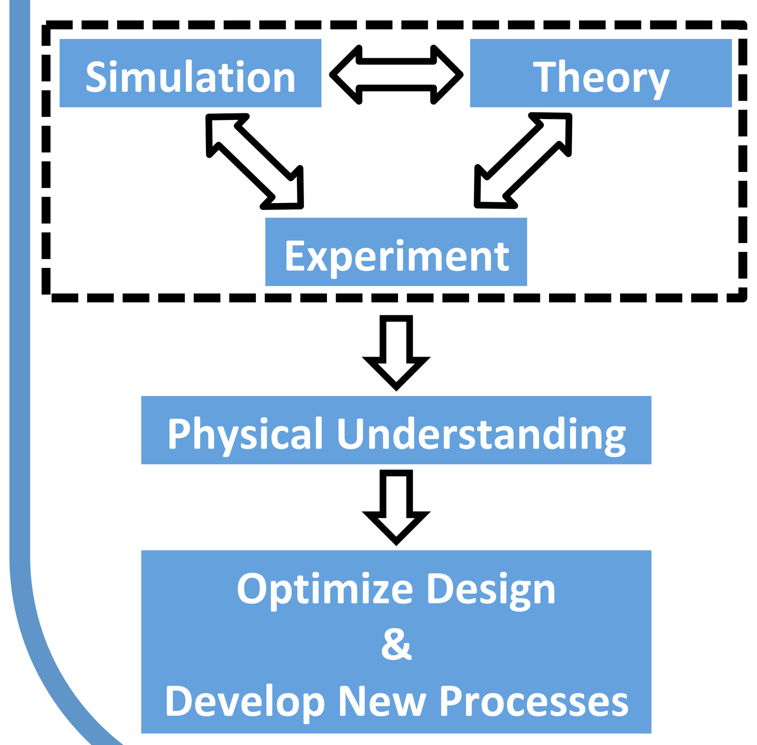
COLUMBIA UNIVERSITY

COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

Motivation

- Fluid-particle flow systems, such as fluidized beds, exhibit fascinating phenomena
- Working to understand these phenomena advances engineering principles and fundamental science
- Flows critical to industrial applications, from clean energy to pharmaceuticals

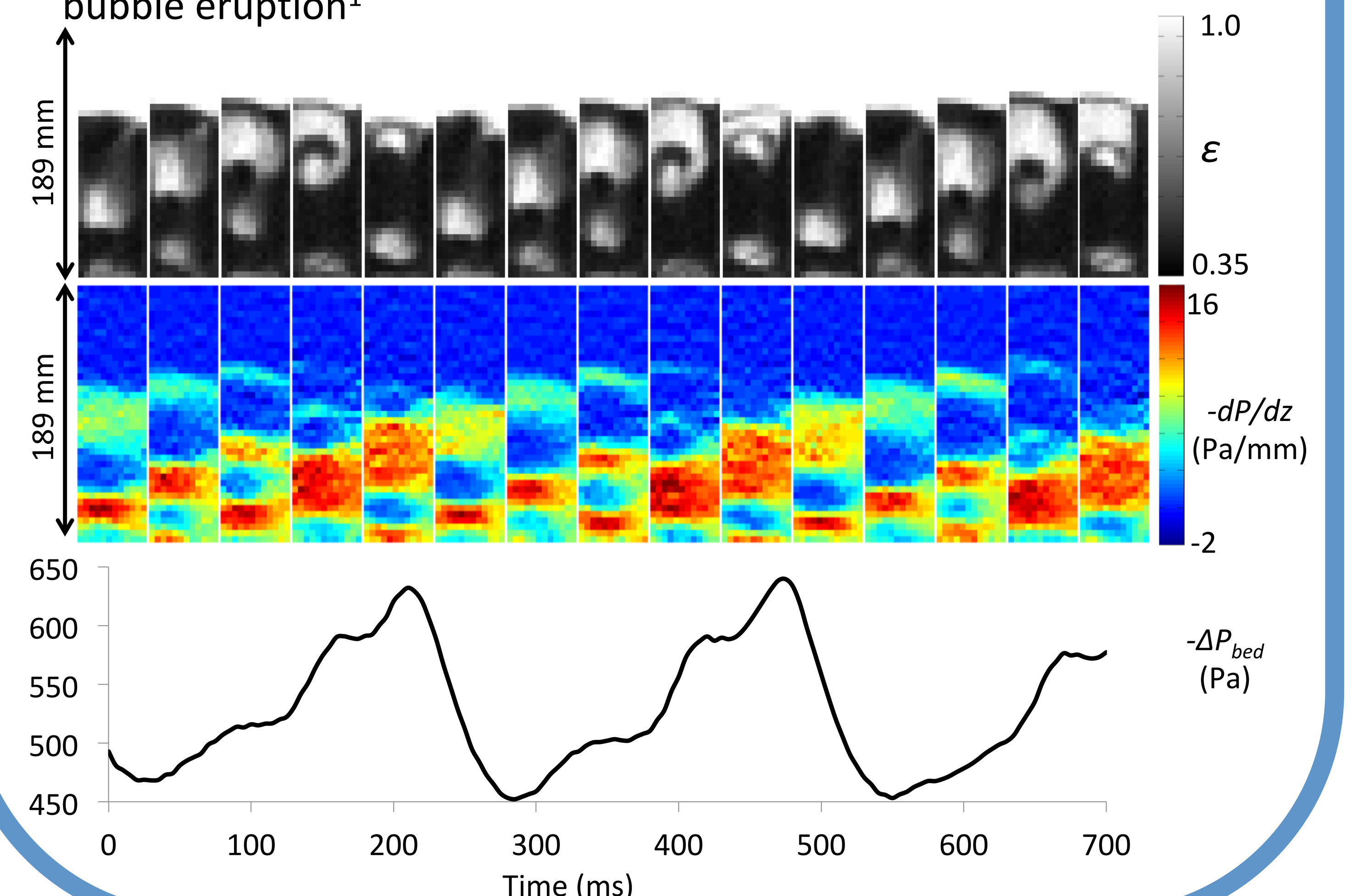




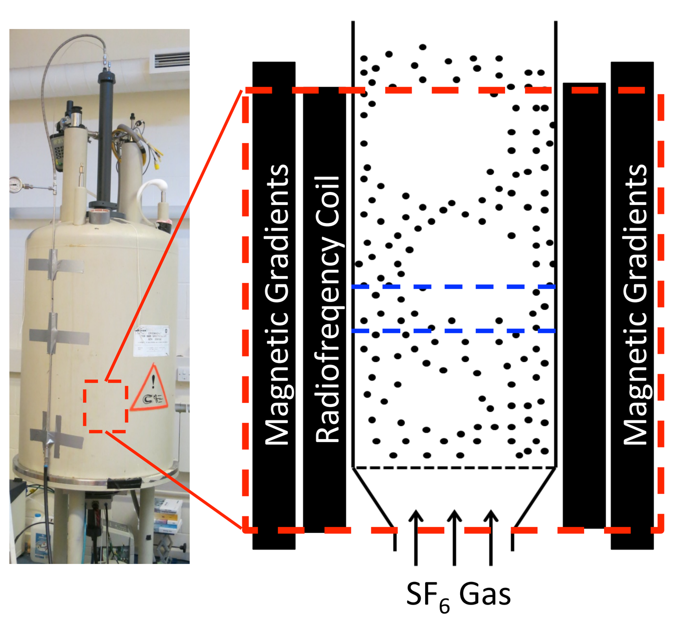
- These flows are not well understood, despite decades of industrial use, due to difficulties in modeling and measuring gas and particle dynamics
- Advances in computational and experimental techniques provide promising new avenues to reveal underlying mechanisms, characterize flows and develop and optimize processes to address 21st Century problems

Pressure Oscillations in Fluidized Beds

- CFD-DEM simulations[1] validated using experimental measurements[2] of frequency of pressure oscillations and bubble eruptions
- CFD-DEM predictions also elucidated aspects of the experimental system which could not be measured experimentally, such as detailed maps of local pressure drop
- Analysis revealed that large regions densely packed with particles create largest pressure drop and these regions are largest just after bubble eruption[1]



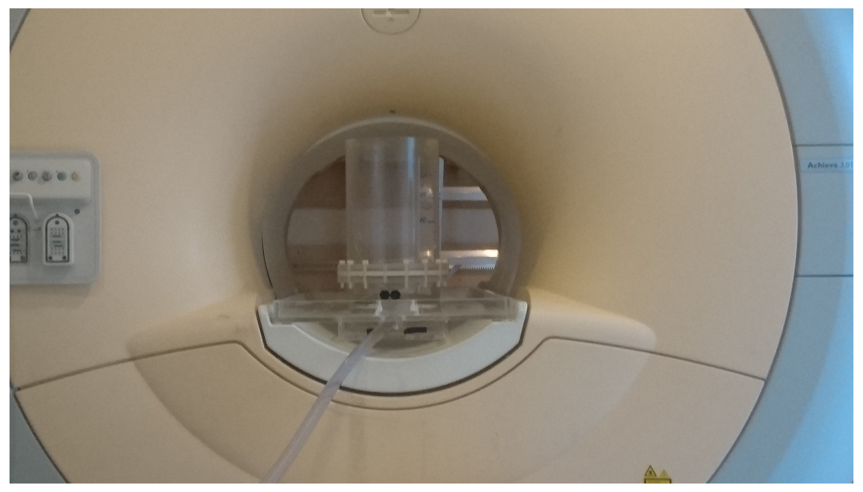
Magnetic Resonance Imaging (MRI)



- MRI enables in-process imaging and quantitative measurements of chemical engineering systems
- MRI can image concentration, velocity, velocity distribution and diffusion of gas, liquid and particles in these systems
- Techniques are developing to image chemical conversion, temperature and interphase transport of species

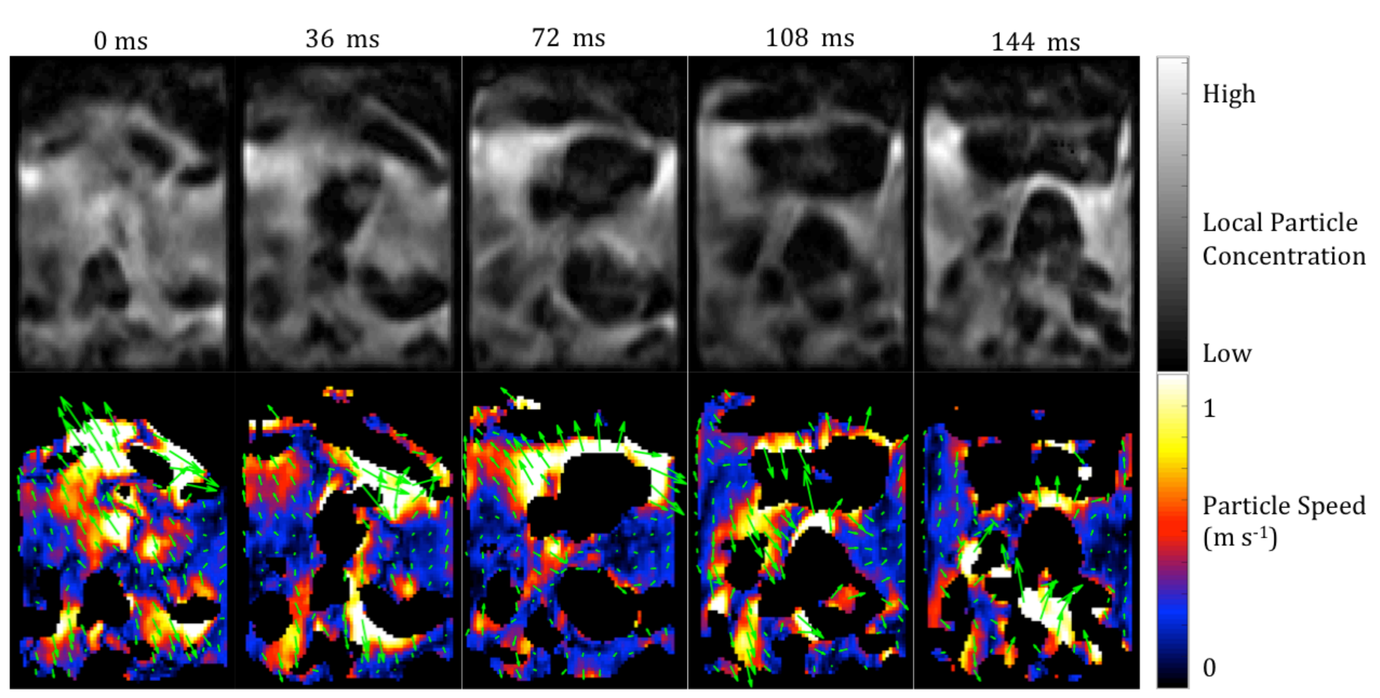
Measuring Gas Velocity

- **Challenge:** Difficult to measure gas velocity in fluidized beds due to gradients in magnetic field near interface with particles[4]

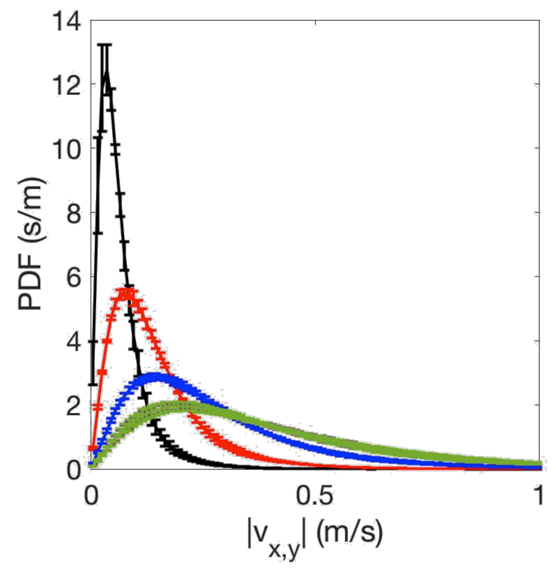


- **New** MRI pulse sequence[5] measures gas velocity more accurately by minimizing attenuation of signal from fastest moving gas, allowing for accurate measurements in multiphase systems with gas flow

Particle Concentration and Speed in Fluidized Beds

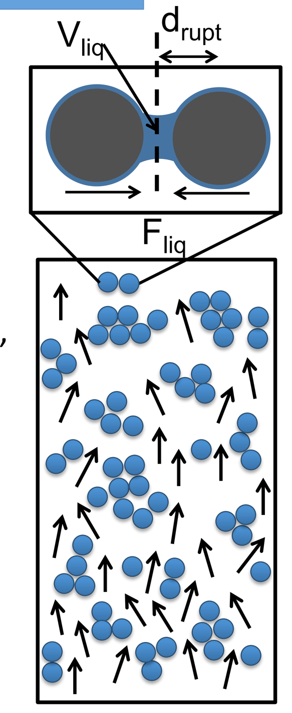


- Local particles concentration and local particle velocities can be obtained using echo planar imaging (EPI) and phase-contrast EPI
- Identifying the in-plane speeds of particle-laden pixels can be used to produce probability density functions (PDFs) of particle speed



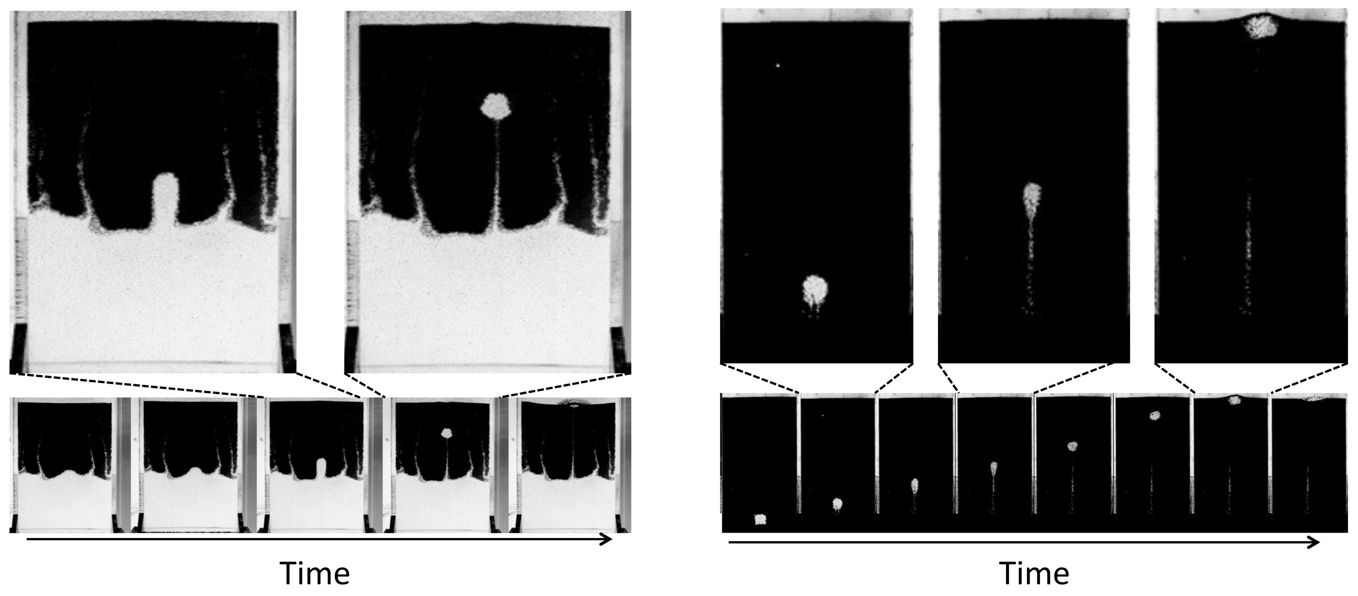
Multi-scale Modeling

- Micro-scale models (DNS[10,11]) [~10^4 particles]
  - Resolve gas flow on grids much smaller than d_p
  - Enable development of closure laws (*e.g.* drag) for CFD-DEM models
- Meso-scale models (CFD-DEM[12]) [~10^7 particles]
  - Resolve each individual particle and detailed inter-particle forces, but gas flow resolved on grids larger than d_p
  - Create physical insights into flow behavior and enable development of coarse-graining closures
- Industrial scale models (MP-PIC[13])
  - Model parcels representative of many particles and use very coarse fluid grids
  - Require accurate closure relationships which account for meso-scale flow features in order to give accurate predictions



Two-phase Suspended Granular Flow

- Particles of different densities can act like liquid phases under specific experimental conditions
- Lower density particles rise through denser phase acting as a two-phase, liquid-liquid like system
- Exhibit surface tension like properties without the addition a liquid phase



Future Directions

- Interplay between hydrodynamics and chemical reactions
  - Measure: hydrodynamics, chemical reactions and interphase mass transfer using MRI and chemical measurement techniques
  - Model: mass transport and chemical reactions within expanded computational model
- Effect of complex interparticle forces on hydrodynamics
  - Model: liquid bridging, van der Waals forces, triboelectric charging
  - Measure: MRI visualization of hydrodynamics of systems with complex interactions
- Coarse-graining for industrial-scale modeling
  - Use CFD-DEM modeling to develop accurate closure relationships for industrial models

References

[1]Boyce *et al.* (2014) *Chem. Eng. Sci.*, **116**, 611-622. [2]Müller *et al.* (2007) *Powder Technol.*, **177**(2), 87-98. [3]Hahn (1950) *Physical Review*. **80**(4), 580–594. [4]Cotts et al. (1989) *J. Magn. Res.*, **83**(2), 252–266. [5]Boyce *et al.* (2015) *Submitted*. [6]Boyce et al. (2015) *In final preparation for submission*. [7]Boyce et al. (2015) *In final preparation for submission*. [10]Chen & Doolen (1998) *Ann. Rev. Fluid Mech.*, **30**(1), 329–364. [11]Choi & Joseph (2001) *J. Fluid Mech.*, **438**, 101–128. [12]Tsuji et al. (1993) *Powder technol*. **77**(1), 79–87. [13]Andrews & O'Rourke (1996) *Int. J. Multiphase Flow.* **22**(2), 379-402.

Acknowledgments

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