Rheological behavior of dense assemblies of granular materials: Experimental Measurements

Co-Principal Investigator: Gabriel I. Tardos
Research Assistant: Mehrdad Kheiripour Langroudi

CCNY: Annual Report, 2008/2009

DoE Annual Review Meeting
Morgantown, April 23, 2009

Collaborators

Principal Investigator:

- **Prof. Sankaran Sundaresan (Princeton University) - Simulation**

Co-principal Investigators:

- **Prof. Gabriel I. Tardos (The City College of the City University of New York) - Experiments**
- **Prof. Shankar Subramaniam (Iowa State University) - Simulation**

Goal for Experimentation: Provide precise and detailed experimental results in simple enough geometries to validate simulations.

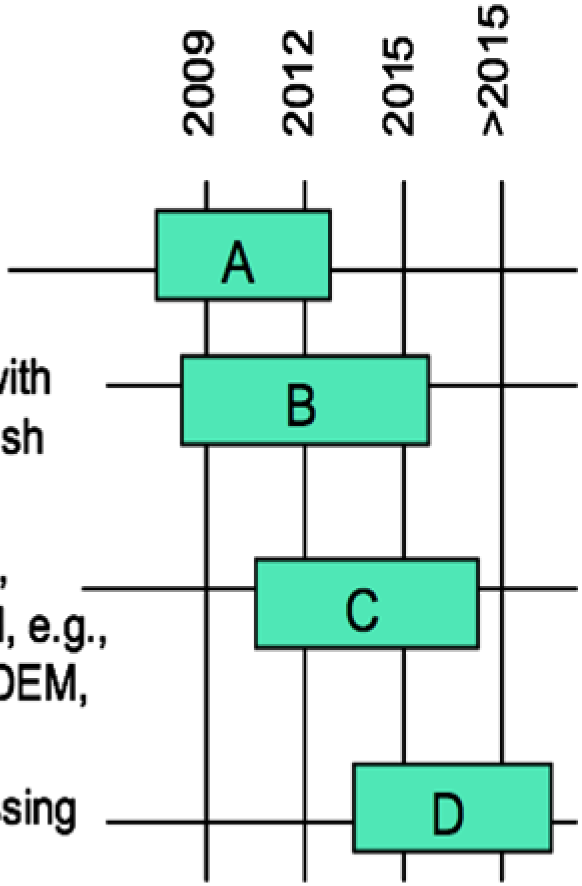
Papers

1. M. Kheiripour Langroudi, S. Turek, A. Ouazzi and G. I. Tardos, “An investigation of frictional and collisional powder flows using a unified constitutive equation”, to be submitted for publication to Powder Technology, April, (2009).
2. M. Kheripour-Langrudi, J. Sun, S. Sundaresan and G. I. Tardos, “Transmission of stresses in static and sheared granular beds: the influence of particle size, shearing rate, layer thickness and sensor size, to be submitted to NETL Special Issue Journal (2009).

Roadmap for Dense Granular Flow

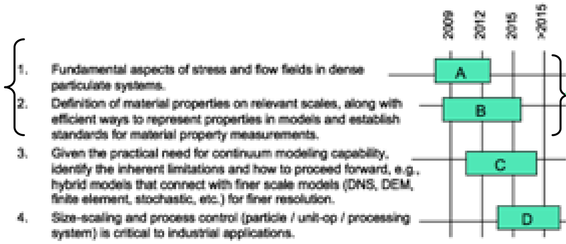
Table 1.1

1. Fundamental aspects of stress and flow fields in dense particulate systems.
2. Definition of material properties on relevant scales, along with efficient ways to represent properties in models and establish standards for material property measurements.
3. Given the practical need for continuum modeling capability, identify the inherent limitations and how to proceed forward, e.g., hybrid models that connect with finer scale models (DNS, DEM, finite element, stochastic, etc.) for finer resolution.
4. Size-scaling and process control (particle / unit-op / processing system) is critical to industrial applications.



Report on Workshop on Multiphase Flow Research, Morgantown, WV, June 6-7, 2006

Connection to Roadmap



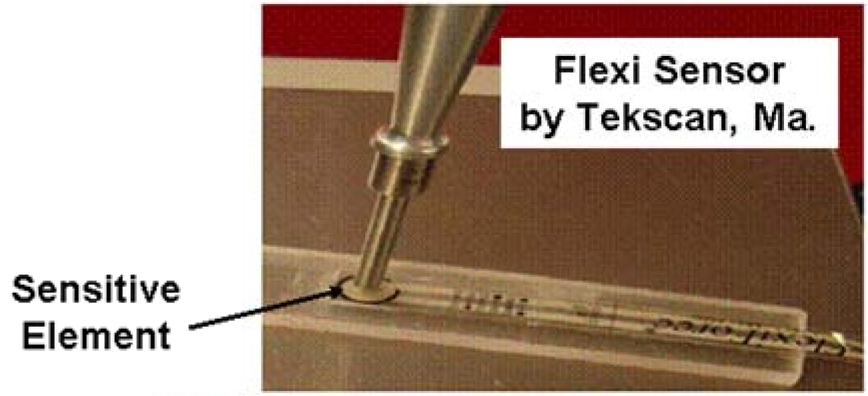
Key questions addressed:

- How to measure stresses and solid fraction in shear?
- How is stress transmitted?
- What parameters control the transitions between granular states?
- Rheological models from quasi-static to intermediate flow regimes?

Action taken in our project:

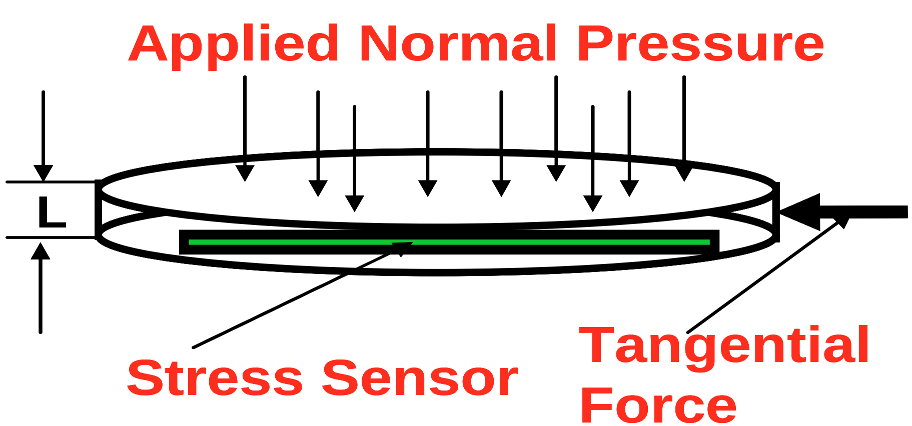
- Identified and modified instrumentation to measure stresses, fluctuations and porosity.
- Used Jenike cell geometry to demonstrate stress transmission.
- Demonstrated the connection between quasi-static transition to “flow” or Intermediate Regime.
- Developed a constitutive equation for the quasi-static and intermediate regimes directly from experiment.

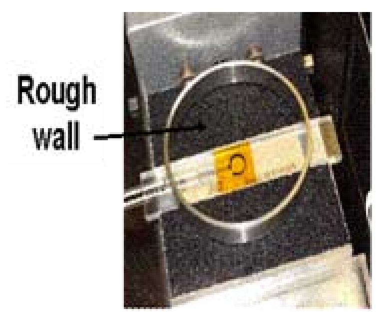
The Flat Geometry of the Jenike Cell
A Study of Stress Transmission

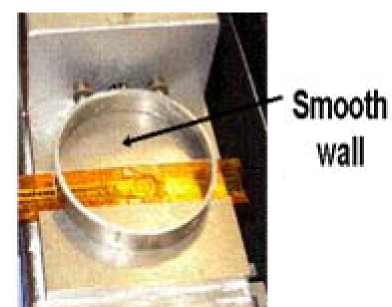


Sensor Selected for Measurement

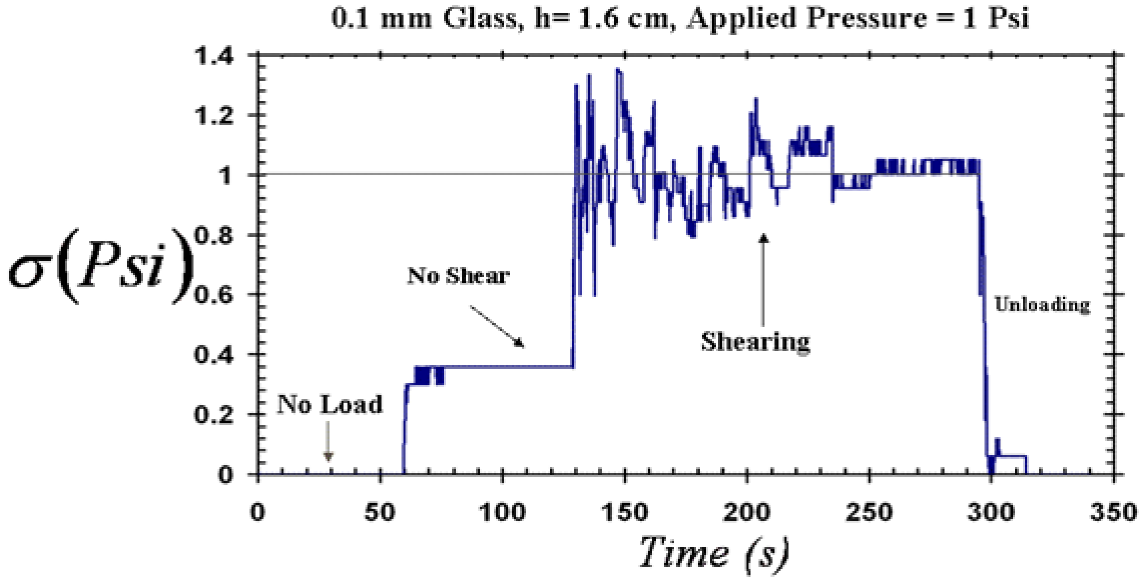
Principle of Measurement
(schematic representation)



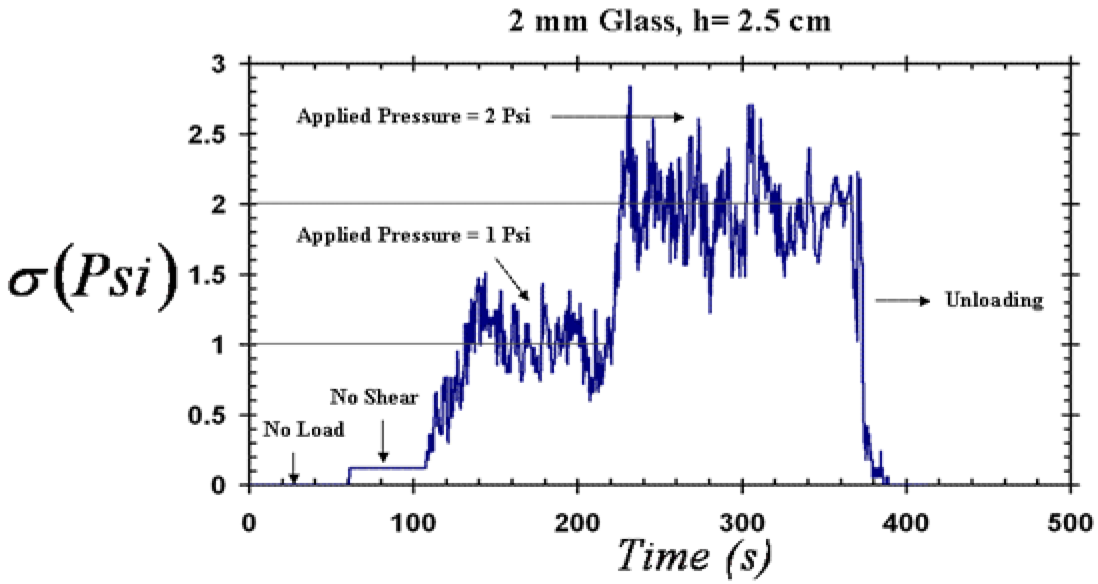




Stress Transmission through Granular Layers

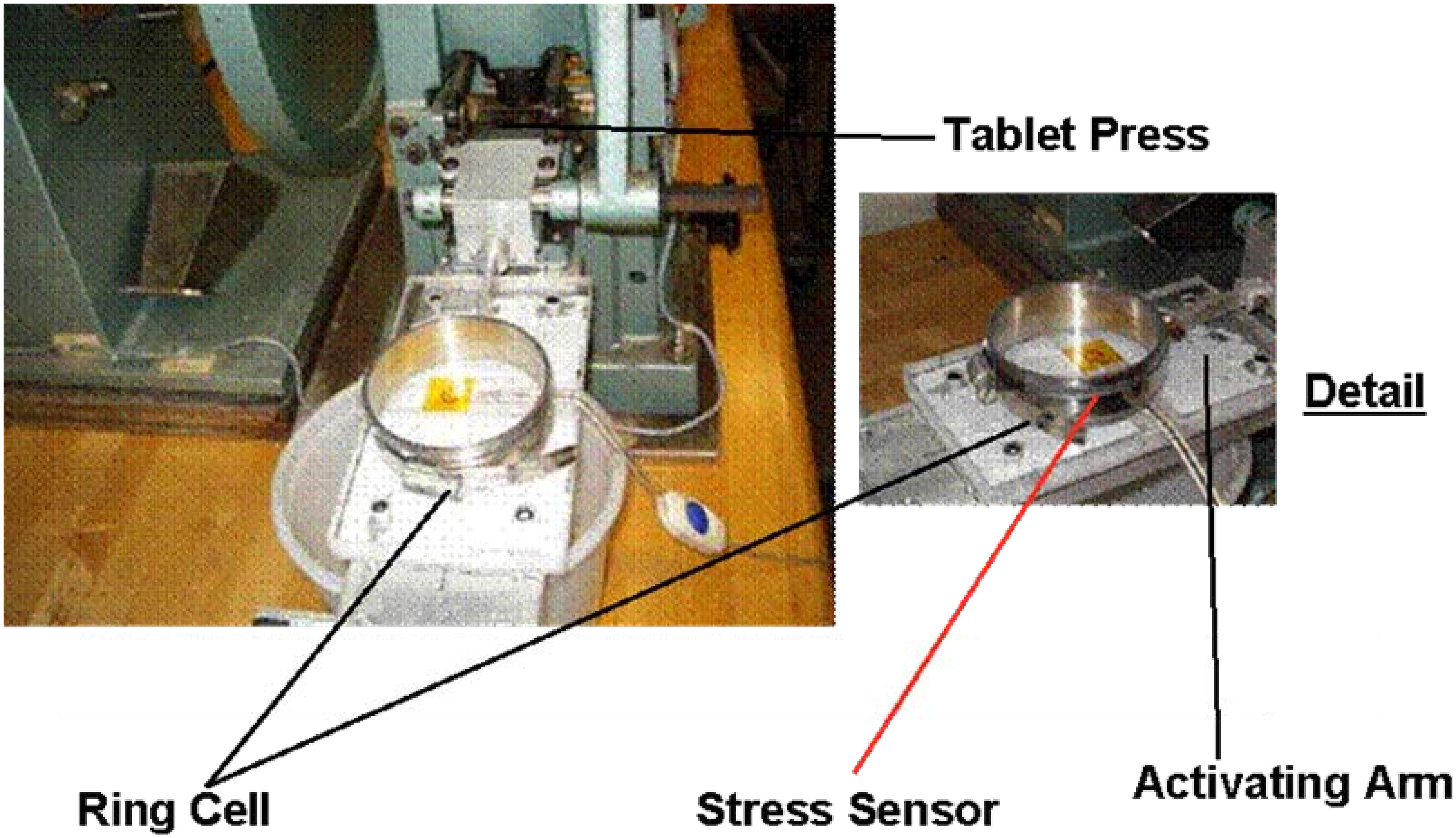


0.1 mm glass
L=1.6 cm
Pressure: 1 Psi



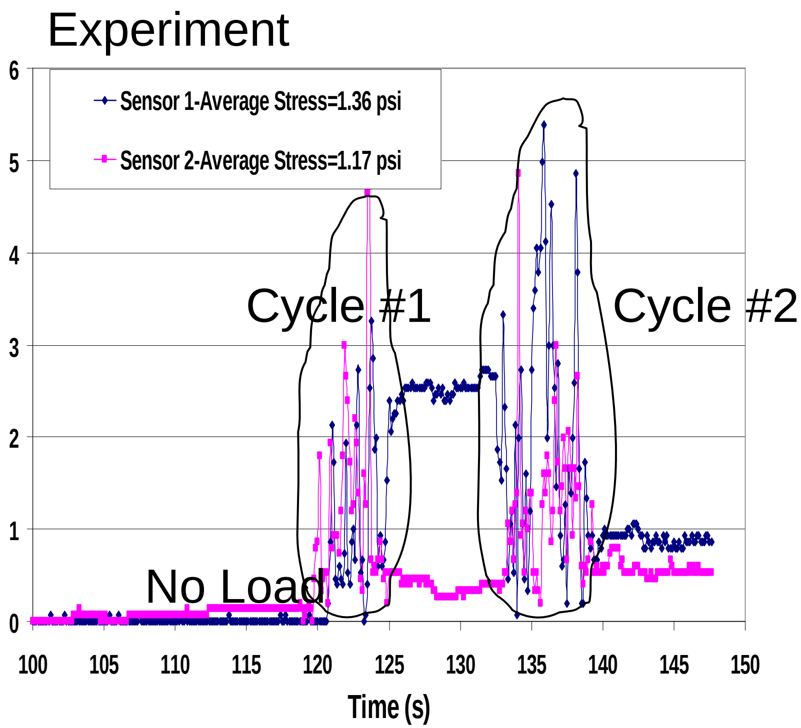
2.0 mm glass
L=2.5 cm
Pressure: 1 Psi
and 2.0 Psi

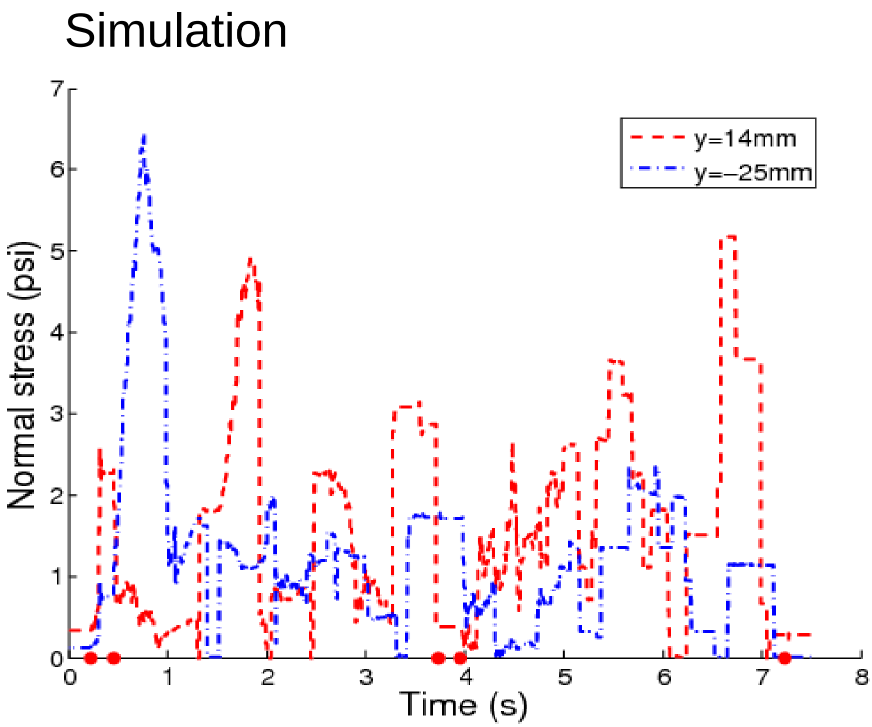
Comparison of Experiment and Simulations
The “fast” Jenike cell



- Up to 500 times the Shear Rate in the Jenike cell
- Multiple sensors at different locations

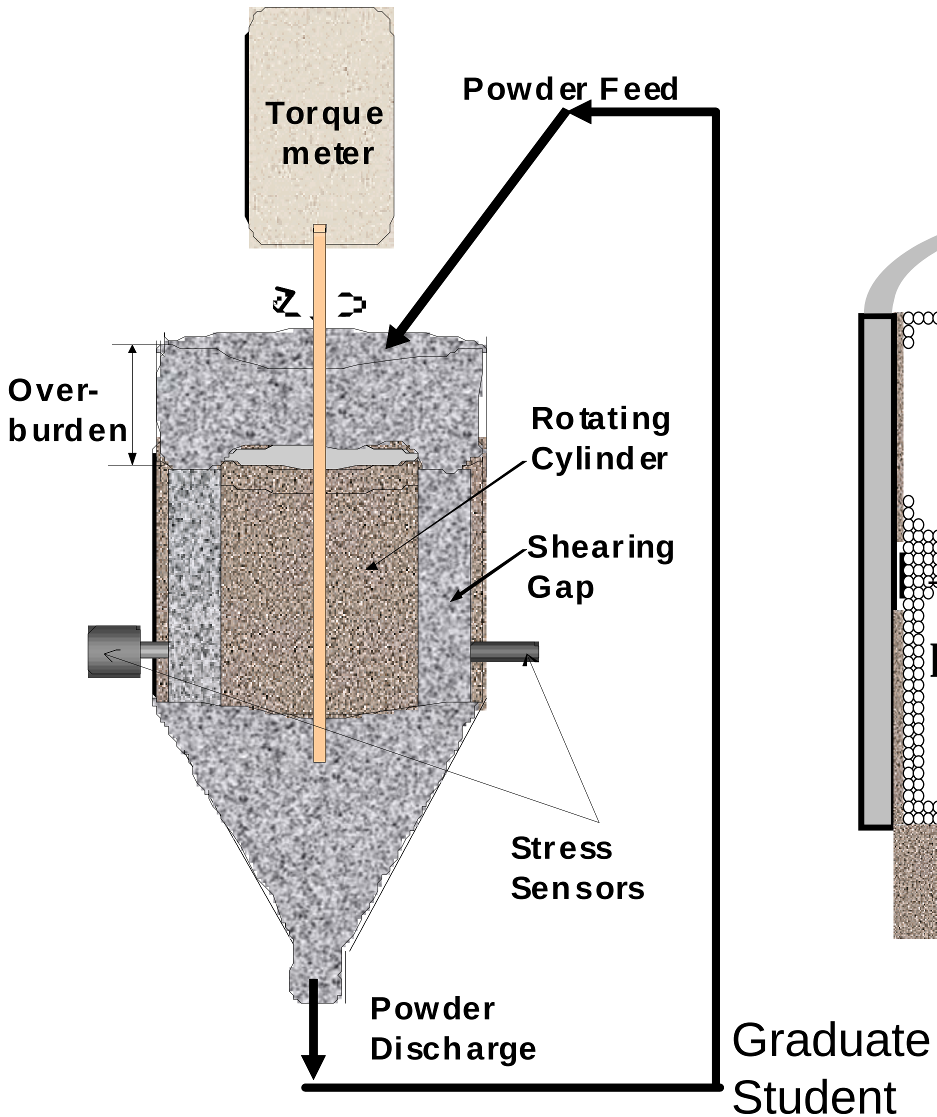
Comparison of Experiment and Simulations

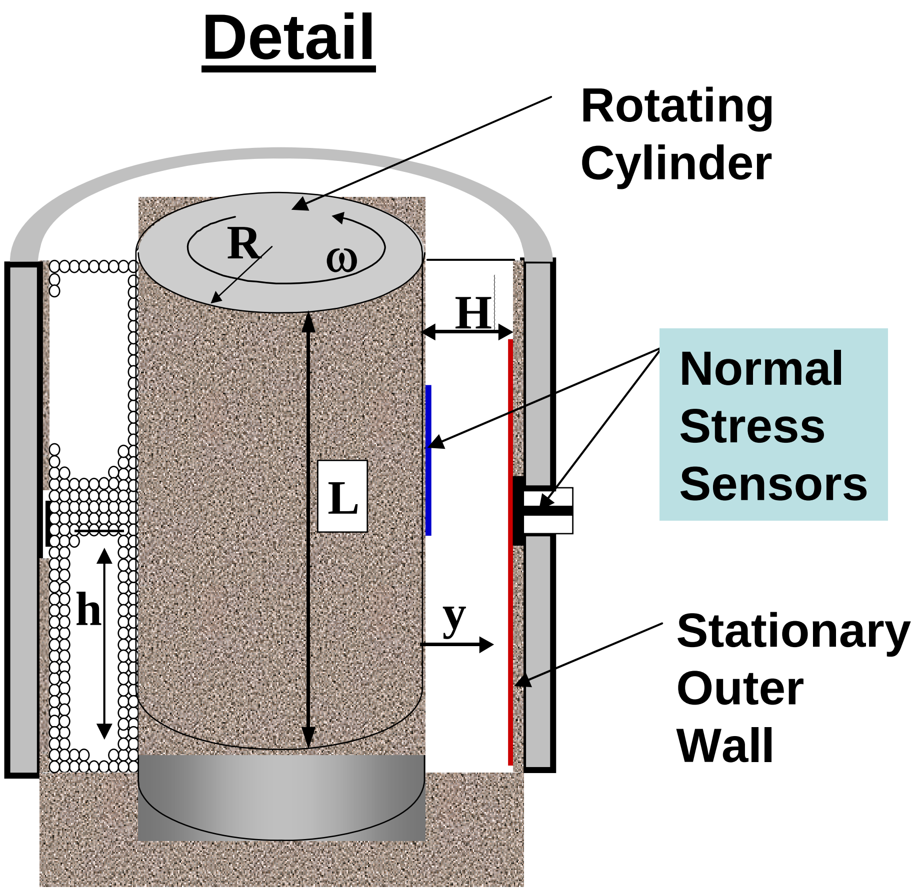




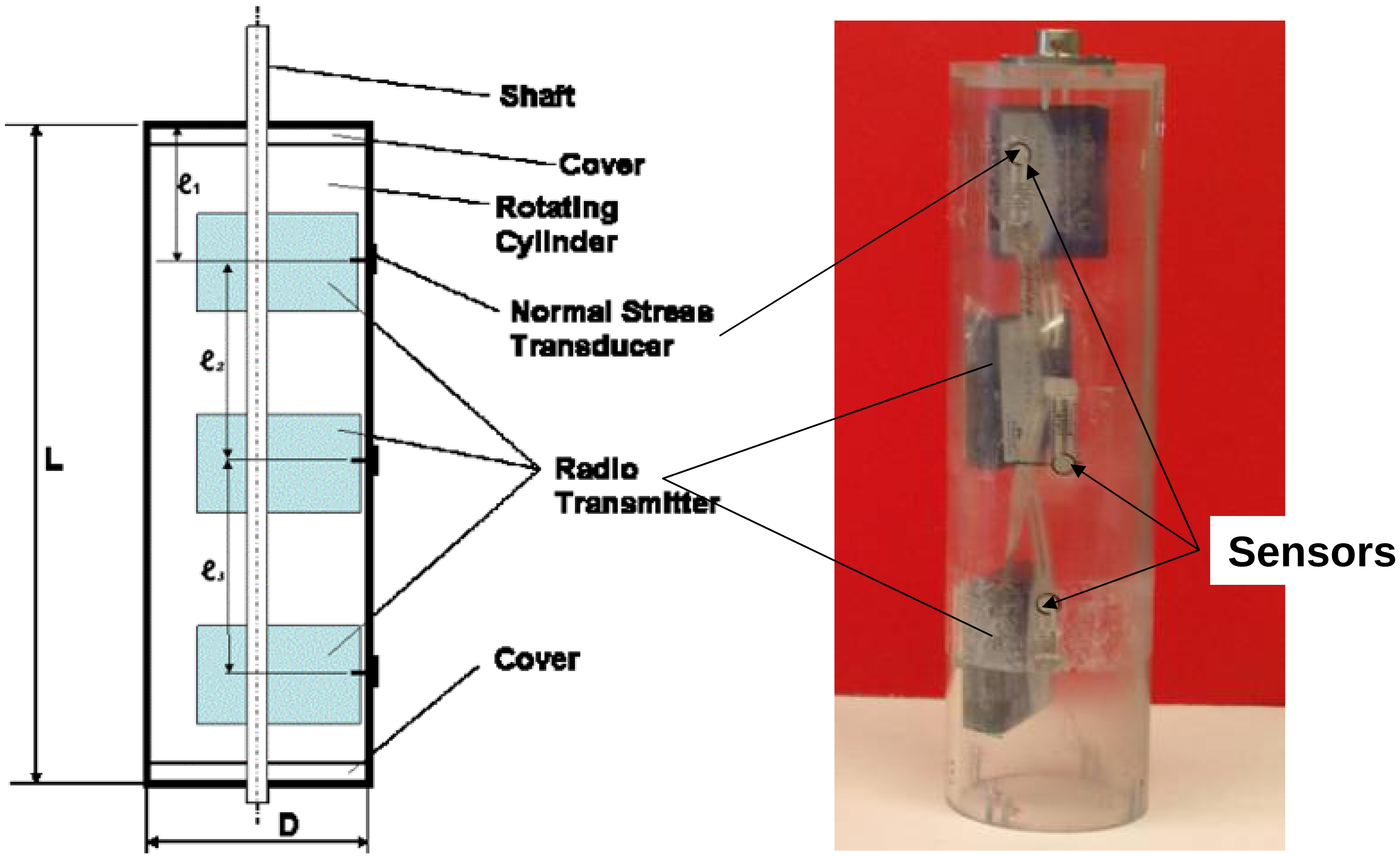
- **Glass beads of 5 mm in diameter sheared at a speed of 16 mm/sec with 1 psi applied normal stress.**
- **Simulation and experiment agree in the mean and fluctuation of the stress.**

Axial Flow Couette Device



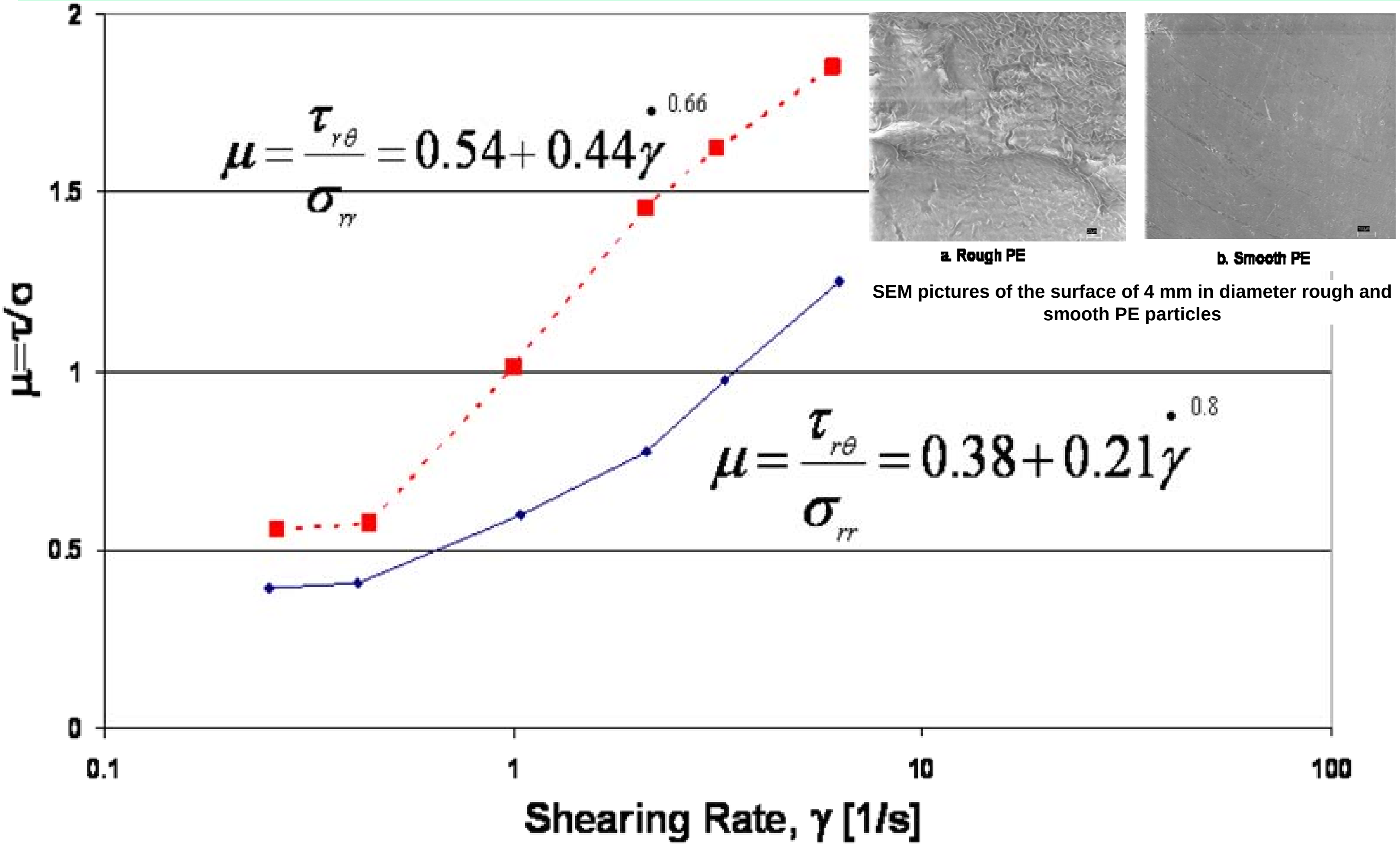


Normal Stress Measurement in Shearing Zone



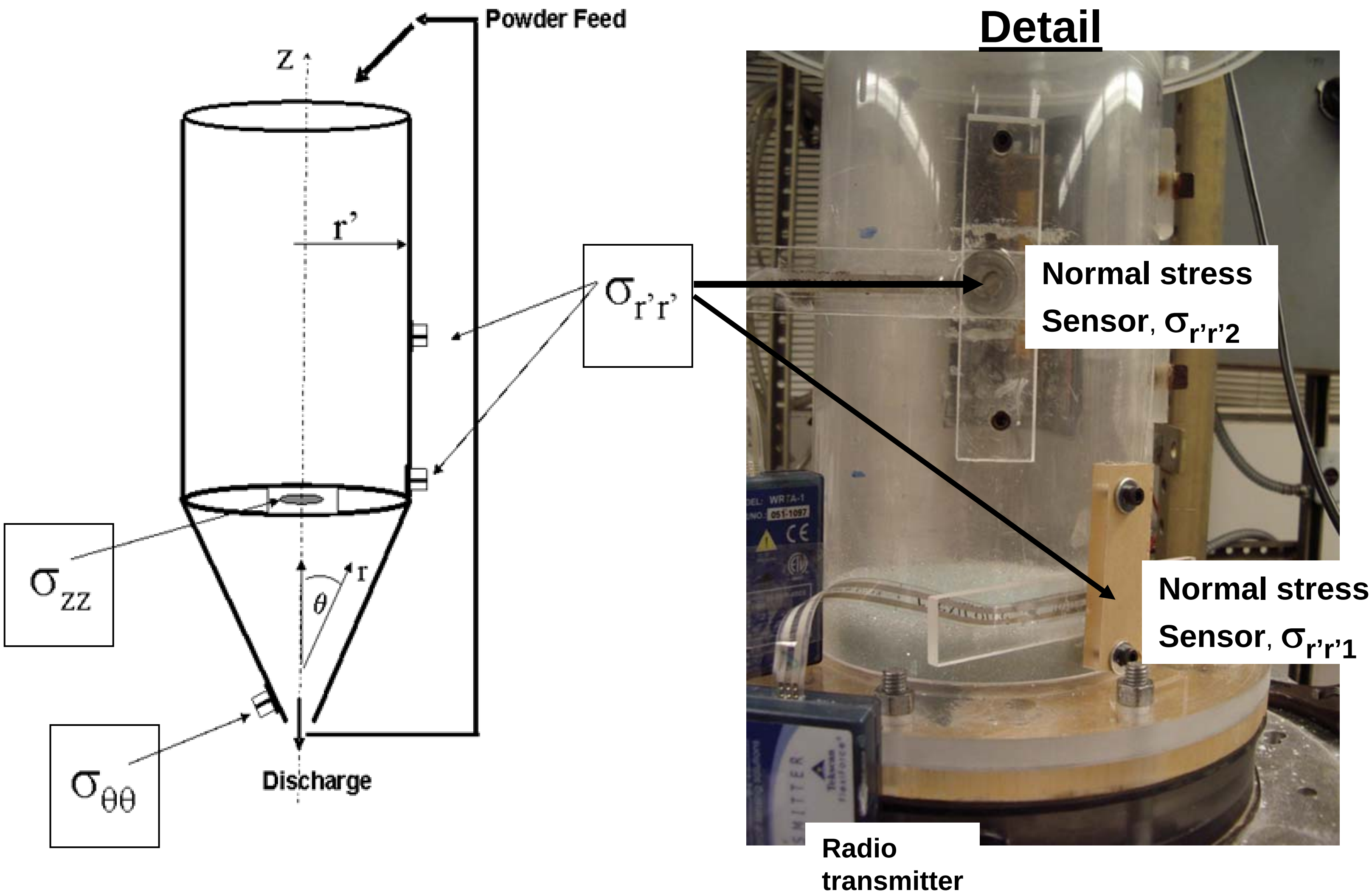
Remote normal stress sensors on the rotating Cylinder

Ratio of Shear to Normal Stresses in the Couette for Rough and Smooth PE particles of 4 mm in diameter

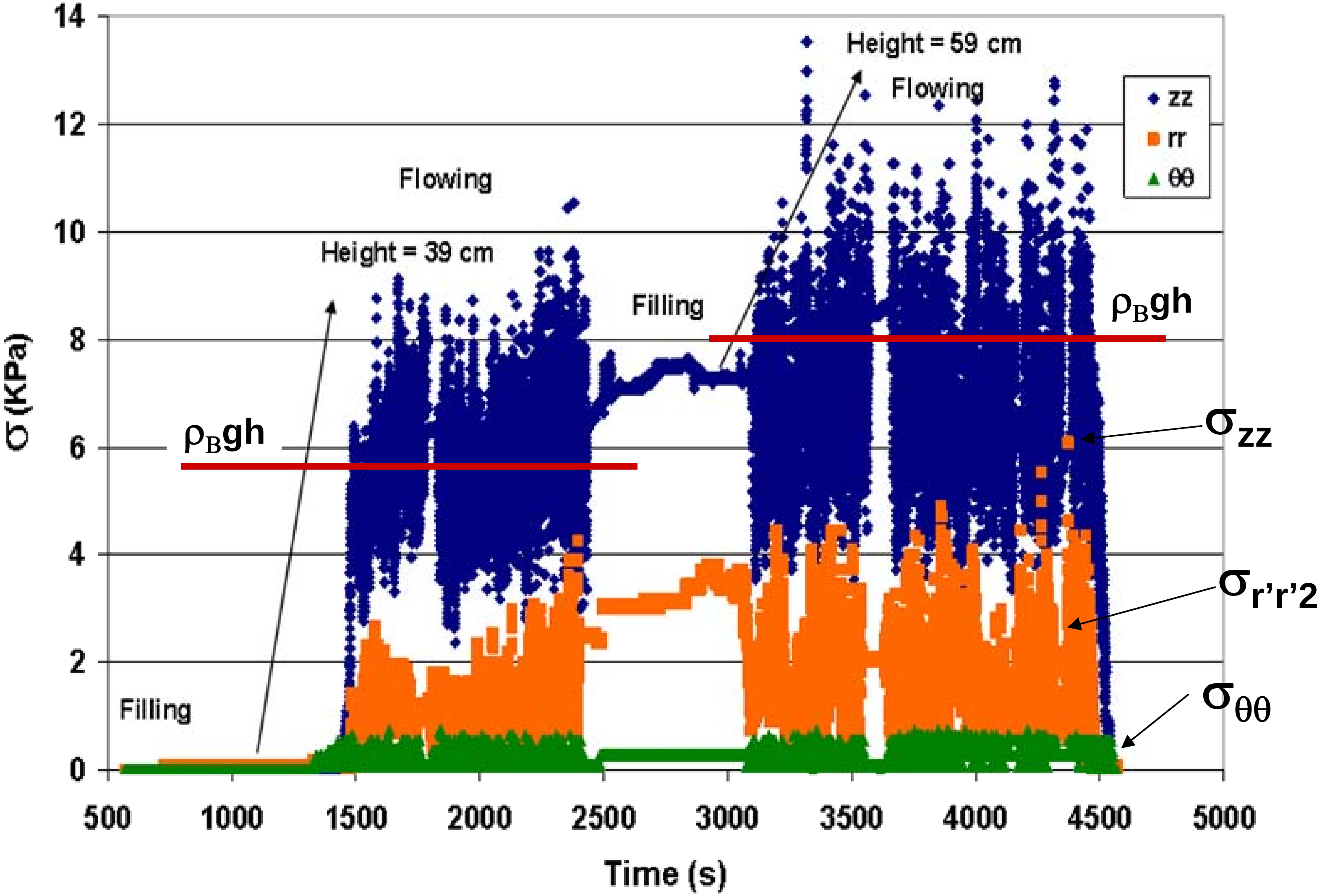


SEM pictures of the surface of 4 mm in diameter rough and smooth PE particles

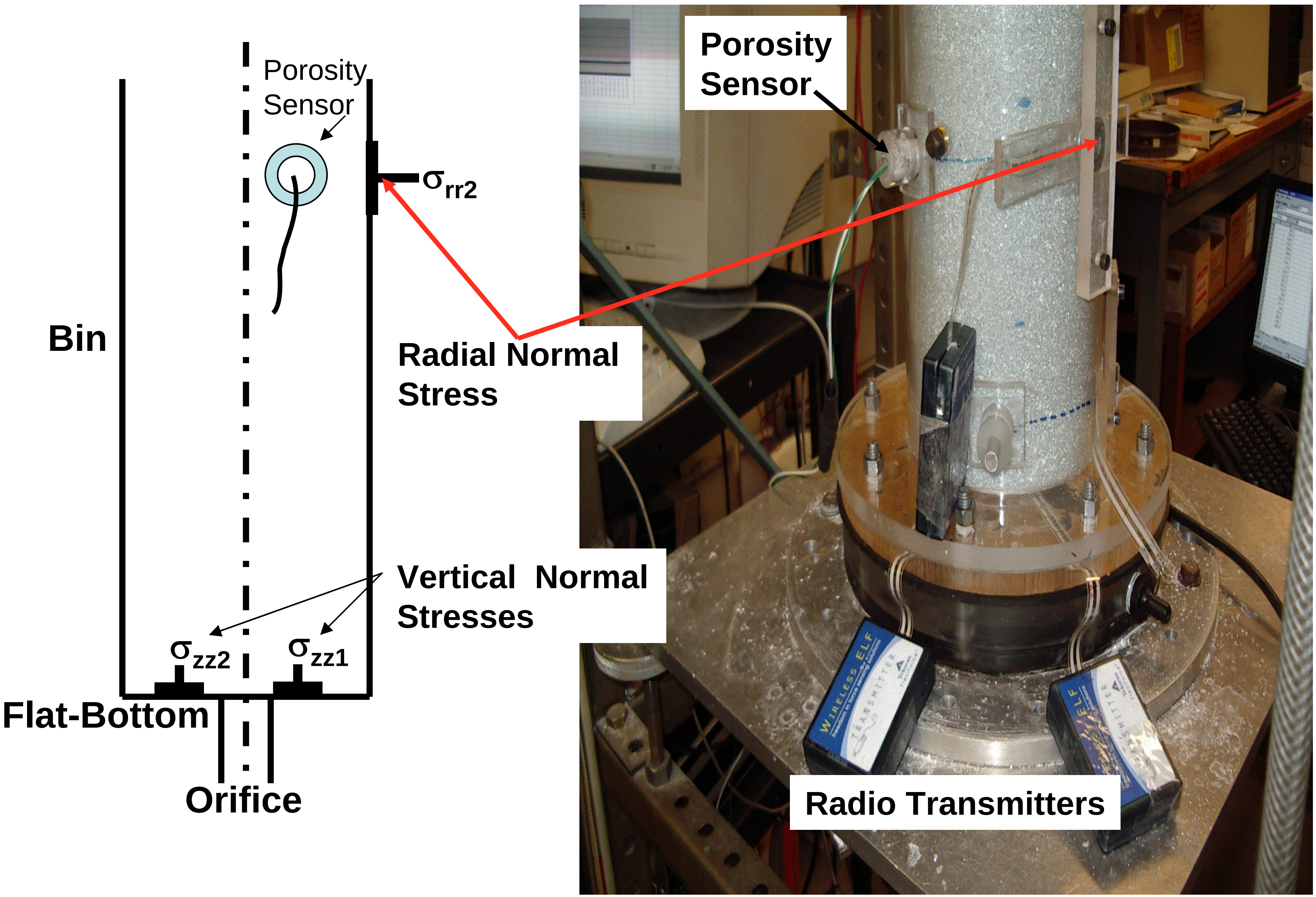
Conical , Mass-flow Hopper - Schematic



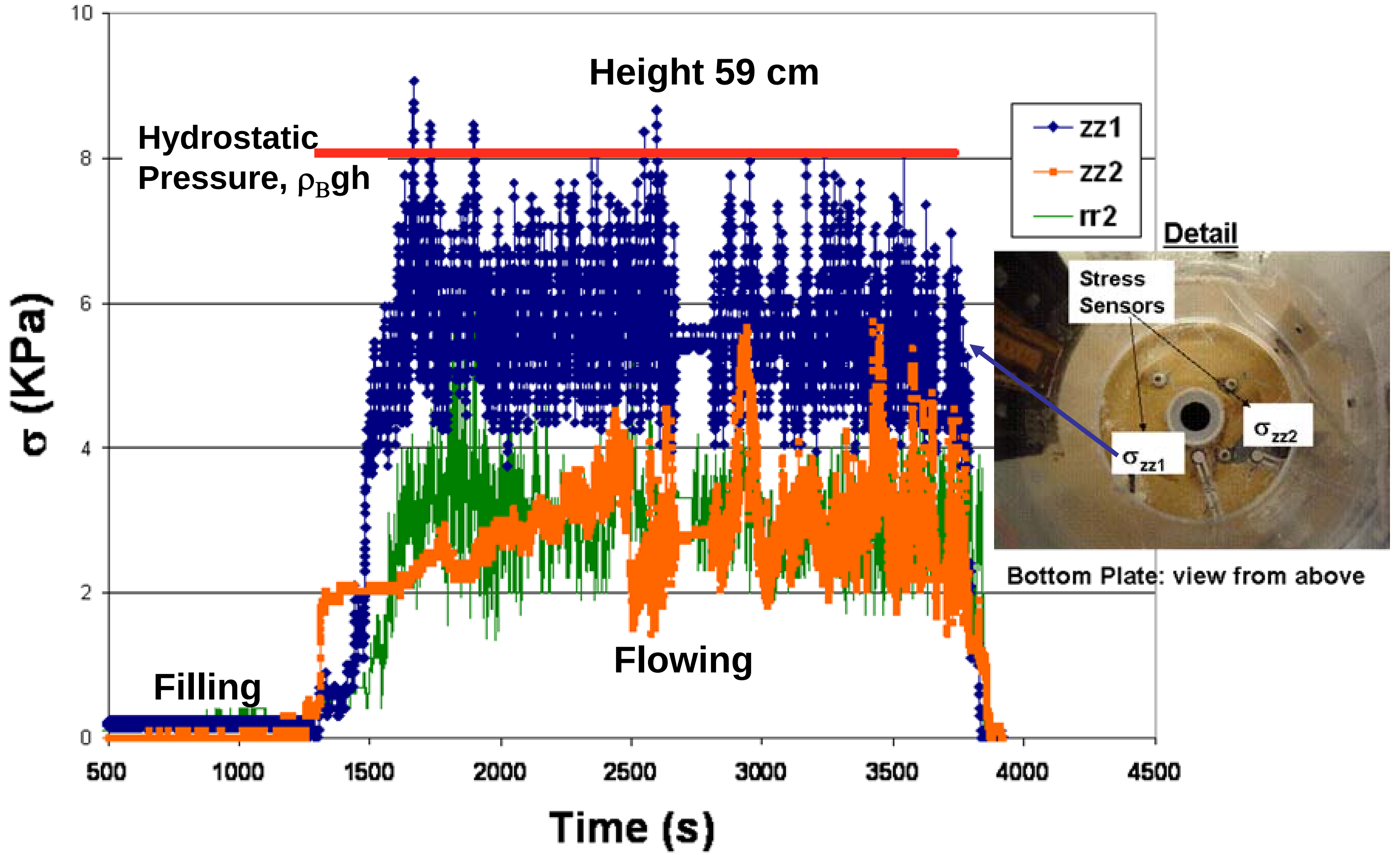
Stresses in the Mass-flow Hopper.



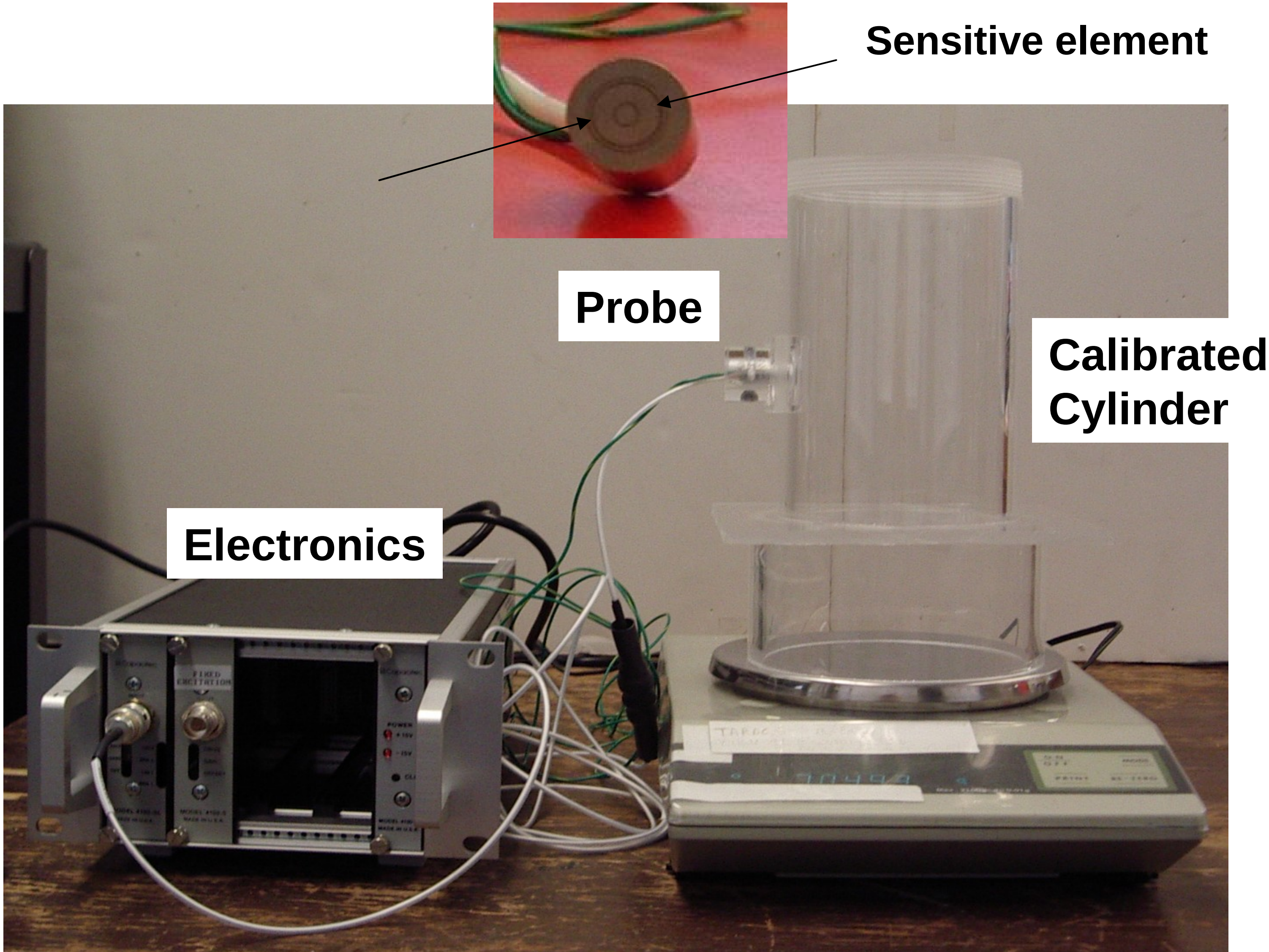
Flat-bottom Hopper - Schematic



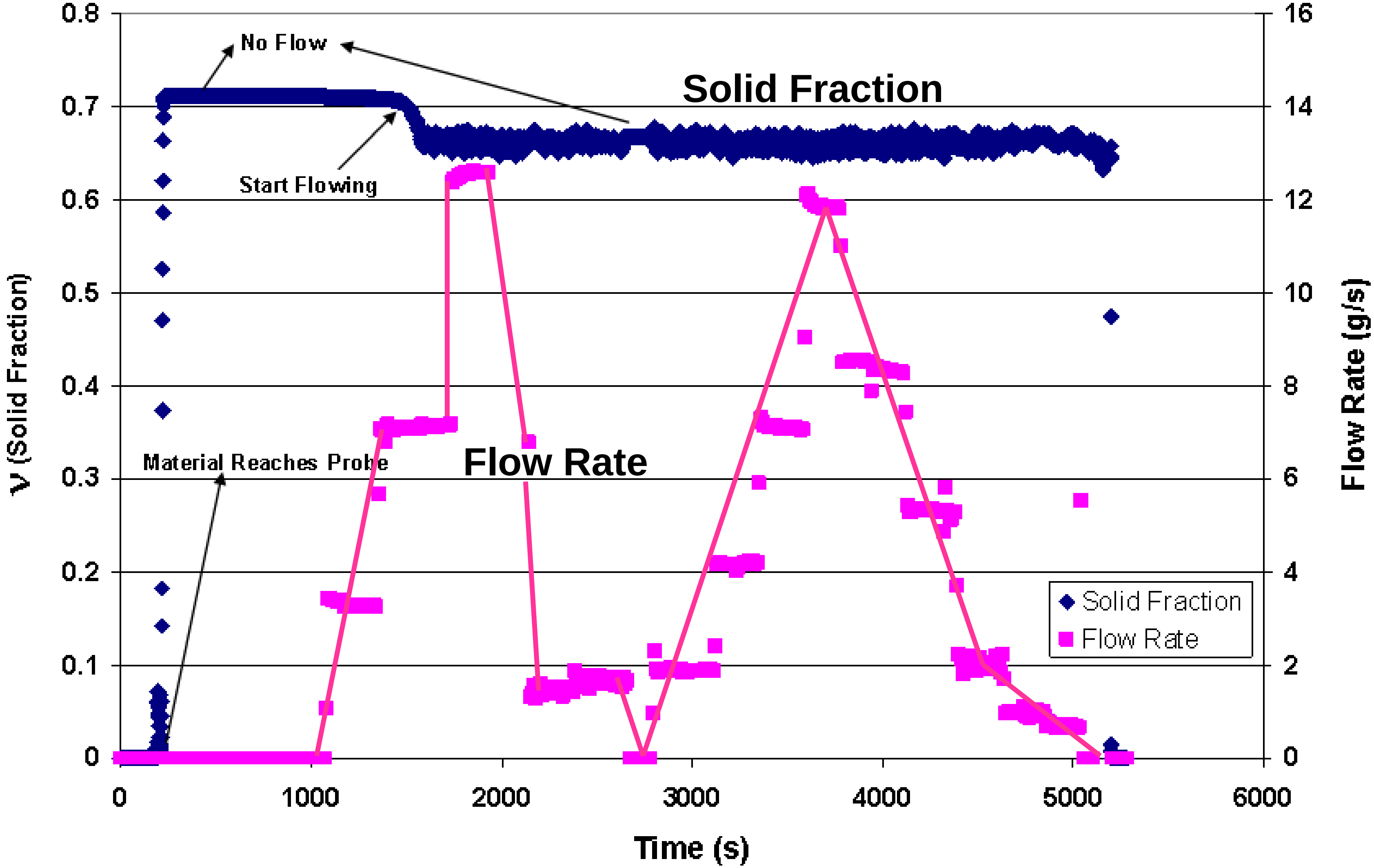
Stresses in the Flat-bottom Hopper.



Capacitance Probe for Solid Fraction Measurements



Solid Fraction in the Flat-bottom Hopper.



Conclusions

- Stresses are measured correctly only under shear
- DEM simulation favorably compare to results from “Fast” Jenike cell
- Solid Fraction measurements showed that the bed has to increase its porosity for the transition to the intermediate regime
- Ratio of Shear Stress to Shear rate is constant at low and increases at higher shear rates – experimental correlation can be used as “constitutive equation”.
- Flat bottom (funnel flow) and conical bottom (mass flow) hoppers behave differently and generate different set of Stresses
- Janssen’s yield theory applies more to mass flow hoppers but only at low flow-rates

Future Work Year III

- ✓ Couette Experiments – study influence of:
  - ✓ Particle size distribution (fines, coarse, mixtures)
  - ✓ Interstitial gas
  - ✓ Evaluation of DEM and “continuum” models
  - ✓ Comparison to MFIX
- ✓ Hopper flow Experiments
  - ✓ Conical-bottom (Mass flow)
  - ✓ Flat-bottom (Funnel Flow)
  - ✓ Evaluation of Hypo-plastic and other models
  - ✓ Comparison to MFIX