The Effect of Particle Shape on Particle-Phase Stress

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Experimental Setup

- Pilot-scale slurry flow facility in the UF Particle Science and Technology Building high bay area

- LDV-PDPA Measurements of Mean and Fluctuating Fluid and Solid Velocity

- Fully-developed, axisymmetric flow

- Explored range of Ba and St by varying flow velocity, solids fraction and particle size

Experimental Conditions

- 0.5, 1.0, & 1.5 mm glass beads in water
- Average fluid velocity = 2.6 m/s – 6.5 m/s
    - Average solids fraction = 0.7% - 3%
    - Bagnold Number ~ 25 – 763
    - Stokes Number ~ 1 - 28

Computational Model – Continuum Approach

- Eulerian approach for the solids phase in multiphase flows
- Can be used to model a full-scale process unit
- Constitutive models are needed to describe the particle-phase stress
  - *Based on concepts from Gas Kinetic Theory (inertia-dominated particulate flows)*
  - *f [solids fraction, particle density and size, coefficient of restitution, shear rate]*
  - ***Spherical Particles***

Effect of Particle Shape

- Virtually all solids handling operations involve particles that are non-spherical in shape

- Role of particle shape on particle flow behavior is significant [Chan and Page, 1997; Shinohara *et al*, 2000; Sukumaran and Ashmawy, 2003; Escudié *et al*., 2006; Xu and Zhu 2006)].
  - Irregular shapes tend to produce intermittent flow
  - Irregular particles tend to have smaller bulk densities and larger angles of repose compared with spherical particles.
  - Irregular particle shapes tend to have larger fluidized bed voidages and larger minimum fluidization velocities due to the mechanical interlocking of particles.

- Experimental studies probing the details of particle impacts are for idealized spherical particles

- CFD simulations – spherical particles are used

What if particles are not spherical?

- Drag Effects
- Modulation of Gas-Phase Turbulence
- **Changes in Particle-Phase Stress**

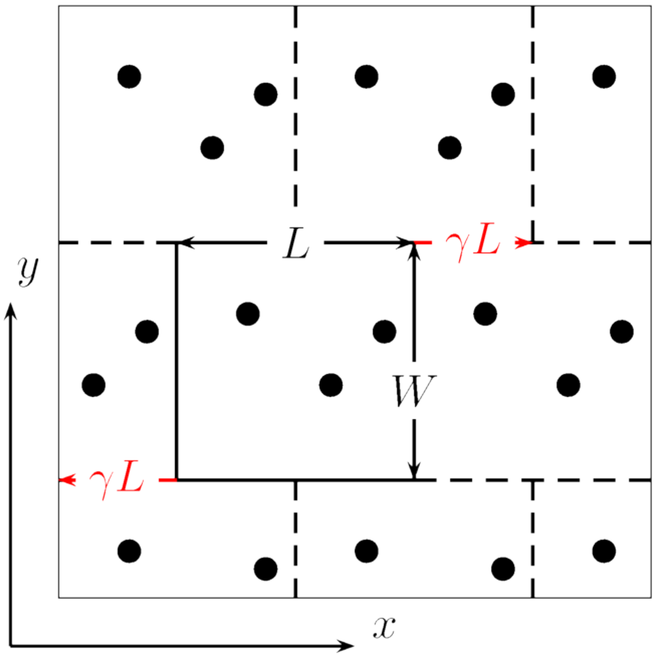
Computational Model - DEM

- Discrete Element Method
  - Dynamics of individual particles are described
  - Physical properties associated with individual particles (*size/size distribution, density, shape*) can be easily varied
  - Provides details on individual particle behavior
  - DEM simulations can be used to build particle-phase stress constitutive relations

DEM - Effect of Particle Shape

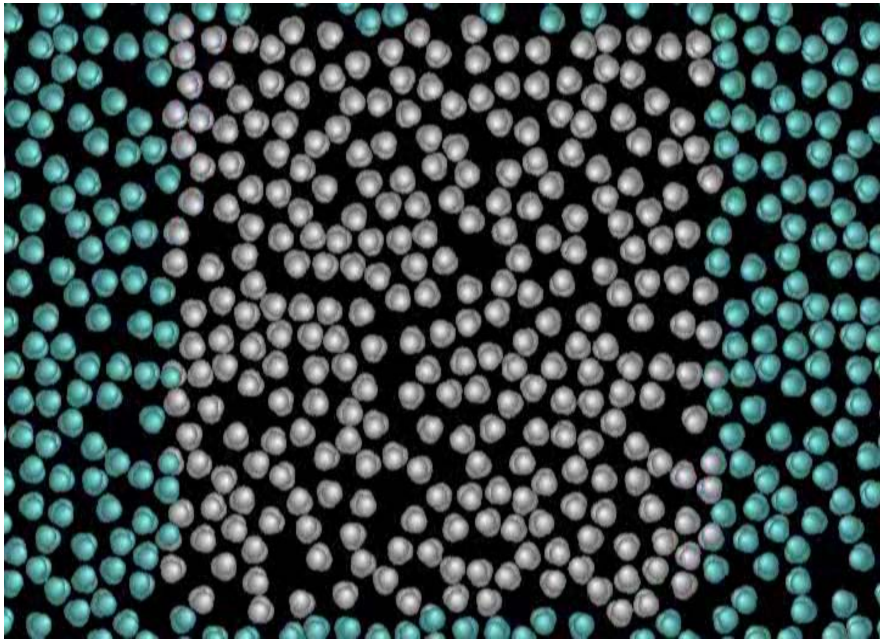
- Linked/overlapping spheres to describe various particle shapes

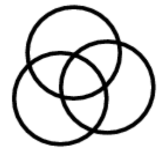
- Determine the effect of particle shape on particle-phase stress
  - Perform DEM simulations in a simple shear flow (initially 2-D, then 3-D) with periodic boundaries
  - Explore the role of particle elongation, roughness, elasticity, friction

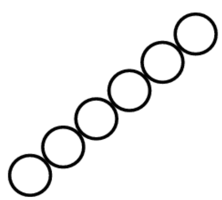


- Develop particle-phase stress relations that incorporate the influence of particle shape

DEM - Effect of Particle Shape







DEM - Describing Particle Shape

Various particle shape models employed in the literature:

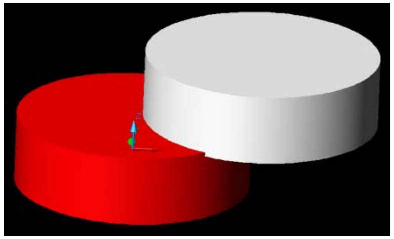
- Sphero-cylinders (cylinders capped with spheres), ellipsoids, superquadrics, discrete function representations and glued-sphere clusters

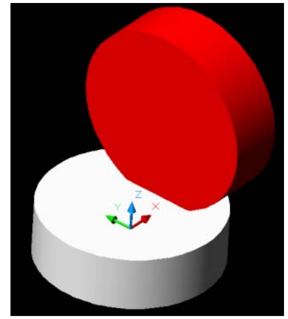
Potapov and Campbell (1998) compared the simulation times during a bin filling process using a variety of particle shape models. They showed that the run times for non-spherical particles described by overlapping discs/spheres were significantly shorter than for particles described by other methods

Contact detection between spheres is simple. Two spheres are in contact if the distance separating their centers is less than the sum of their radii

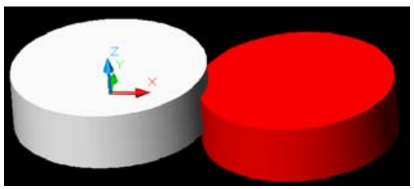
Added cost in terms of memory and additional sphere-sphere contact checks is generally smaller than the contact detection cost of more complex algorithms for irregular particle shapes

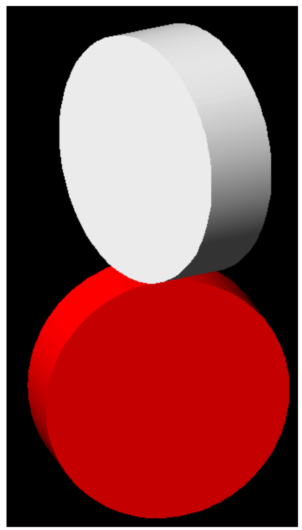
DEM - Describing Particle Shape

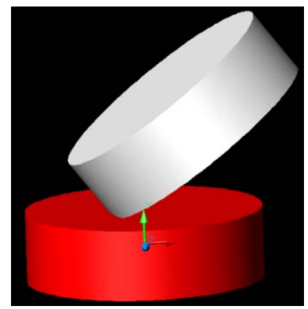


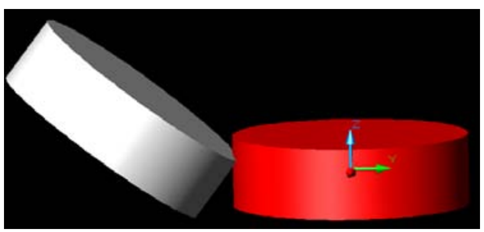


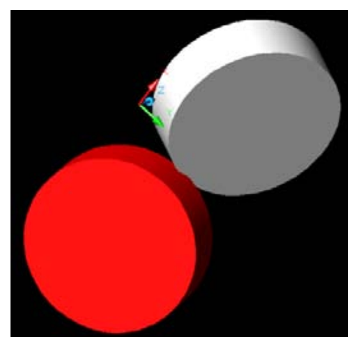
Contact Detection for Cylinders











- Face – Face
- Face - Band
- Band – Band (Parallel)
- Band – Band (Skewed)
- Face - Edge
- Band – Edge
- Edge – Edge

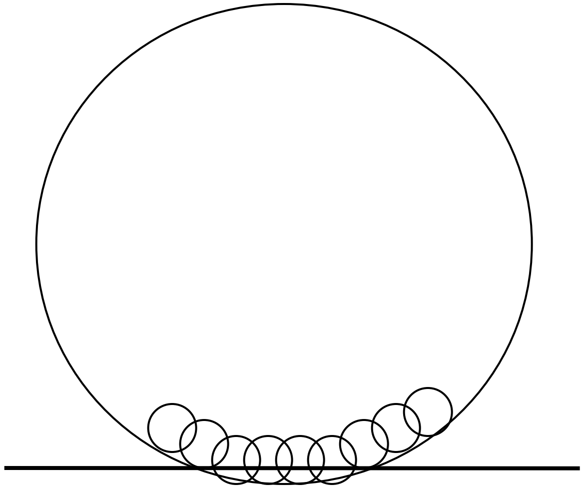
Kodam, M., Bharadwaj, R., Curtis, J., Hancock, B., and Wassgren, C., "Cylindrical Object Contact Detection for Use in Discrete Element Method Simulations, Part I – Contact Detection Algorithms," *Submitted to Chemical Engineering Science.*

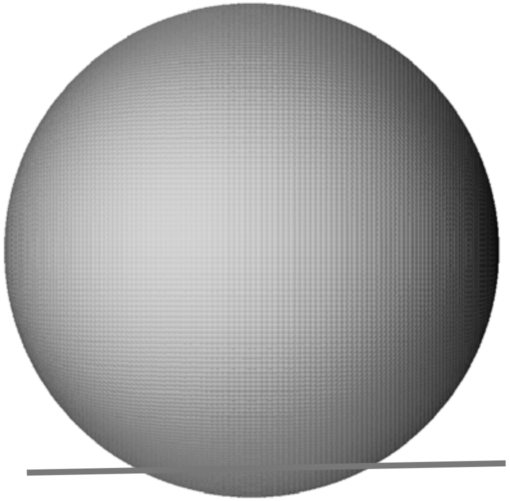
DEM - Describing Particle Shape

Disadvantages of glued spheres

- Do not duplicate shape exactly – additional surface roughness
- Large number of spheres degrades force modeling due to the larger number of spheres that may make contact simultaneously

Two forces are not exactly equal

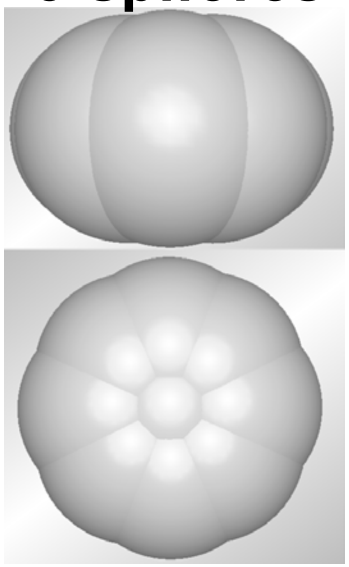




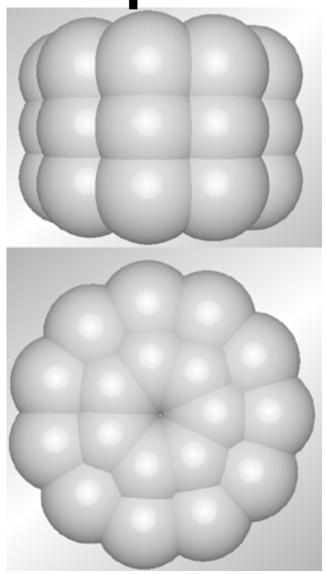
Kodam, M., Bharadwaj, R., Curtis, J., Hancock, B., and Wassgren, C., 2009. "Force model considerations for glued sphere discrete element method simulations", Chemical Engineering Science, 64(15), 3466-3475.

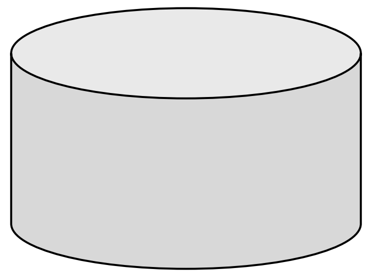
DEM - Describing Particle Shape

9 spheres



54 spheres





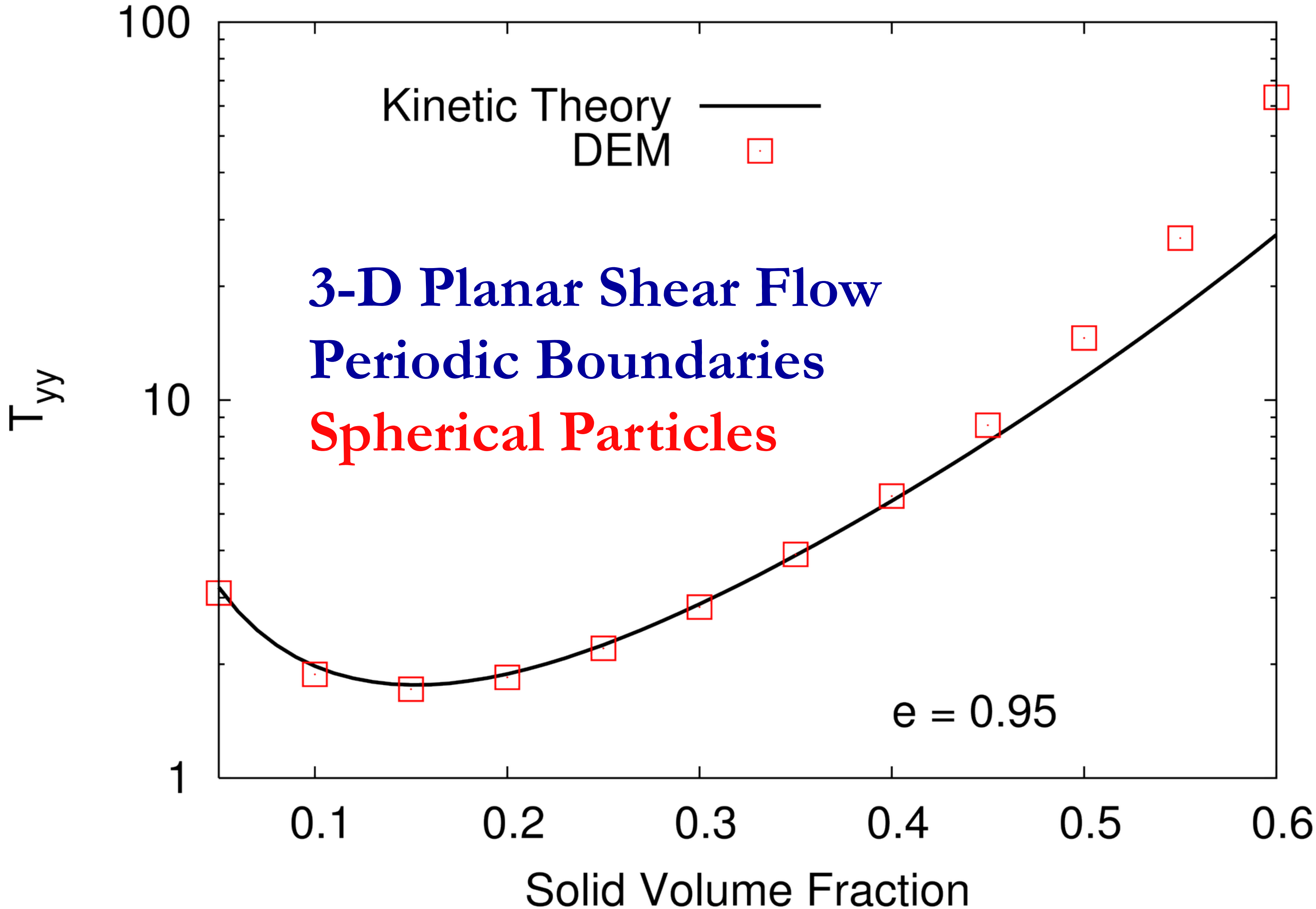
Packing Fraction

0.585 **0.562** **0.589**

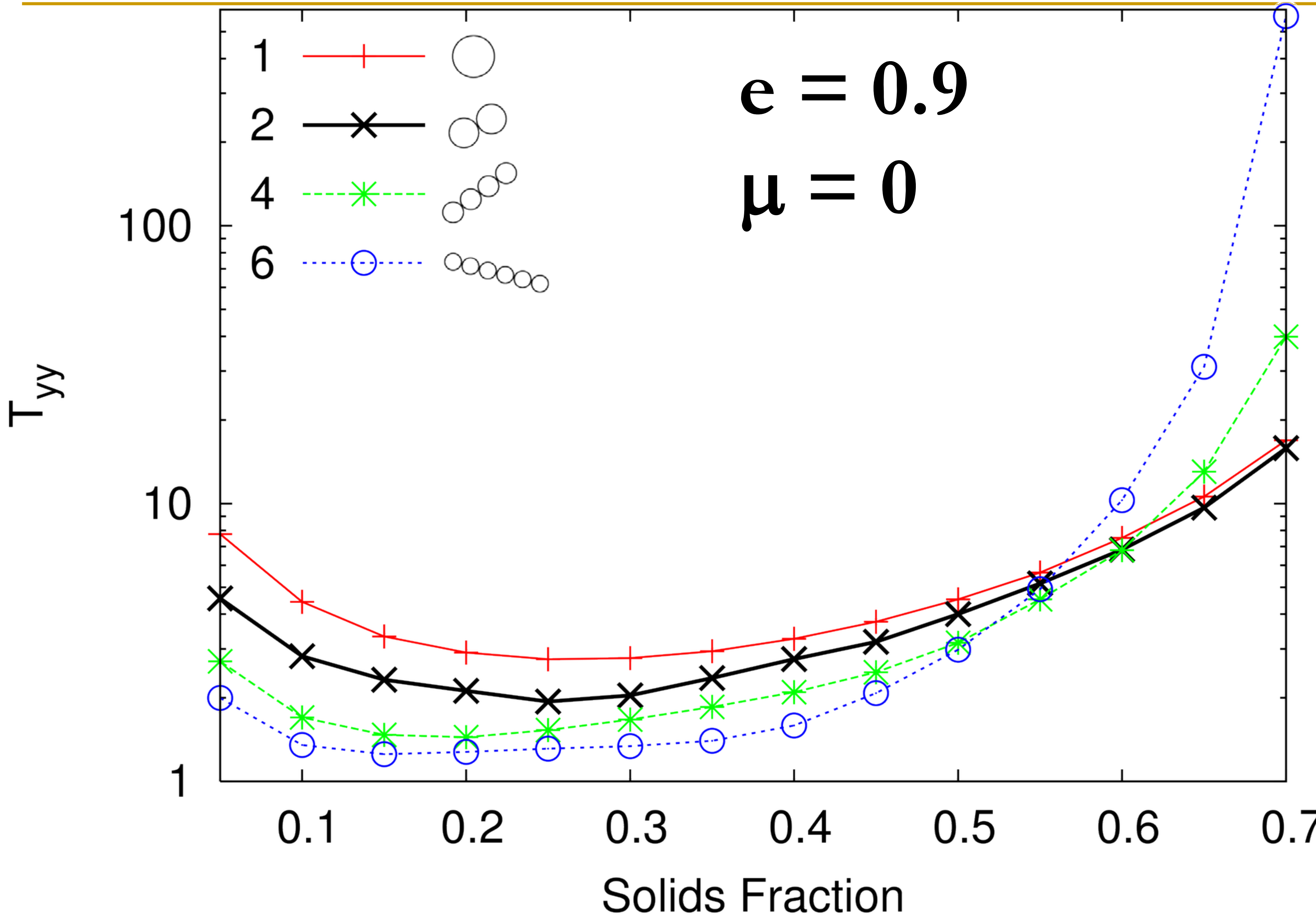
Kodam, M., Bharadwaj, R., Curtis, J., Hancock, B., and Wassgren, C., “Cylindrical Object Contact Detection for Use in Discrete Element Method Simulations, Part II – Validation,” *Submitted to Chemical Engineering Science.*

Relationship Between DEM and Kinetic Theory

T is scaled by $\rho d^2\gamma^2$ (ρ particle density, γ shear rate, d particle diameter)

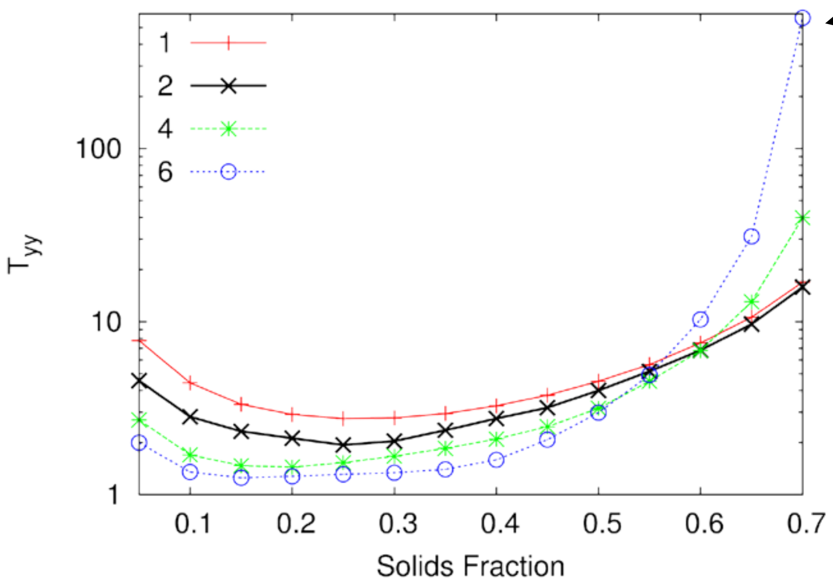


Stress Behavior for Elongated Particles



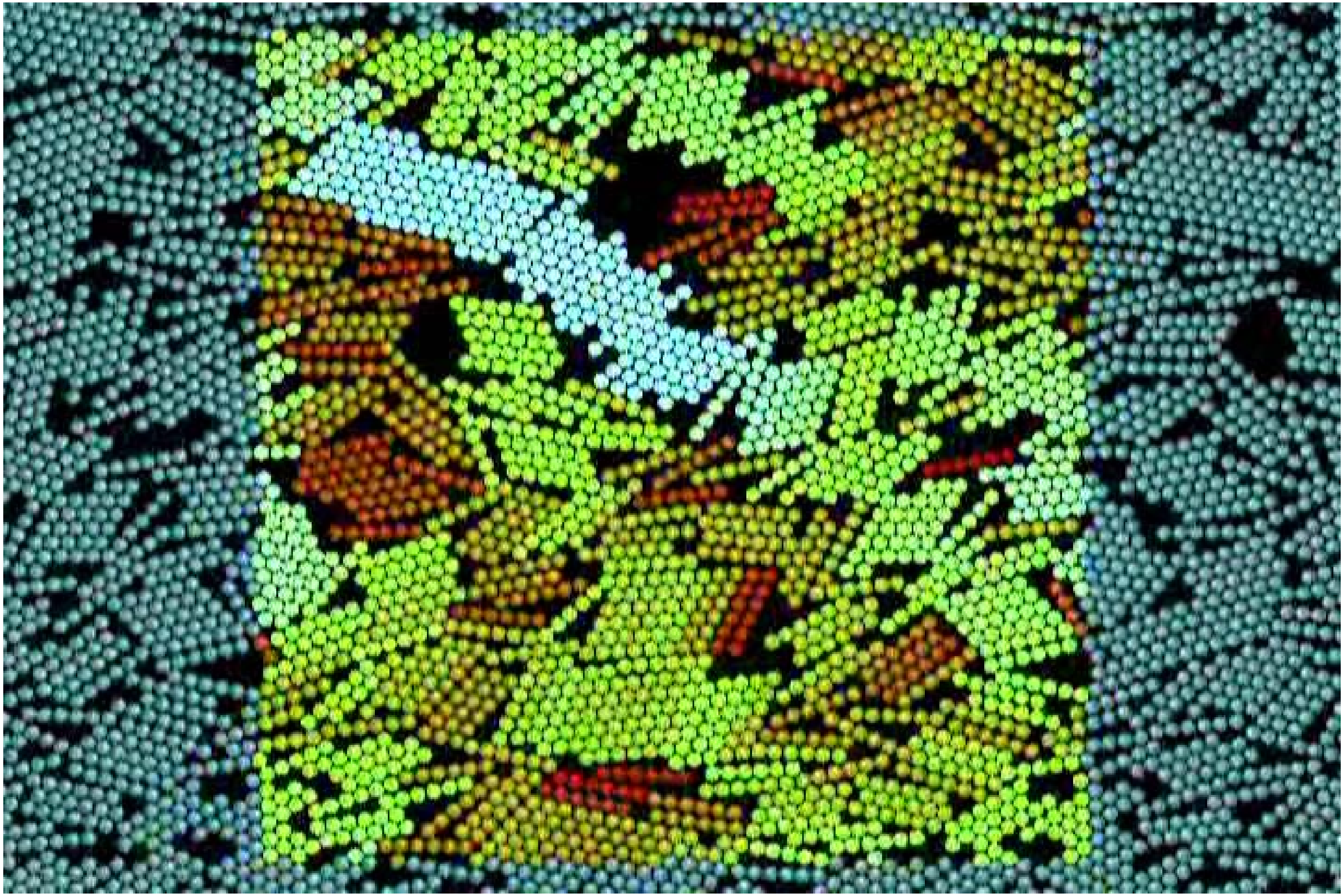
Stress Behavior for Elongated Particles

Aspect Ratio = 6
Solids Fraction = 0.7



Collision Rate

- < 100 collisions/s
- > 10,000 collisions/s



Particle-Phase Stress Relationship
Dilute-Phase Regime

Stress ~ Granular Temperature ~ Particle Velocity Variance

Velocity Deviation ~ Time between Particle Collisions

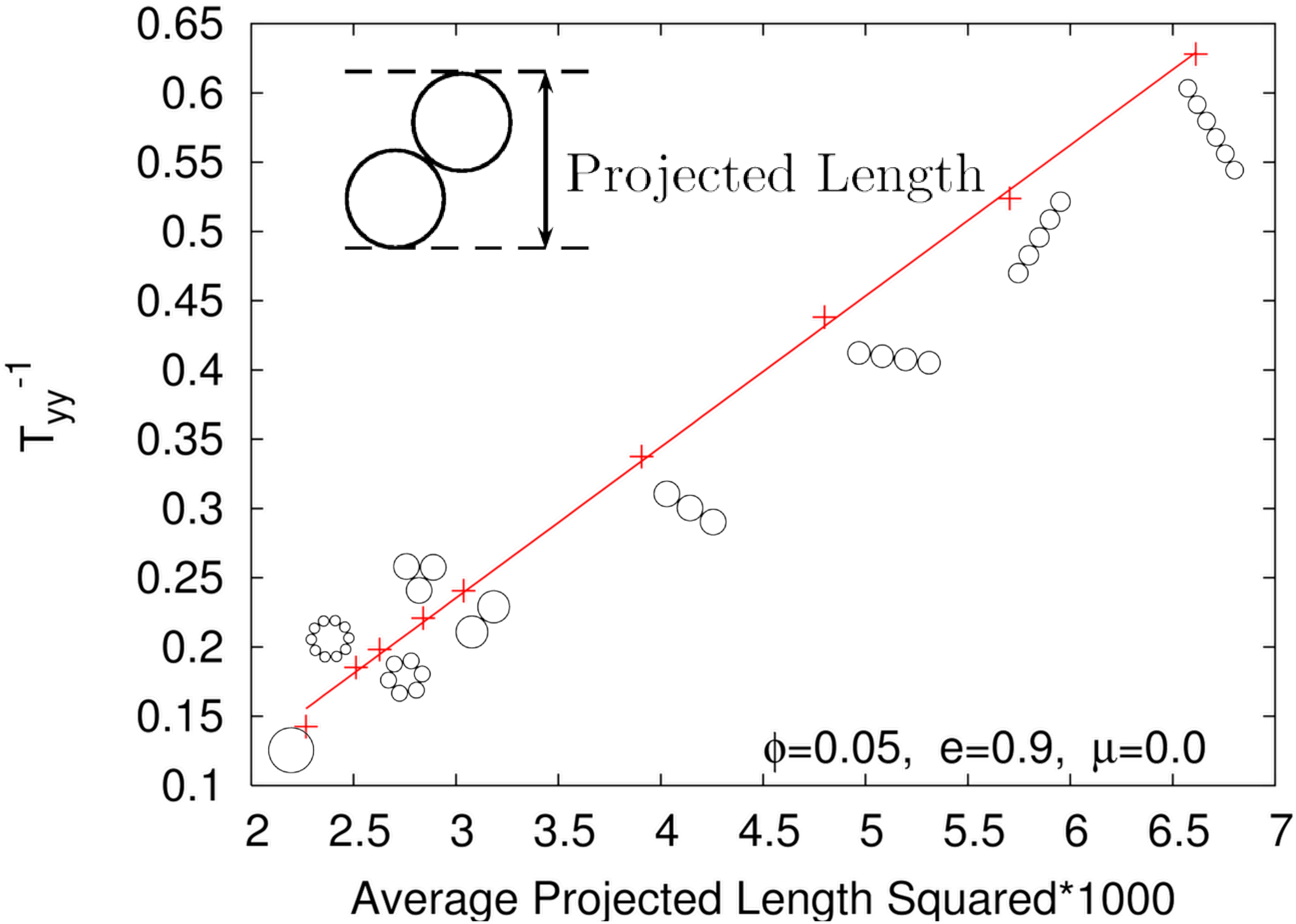
Time Between Particle Collisions ~ 1/Probability of a Particle Collision

Probability of a Particle Collision ~ Average Projected Particle Length

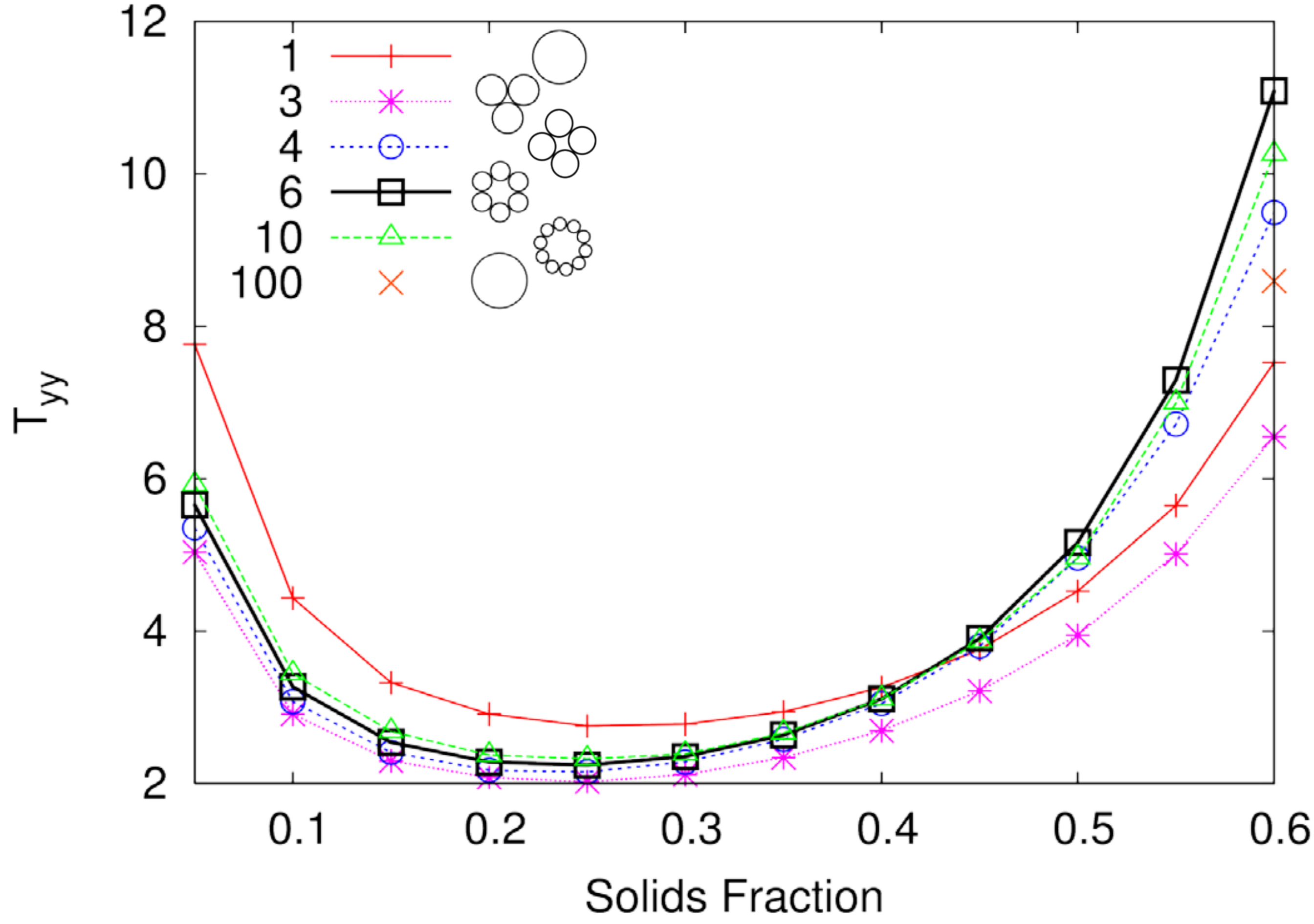
↓

Stress ~ 1/(Average Projected Particle Length)^2

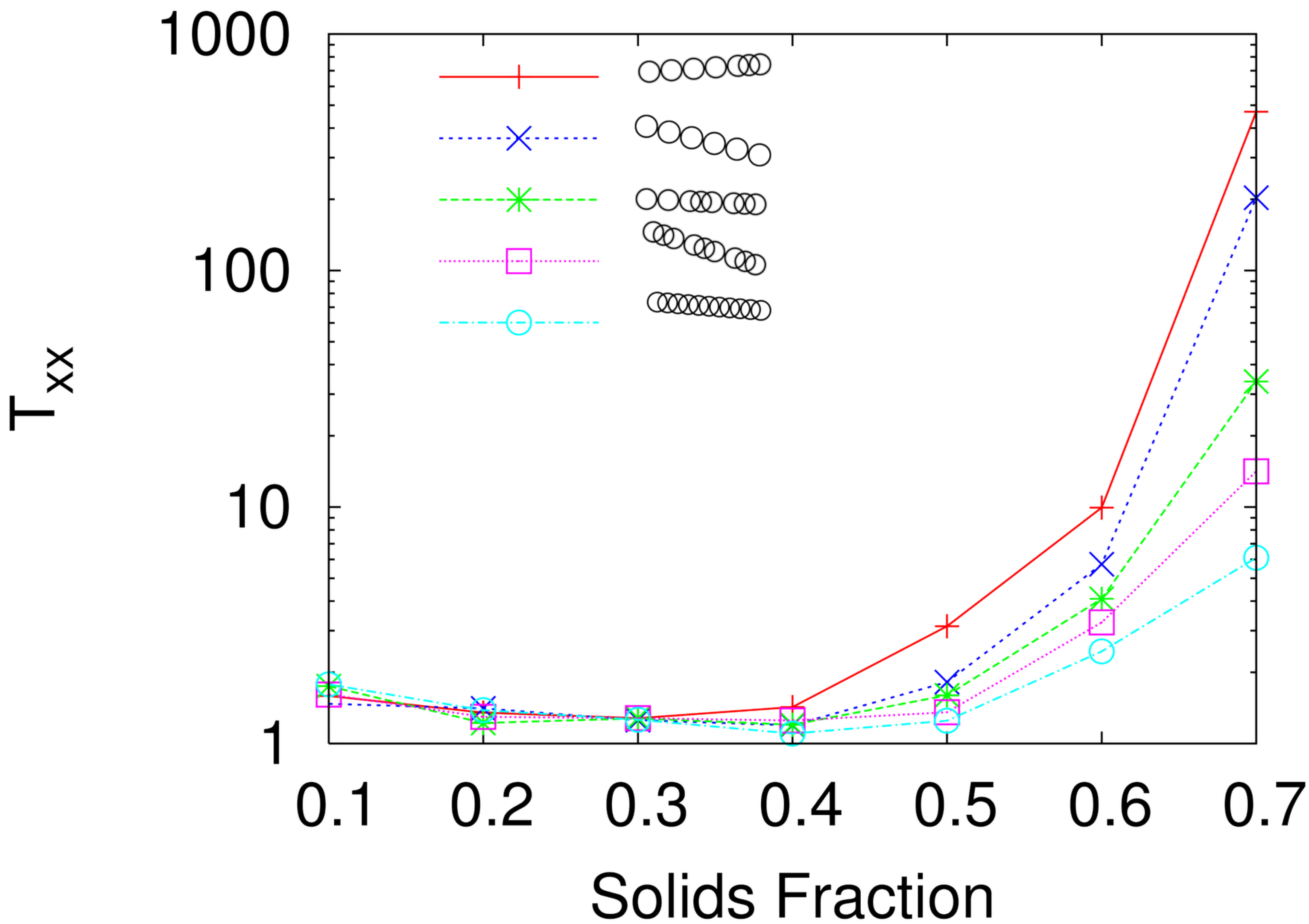
Particle-Phase Stress Relationship



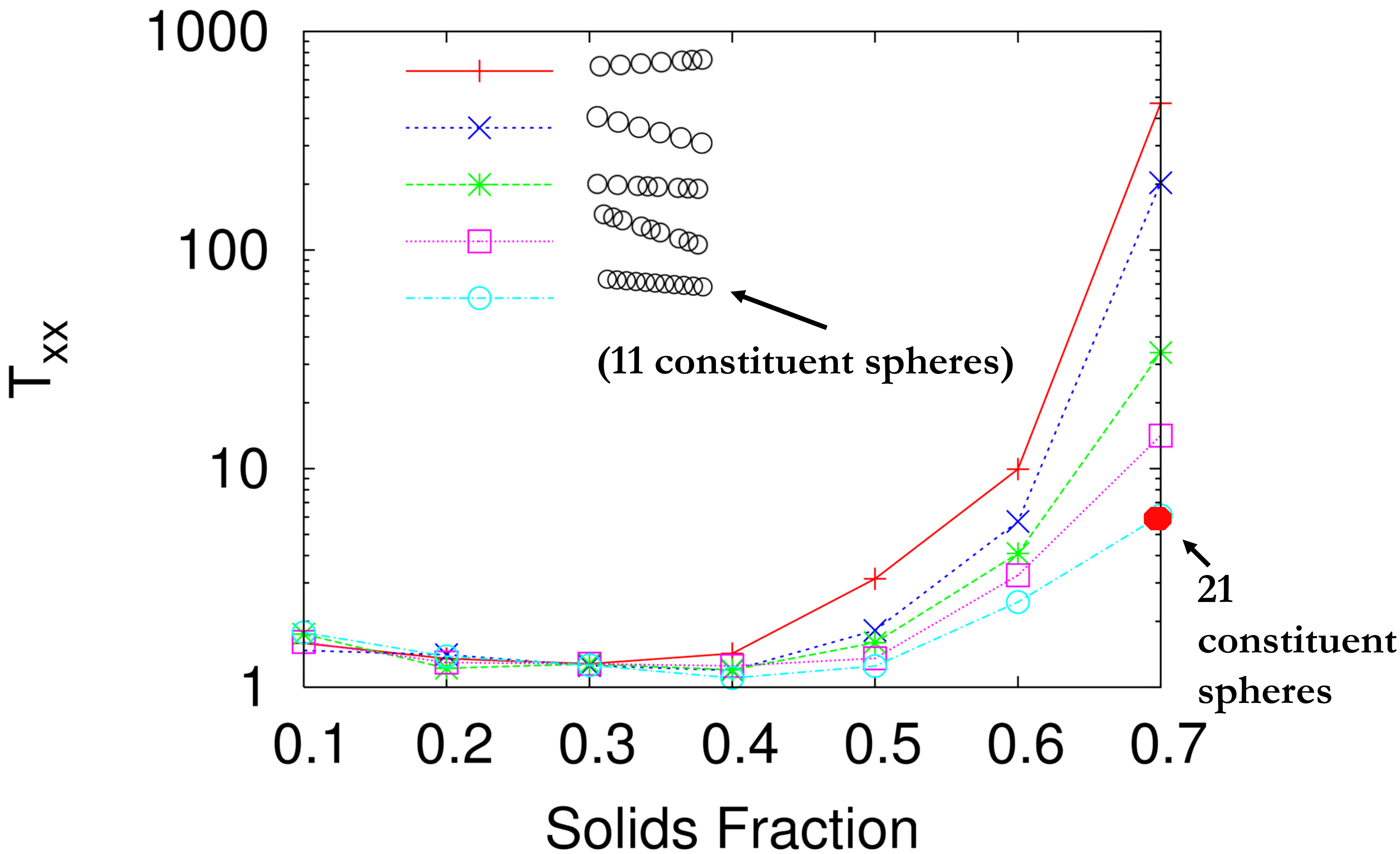
Stress Behavior for "Rough" Particles



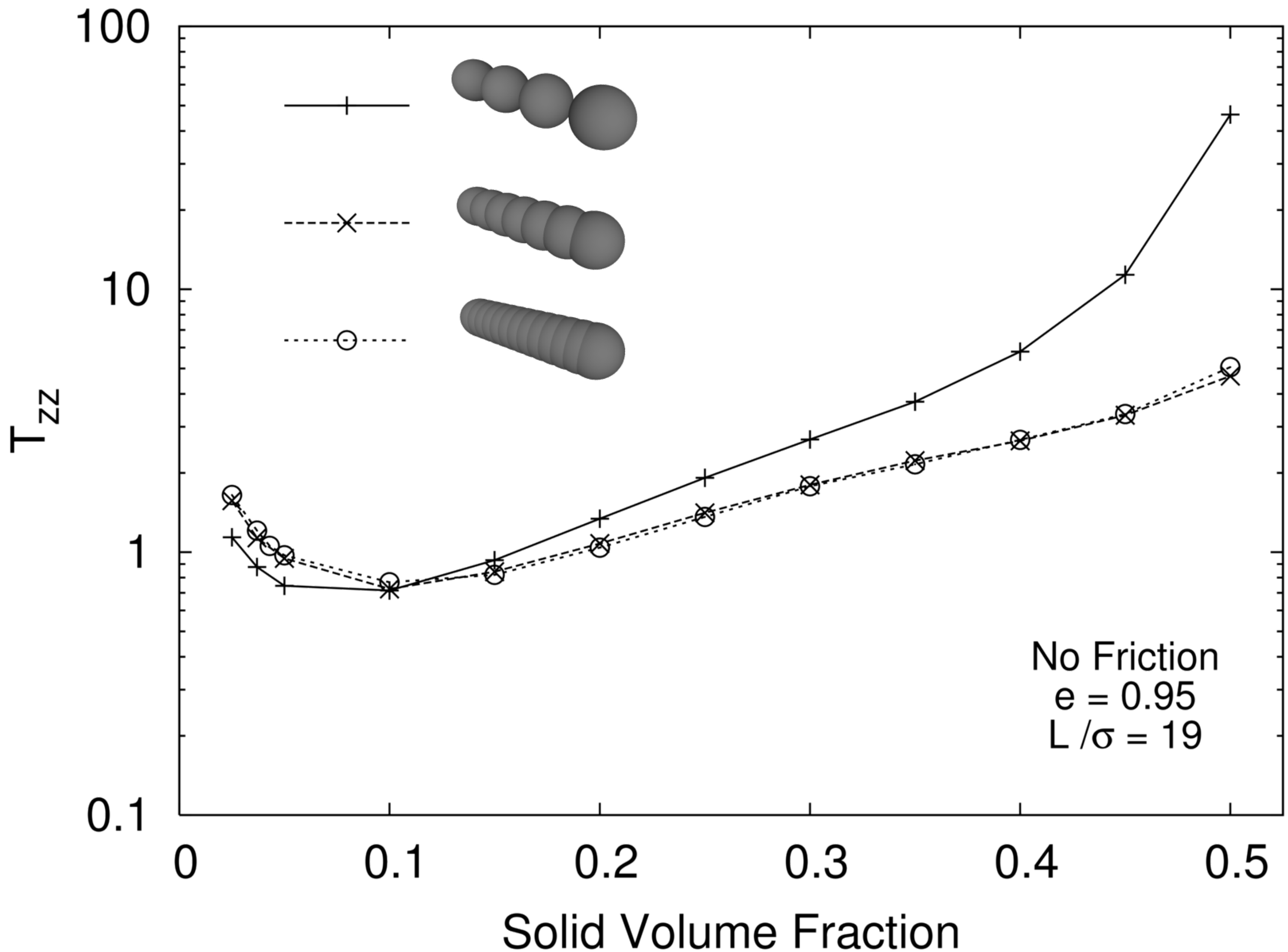
Stress Behavior for Elongated "Smooth" Particles



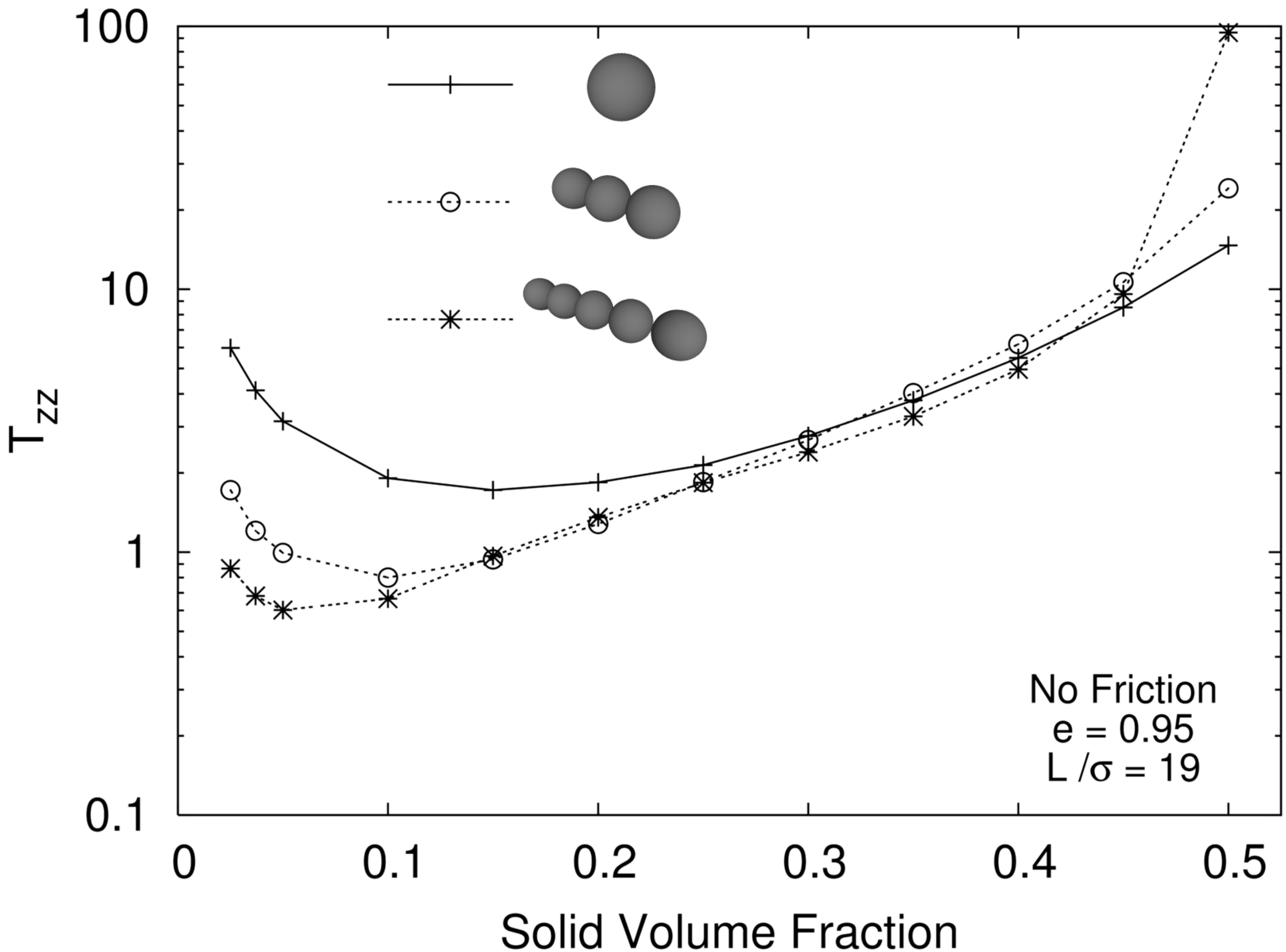
Stress Behavior for Elongated "Smooth" Particles



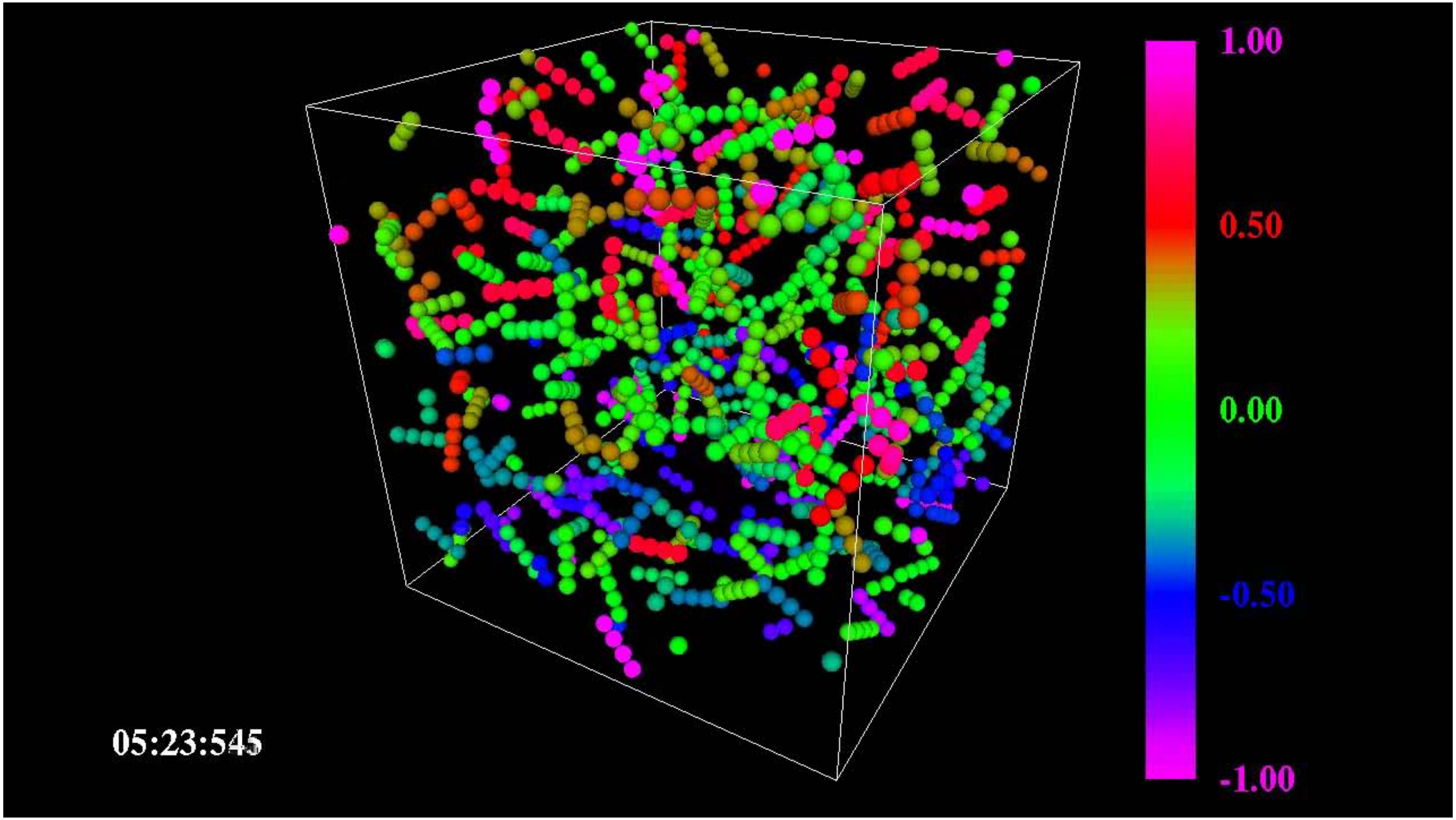
3-D Stress Behavior for Elongated Smooth vs. Rough Particles



3-D Stress Behavior for Elongated Particles

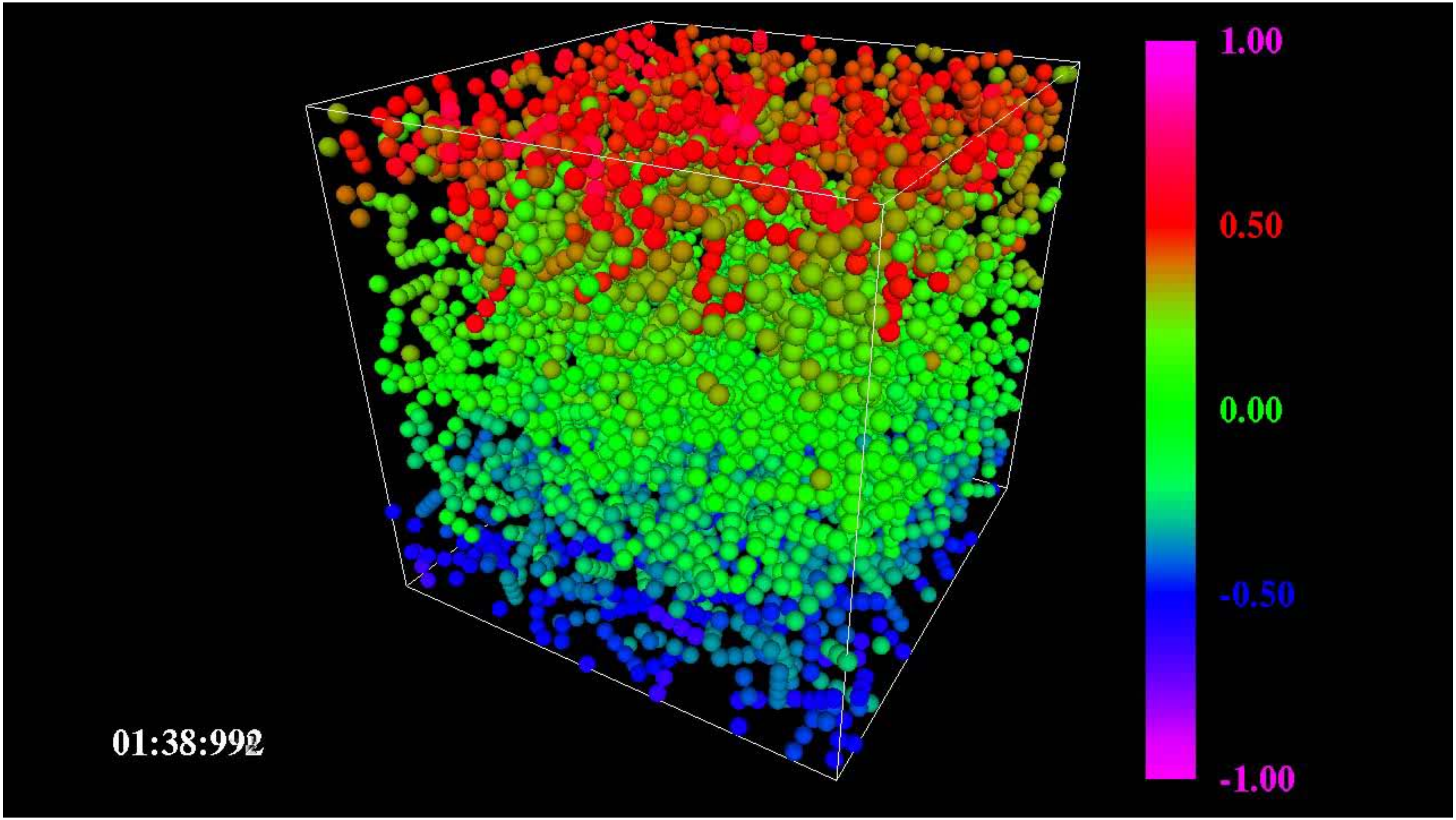


3-D Stress Behavior for Rough, Elongated Particles (aspect ratio 4)



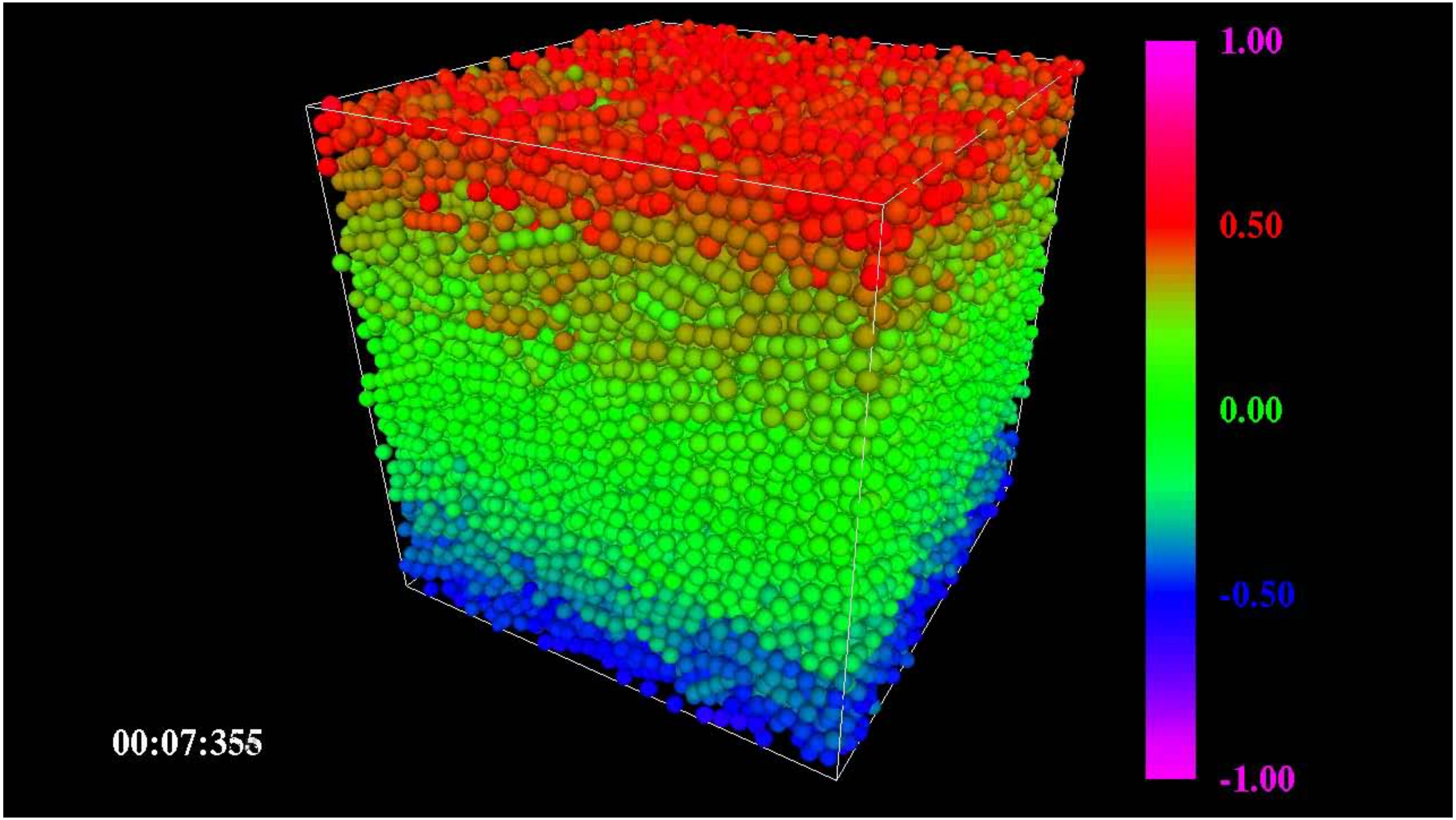
2.5% solids fraction

3-D Stress Behavior for Rough, Elongated Particles (aspect ratio 4)



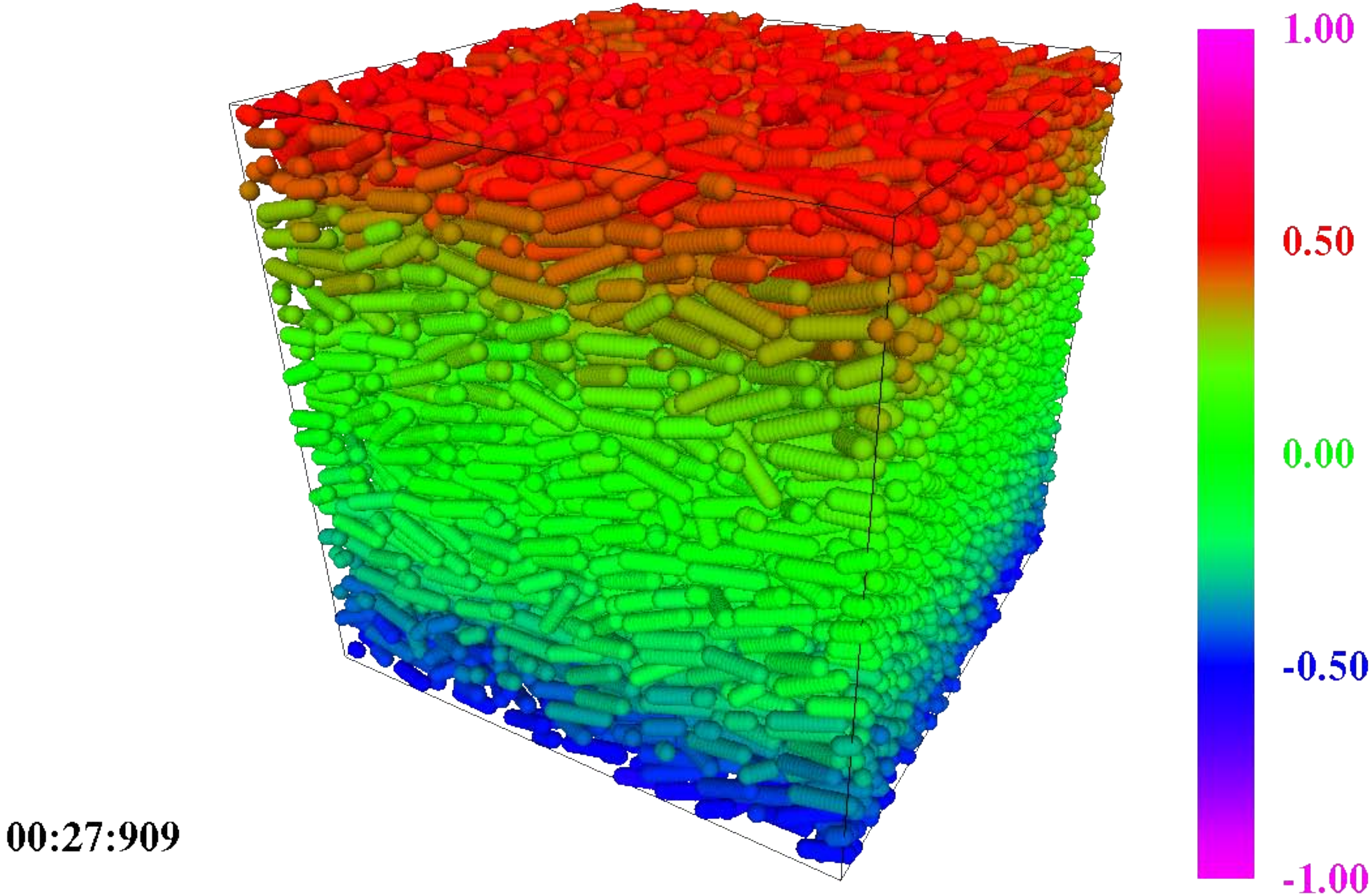
10% solids fraction

3-D Stress Behavior for Rough, Elongated Particles (aspect ratio 4)



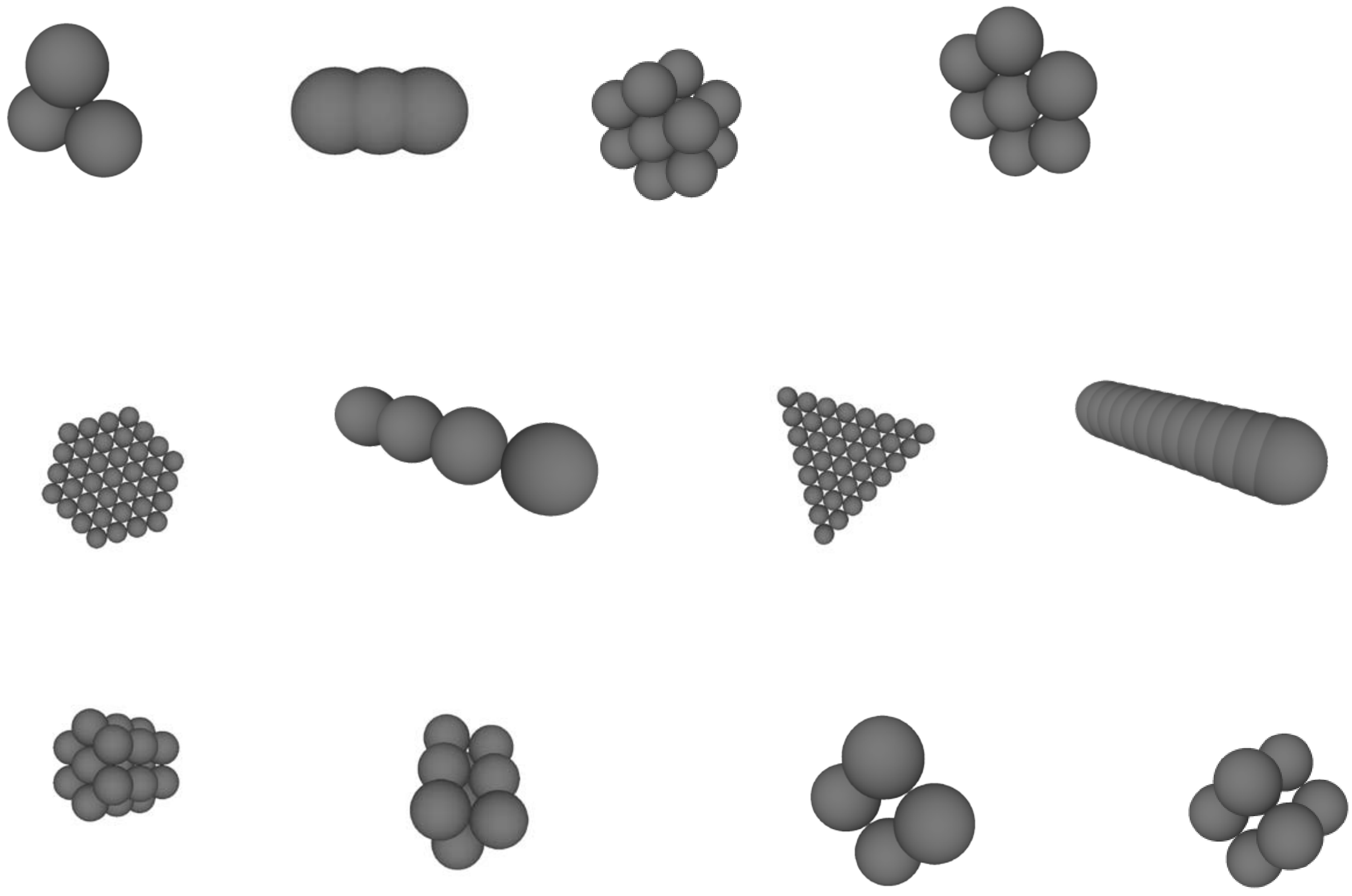
50% solids fraction

3-D Stress Behavior for Smooth, Elongated Particles (aspect ratio 4)



50% solids fraction

Wide Variety of Particle Shape Considered Same Equivalent Volume Diameter



Particle-Phase Stress Relationship (3-D) Dilute-Phase Regime

Stress ~ Granular Temperature ~ Particle Velocity Variance

Velocity Deviation ~ Time between Particle Collisions

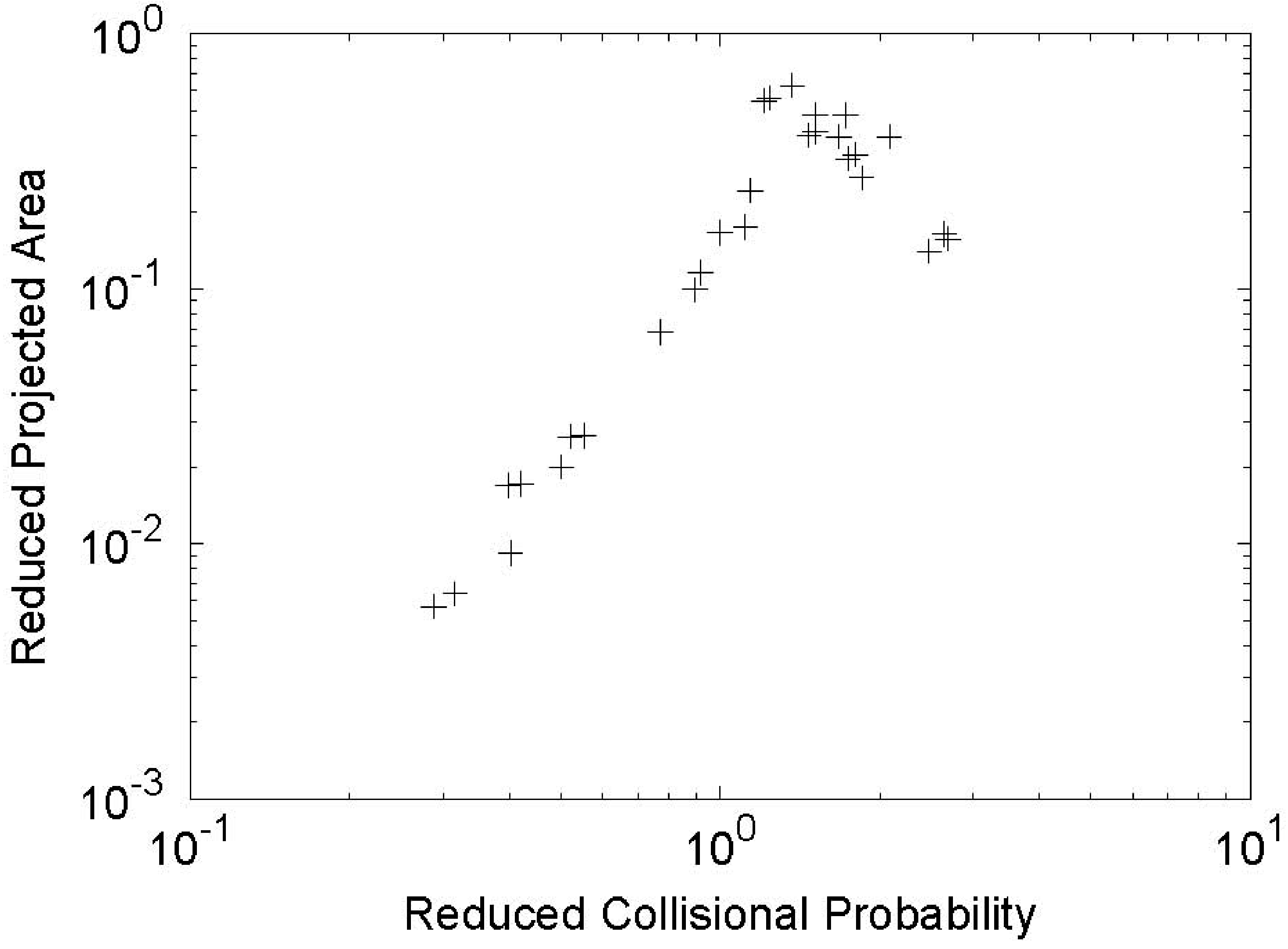
Time Between Particle Collisions ~ 1/Probability of a Particle Collision

Probability of a Particle Collision ~ Average Projected Area ??

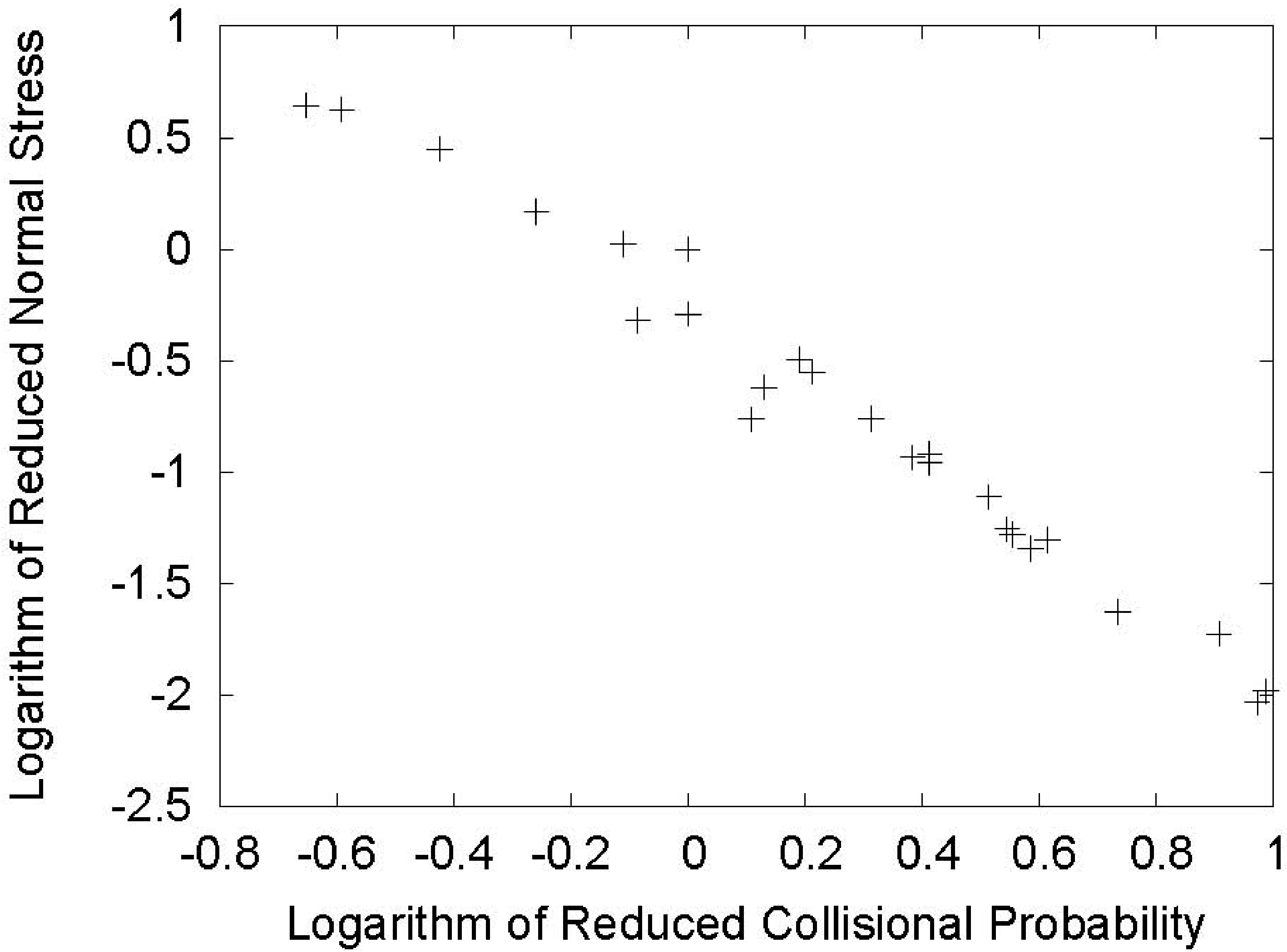
↓

Stress ~ 1/(Average Projected Particle Area)^2 ??

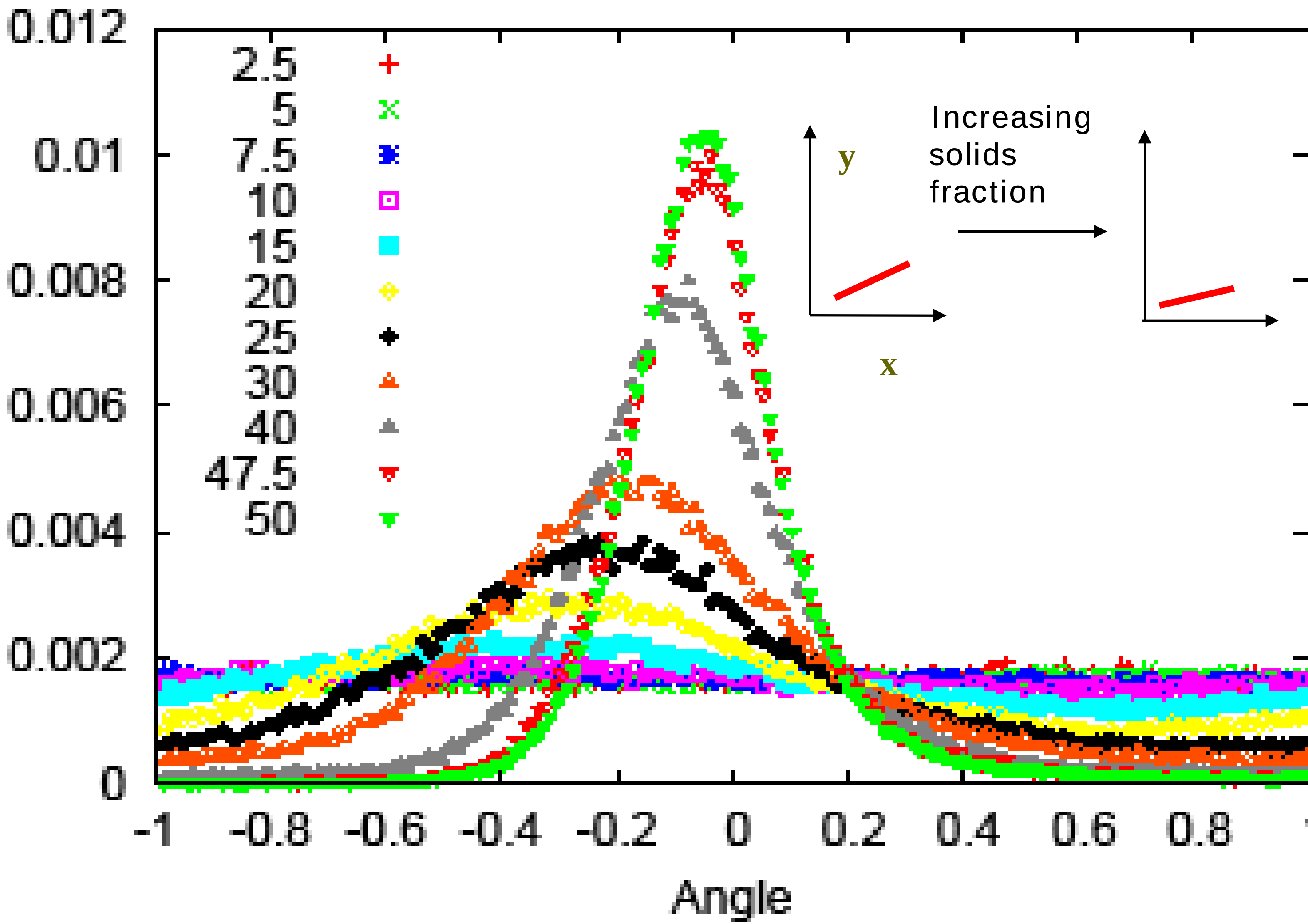
Projected area does not scale with collisional probability in 3-D



Scaling for Particle-Phase Stress (3-D)



Particle Orientation – Elongated Particles



Conclusions

- Particle-Phase Stress for Non-Spherical Particles (Dilute Regime)

  f [ϕ, ρ, d, e, γ]

  Spherical Particles

  ↓

  f [ϕ, ρ, d, e, γ, projected particle length (2-D)]

  Non-Spherical Particles

  f [ϕ, ρ, d, e, γ, collisional probability (3-D)]

  Non-Spherical Particles

- Combined effect of particle elongation and roughness, results in huge increases in particle-phase stress in dense-phase flows
- Particle-phase stress for rough, round-shaped particles does not vary significantly from a perfect sphere
- Deviation in particle-phase stress by approximating a smooth surface via non-overlapping spheres is very small in dilute-phase flow but is significant in dense-phase flow
- Not a large number of constituent spheres are necessary for particle-phase stress to asymptote

Experimental Setup

A) water tank

B) pump

C) venturi eductor

D) electromagnetic flow meter

E) test section

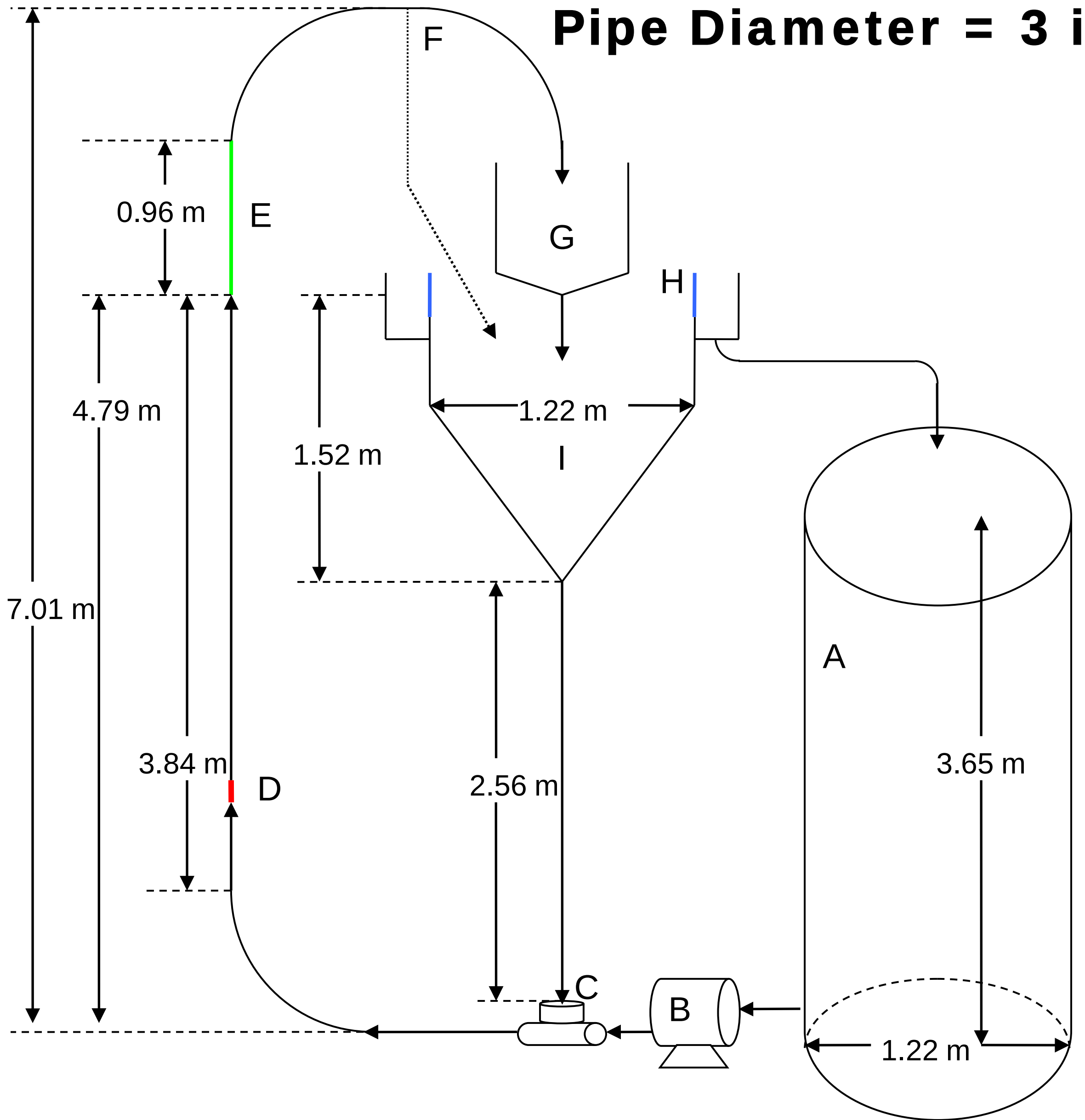
F) by-pass

G) sampling tank

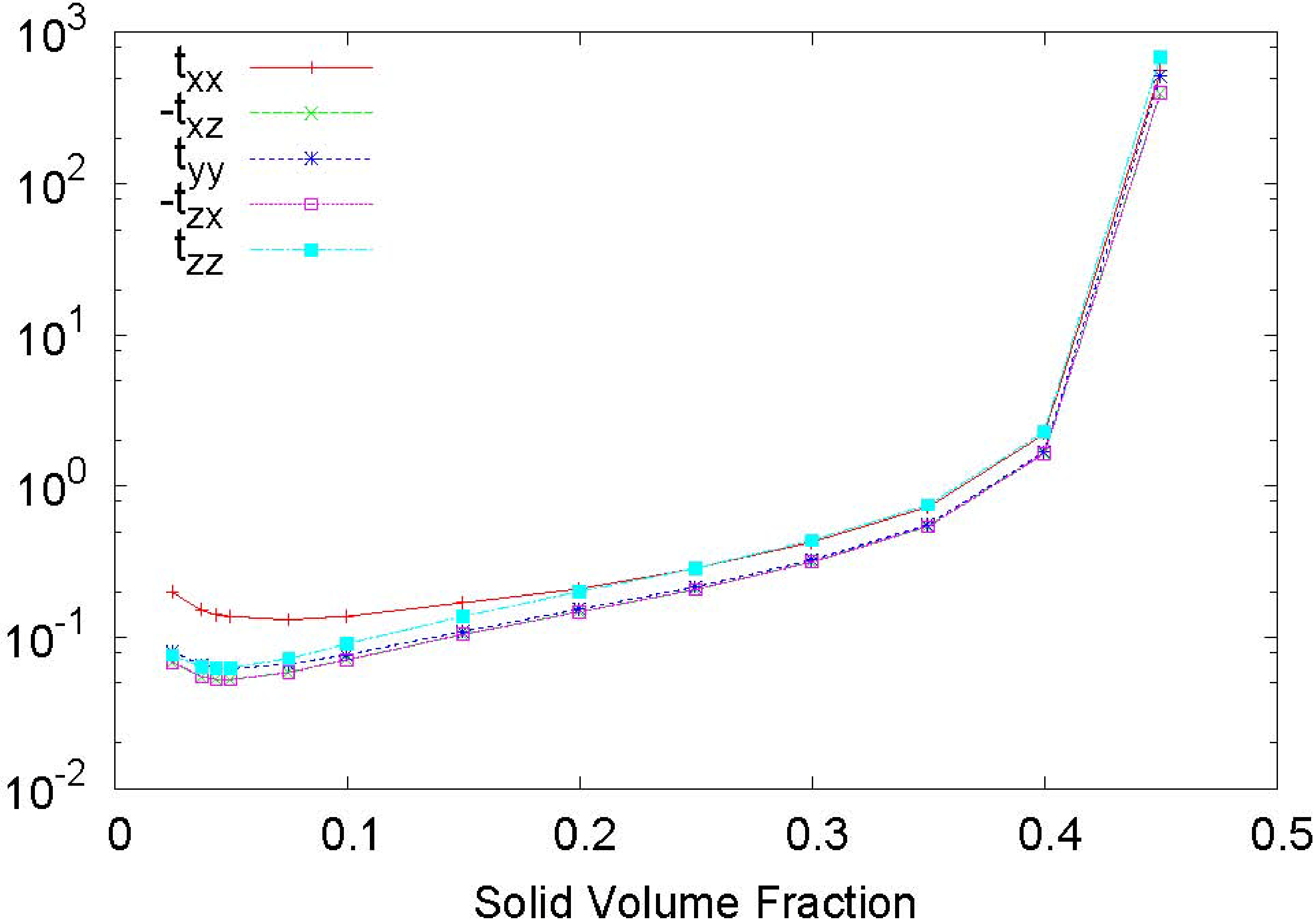
H) particle screen

I) particle separator

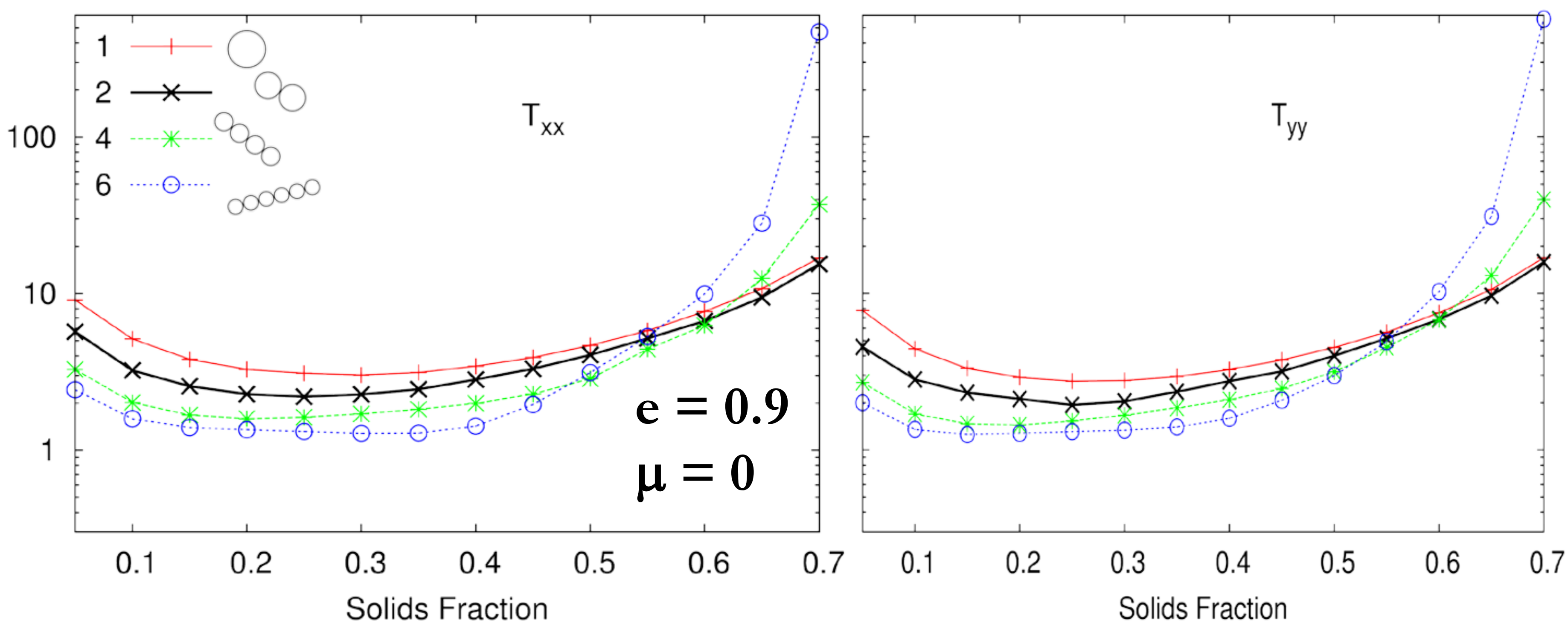
Pipe Diameter = 3 in.



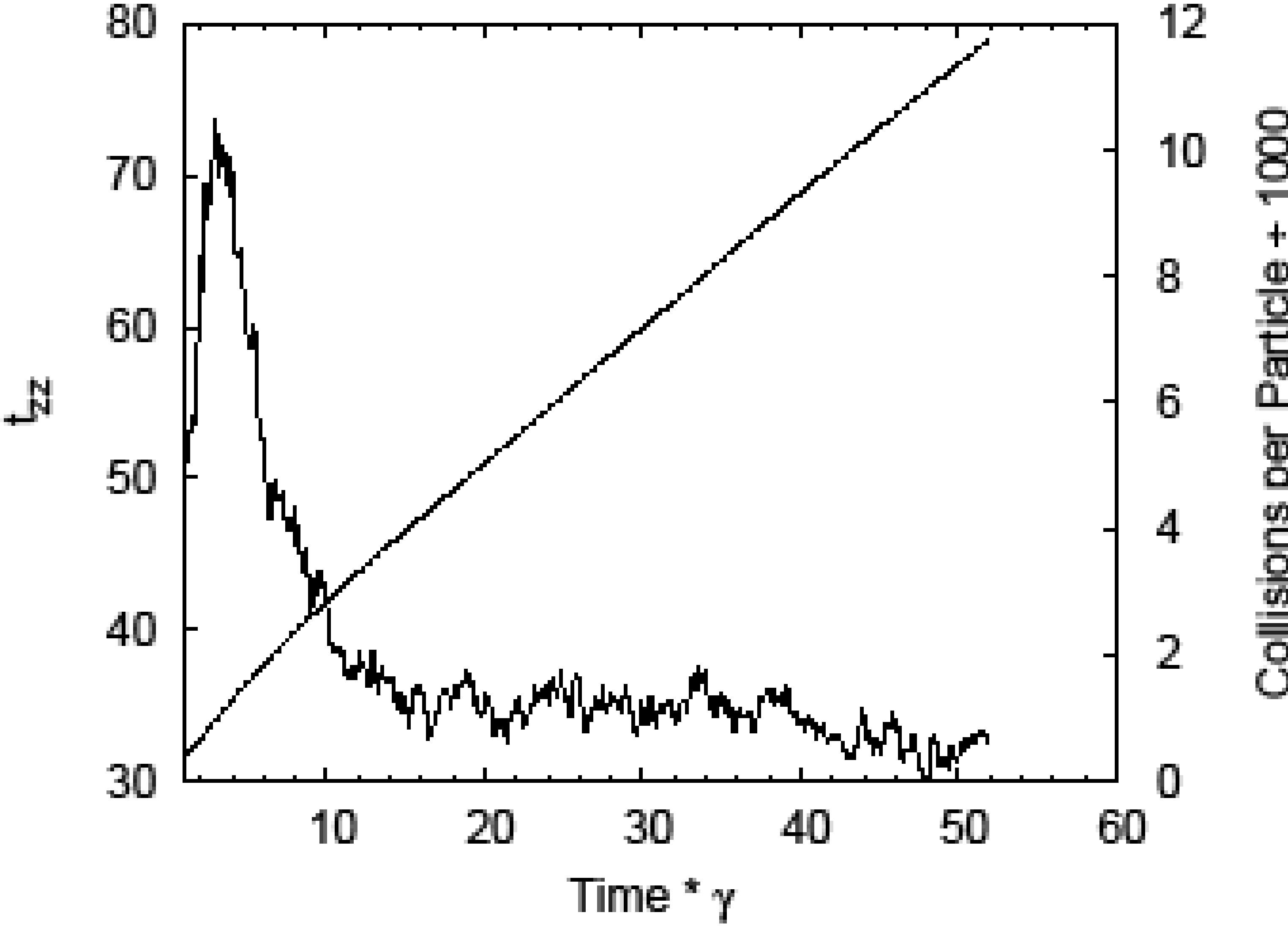
Stress Tensor Components



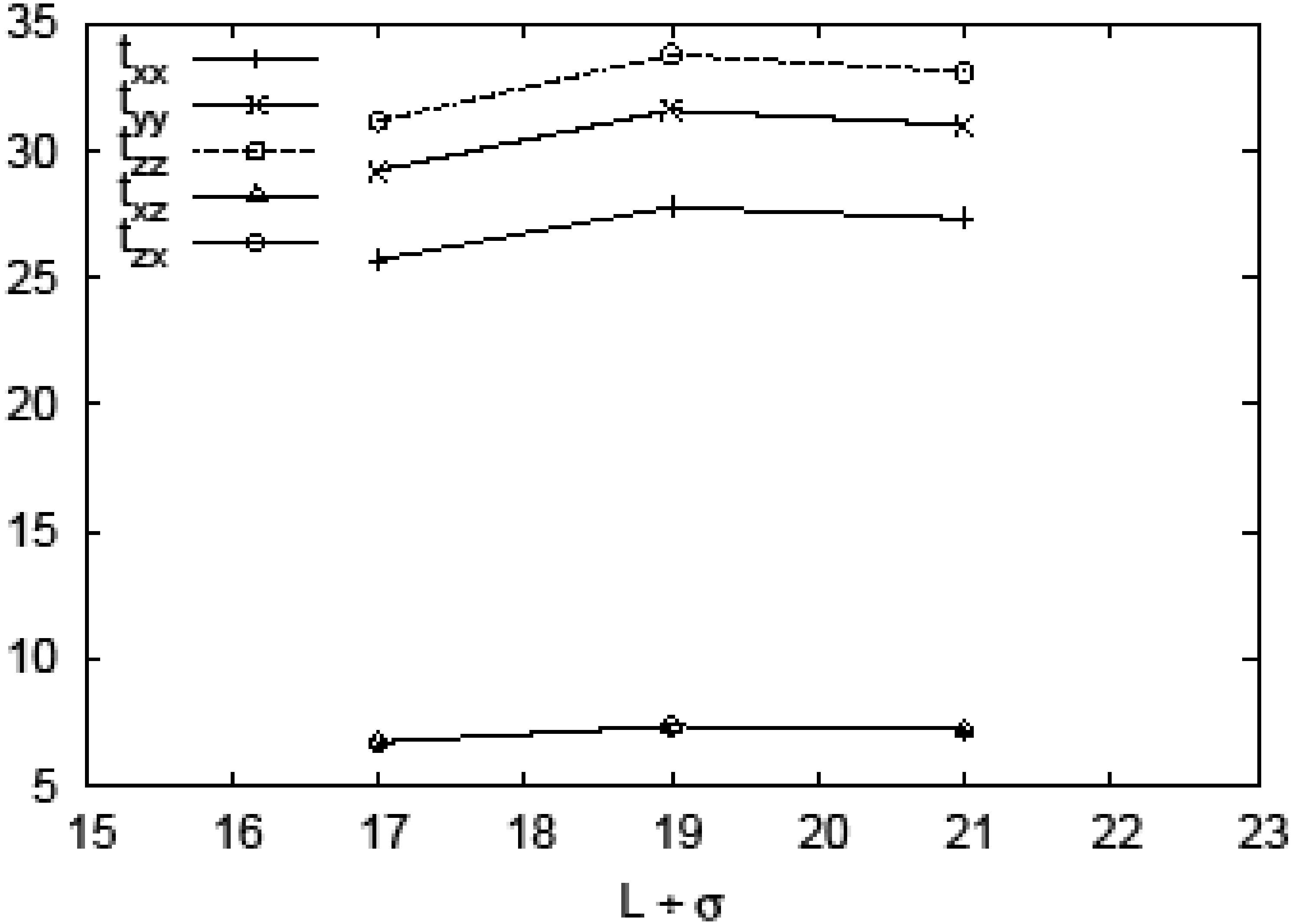
Stress Tensor Components



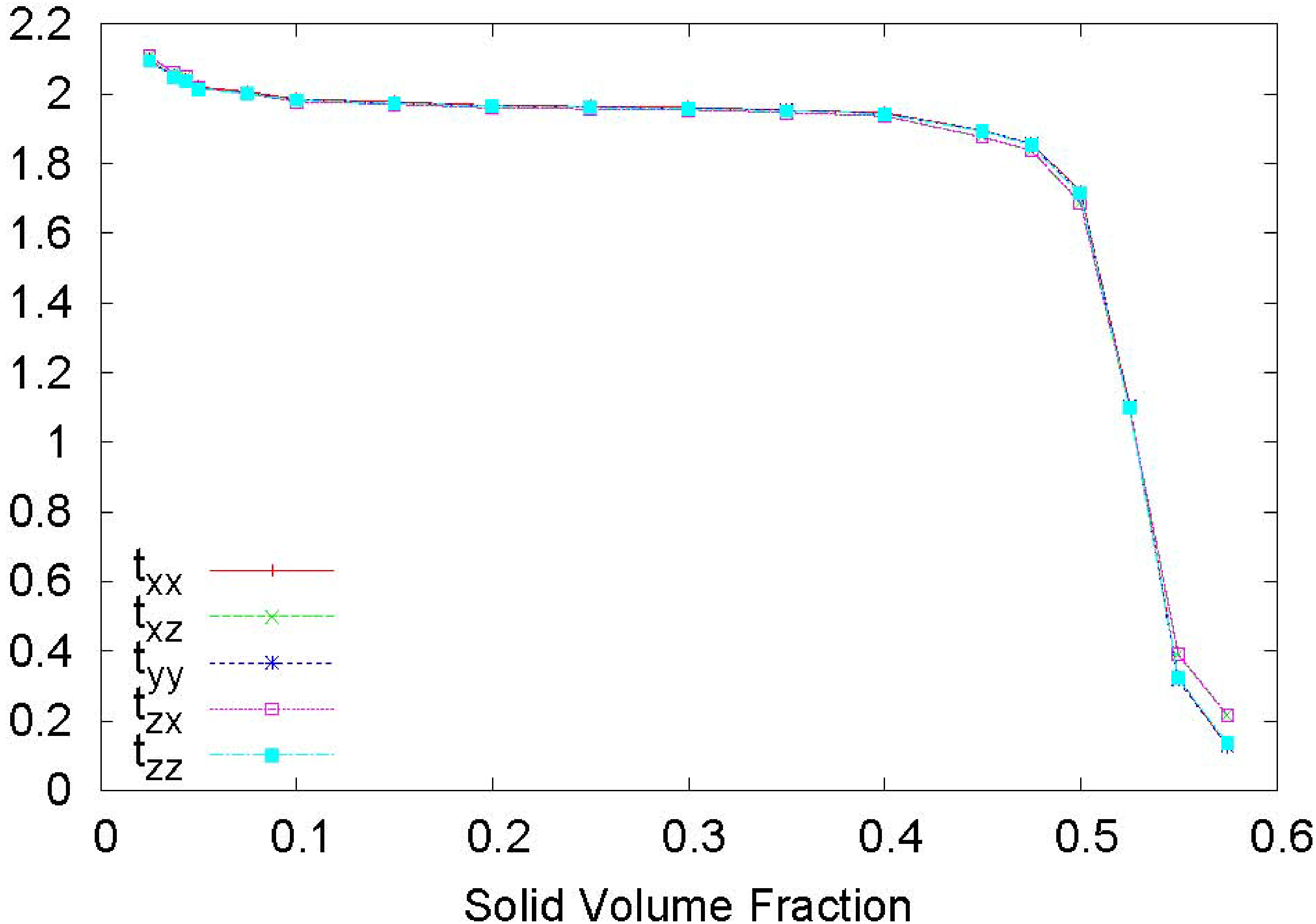
Number of Collisions Per Particle



Effect of System Size

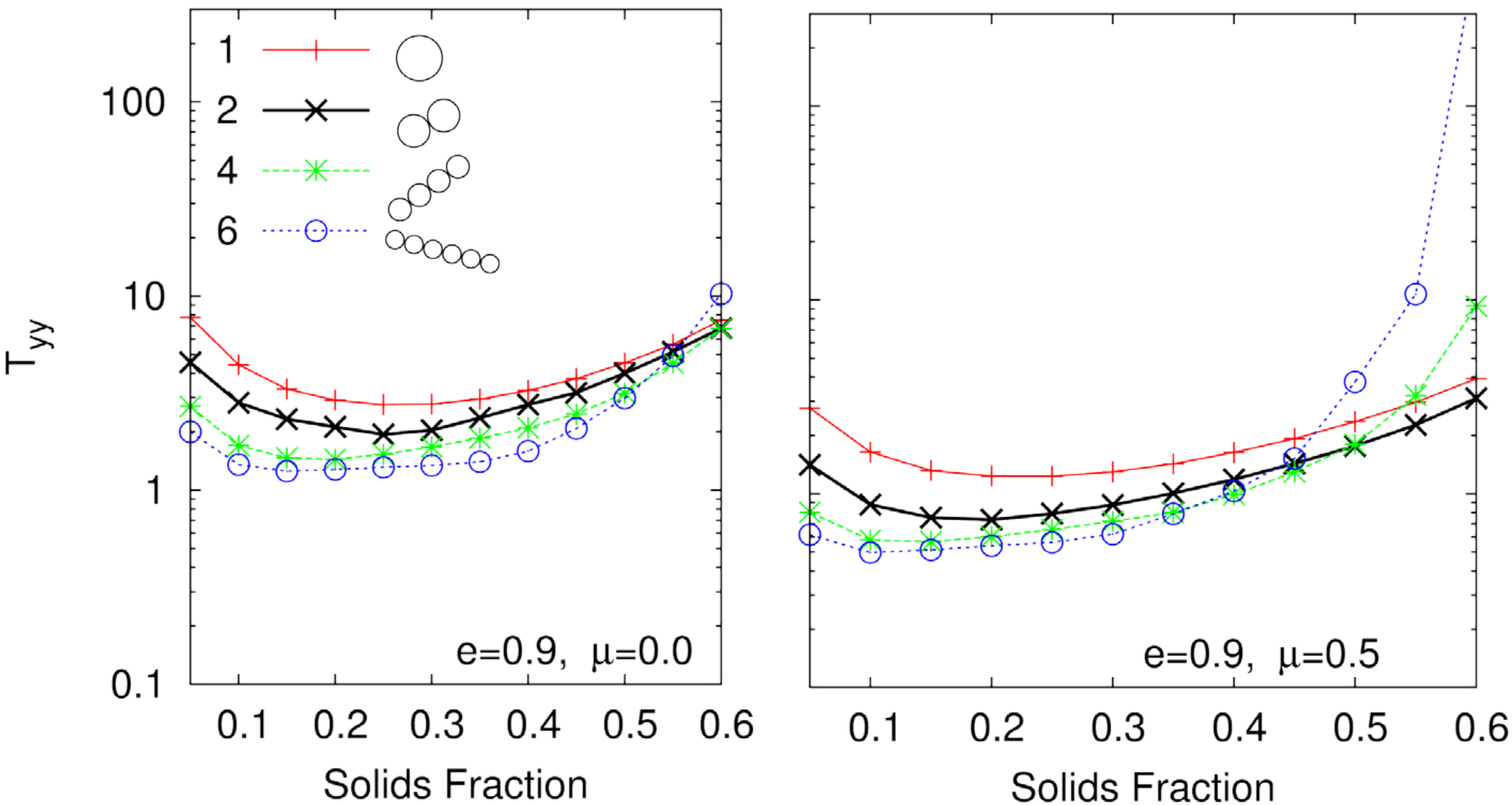


Scaling of Stress with Shear Rate



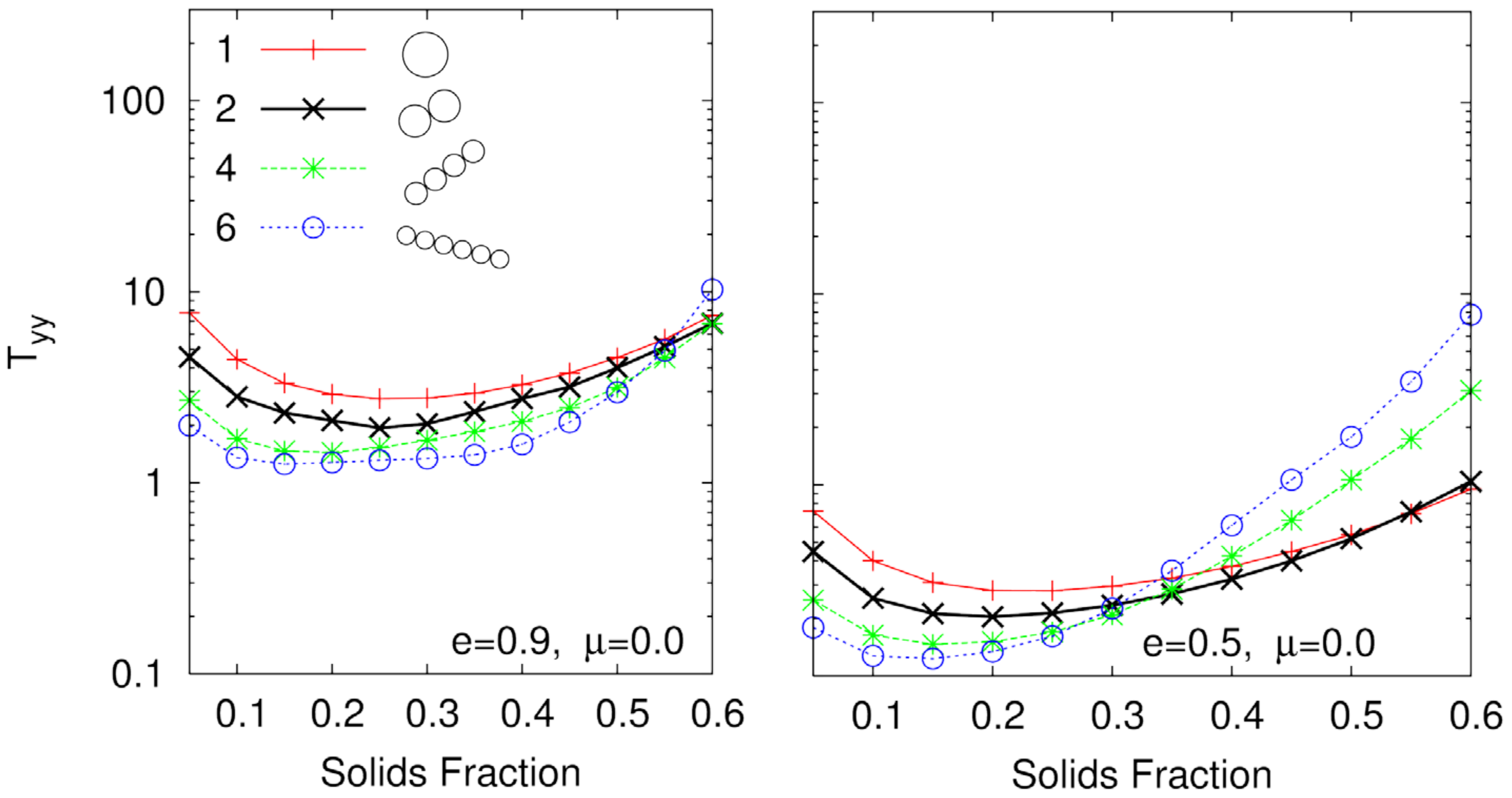
Effect of Increasing Particle Friction

Loss of Translational Energy to Rotational Energy with Increasing Friction



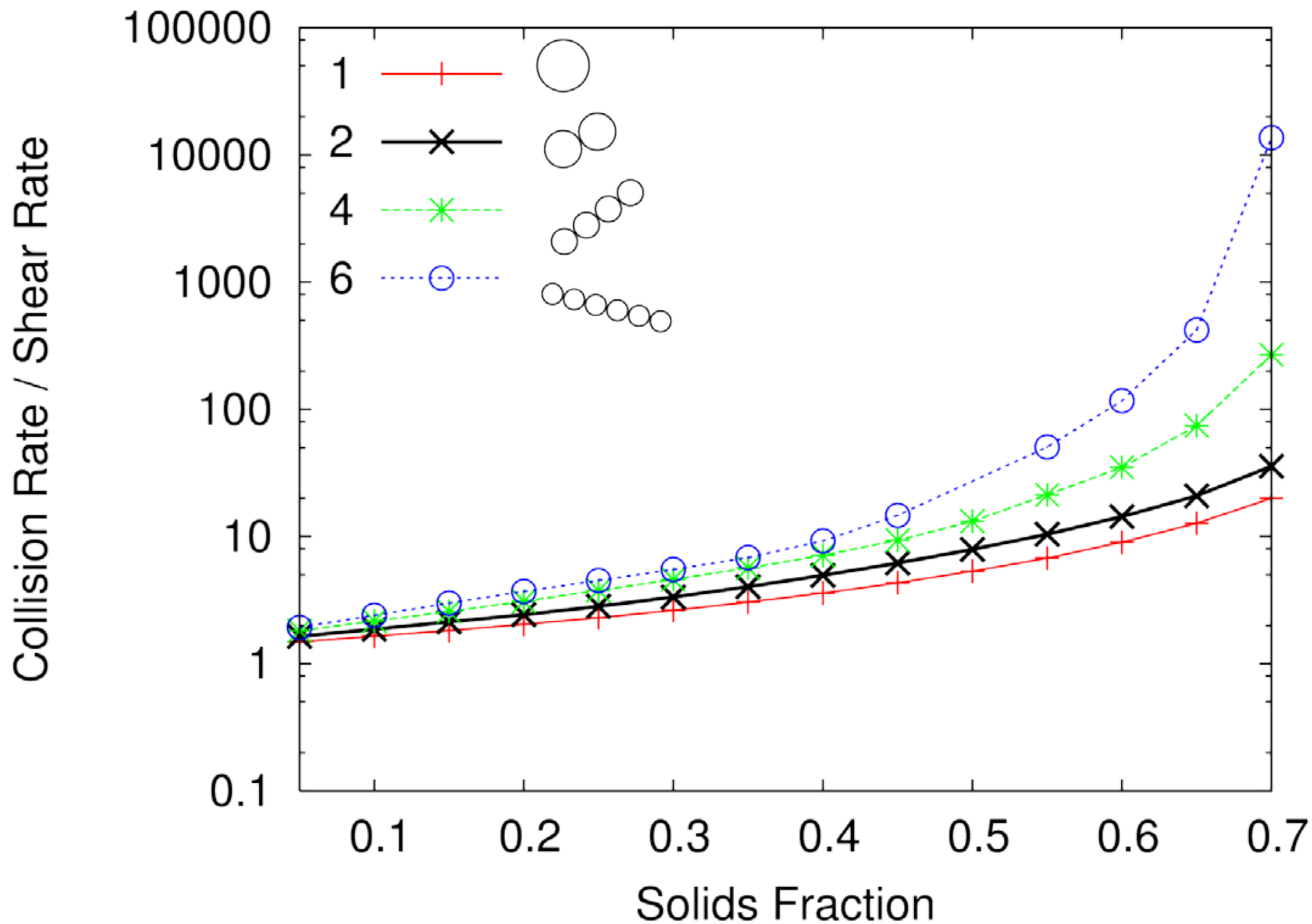
Effect of Decreasing Particle Elasticity

Loss of Particle Fluctuating Energy with Decreasing Particle Elasticity

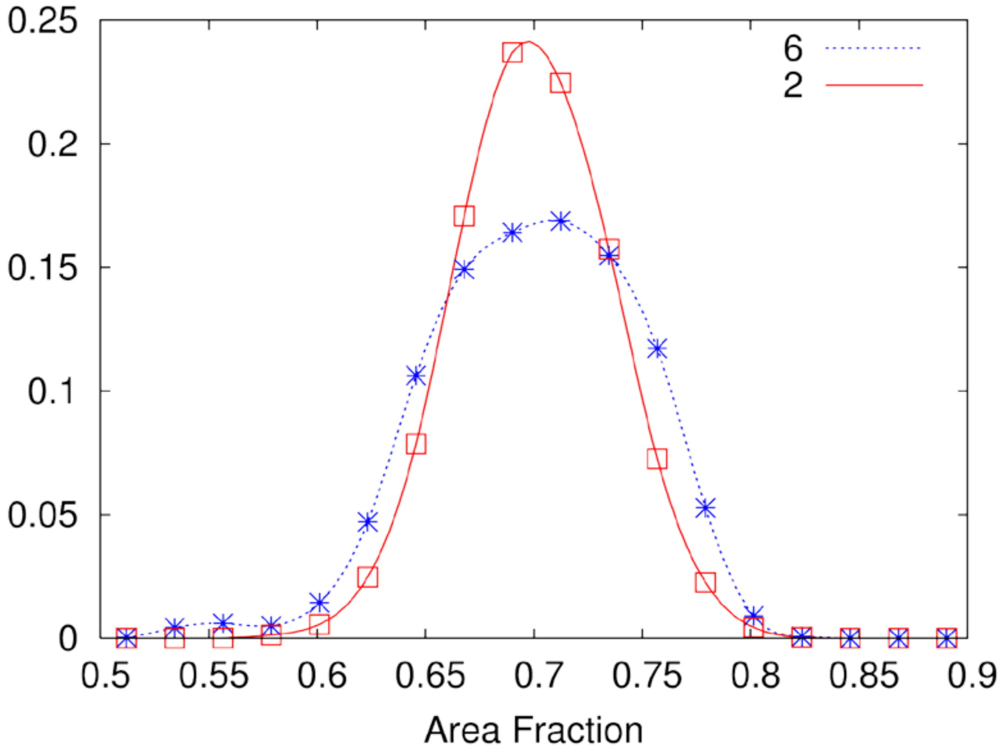


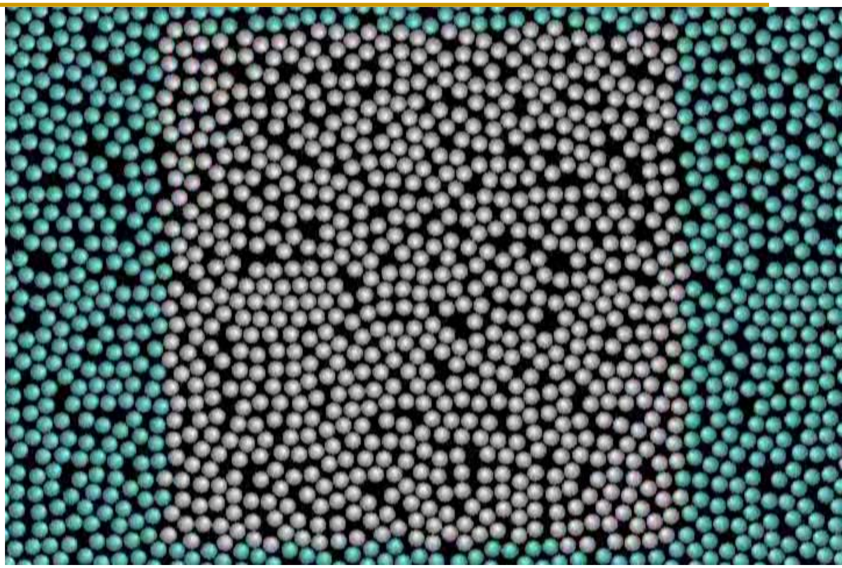
Collision Rate – Elongated Particles

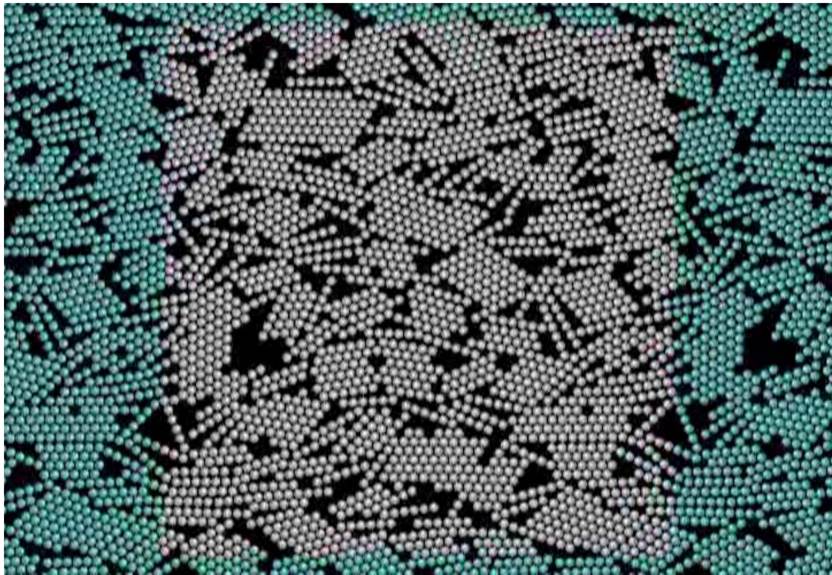
Collision rate increases three orders of magnitude



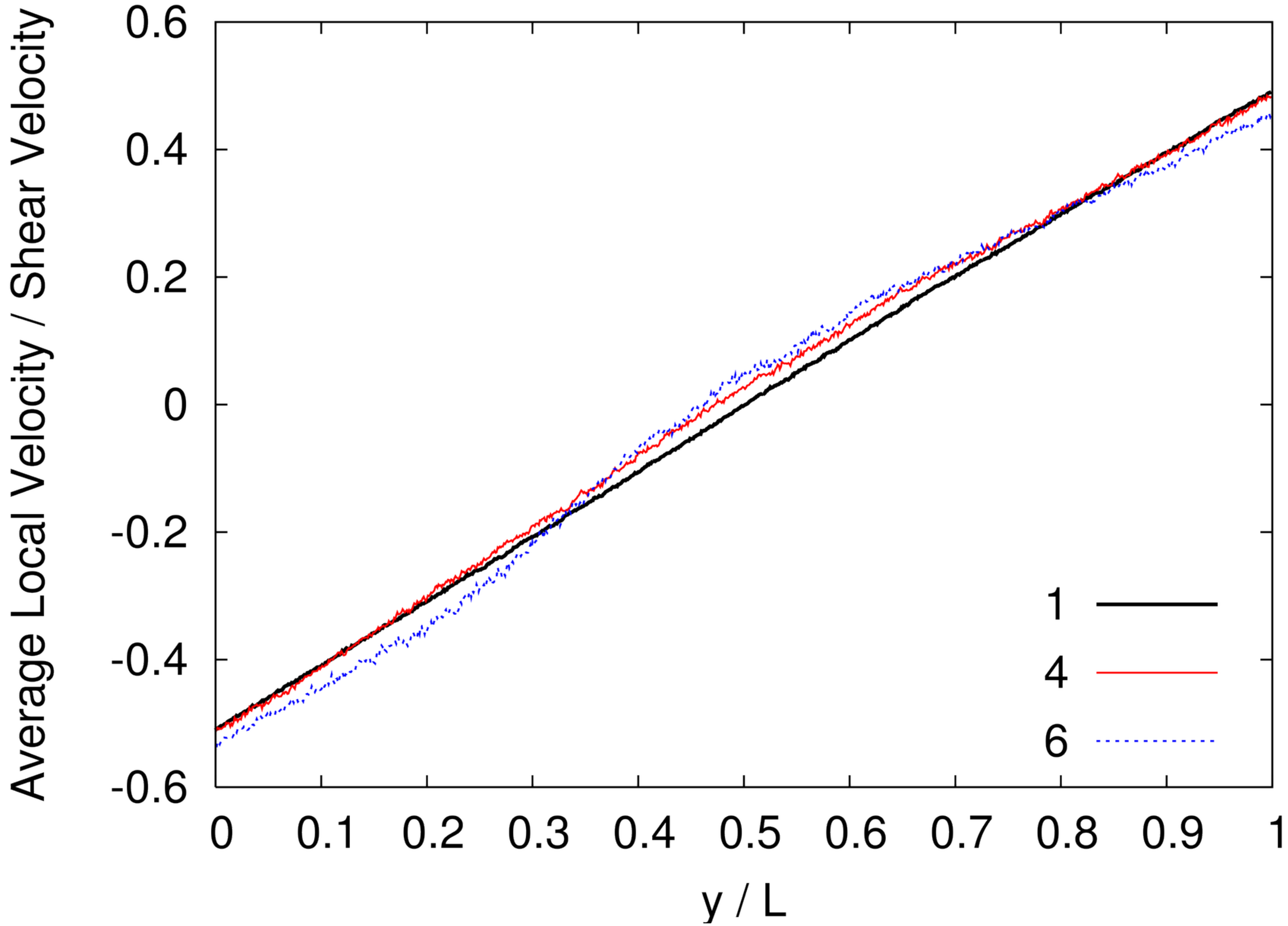
Frequency Distribution of Solids Fraction

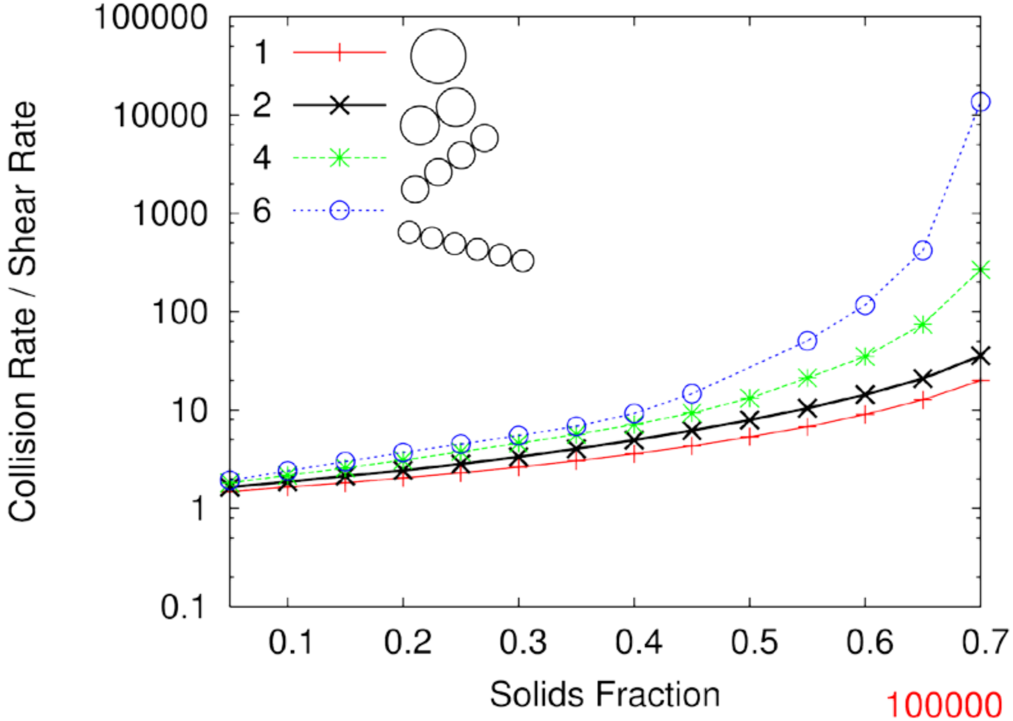




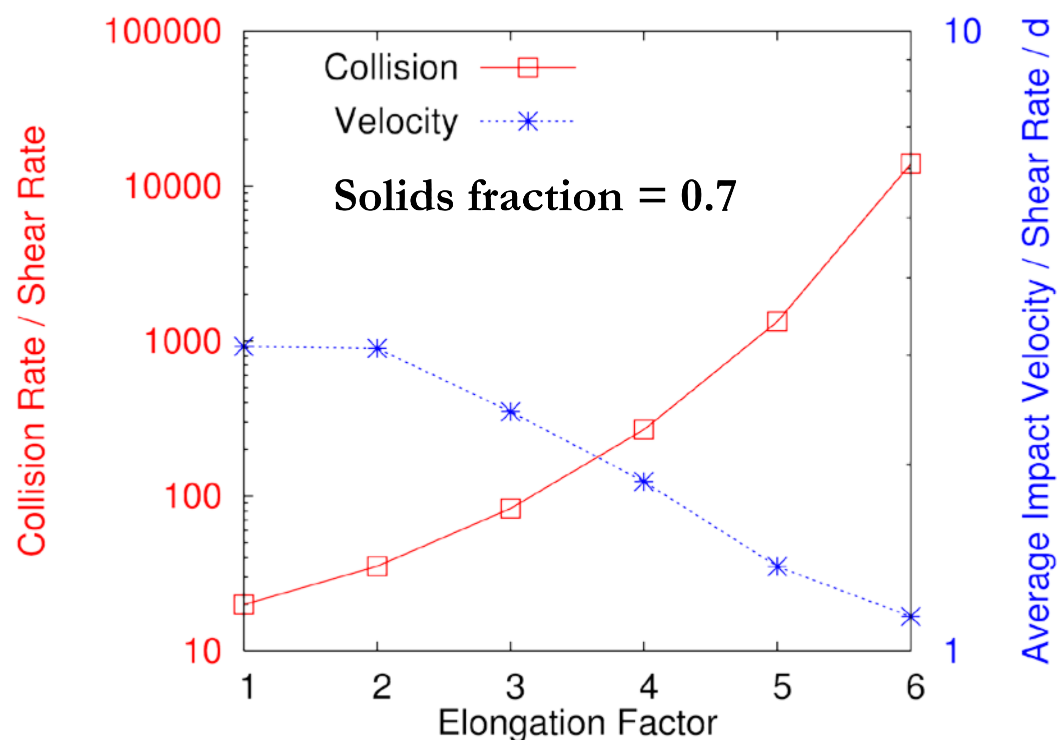


Velocity Profile – Elongated Particles





Collision rate increases three orders of magnitude



Impact velocity decreases over an order of magnitude

Stress Behavior for Elongated Particles