https://ntrs.nasa.gov/search.jsp?R=20030003647 2018-02-22T19:37:24+00:00Z

Dynamics of Sheared Granular Materials

Lou Kondic
Department of Mathematical Sciences and Center for Applied Mathematics & Statistics,
New Jersey Institute of Technology, Newark, NJ 07102

Brian Utter and Robert P. Behringer
Department of Physics and Center for Nonlinear and Complex Systems
Duke University, Durham, NC 27708

ABSTRACT

This work focuses on the properties of sheared granular materials near the jamming transition. The project currently involves two aspects. The first of these is an experiment that is a prototype for a planned ISS flight. The second is discrete element simulations (DES) that can give insight into the behavior one might expect in a reduced-g environment.

The experimental arrangement consists of an annular channel that contains the granular material. One surface, say the upper surface, rotates so as to shear the material contained in the annulus. The lower surface controls the mean density/mean stress on the sample through an actuator or other control system. A novel feature under development is the ability to 'thermalize' the layer–i.e. create a larger amount of random motion in the material, by using the actuating system to provide vibrations as well control the mean volume of the annulus. The stress states of the system are determined by transducers on the non-rotating wall. These measure both shear and normal components of the stress on different size scales. Here, the idea is to characterize the system as the density varies through values spanning dense almost solid to relatively mobile granular states. This transition regime encompasses the regime usually thought of as the glass transition, and/or the jamming transition.

Motivation for this experiment springs from ideas of a granular glass transition, a related jamming transition, and from recent experiments. In particular, we note recent experiments carried out by our group to characterize this type of transition (Howell et al. Phys. Rev. Lett. **82**, 5241 (1999)) and also to demonstrate/characterize fluctuations in slowly sheared systems (Miller et al. Phys. Rev. Lett. **77**, 3110 (1996)). These experiments give key insights into what one might expect in near-zero g. In particular, they show that the compressibility of granular systems diverges at a transition or critical point. It is this divergence, coupled to gravity, that makes it extremely difficult if not impossible to characterize the transition region in an earth-bound experiment.

In the DE modeling, we analyze dynamics of a sheared granular system in Couette geometry in two (2D) and three (3D) space dimensions. Here, the idea is to both better understand what we might encounter in a reduced-g environment, and at a deeper level to deduce the physics of sheared systems in a density regime that has not been addressed by past experiments or simulations.

One aspect of the simulations addresses sheared 2D system in zero-g environment. For low volume fractions, the expected dynamics of this type of system is relatively well understood. However, as the volume fraction is increased, the system undergoes a phase transition, as explained above. The DES concentrate on the evolution of the system as the solid volume fraction is slowly increased, and in particular on the behavior of very dense systems. For these configurations, the simulations show that polydispersity of the sheared particles is a crucial factor that determines the system response. Figures 1 and 2 below, that present the total force on each grain, show that even relatively small (10 %) nonuniformity of the size

of the grains (expected in typical experiments) may lead to significant modifications of the system properties, such as velocity profiles, temperature, force propagation, and formation of shear bands.

The simulations are extended in a few other directions, in order to provide additional insight to the experimental system analyzed above. In one direction, both gravity, and driving due to vibrations are included. These simulations allow for predictions on the driving regime that is required in the experiments in order to analyze the jamming transition. Furthermore, direct comparison of experiments and DES will allow for verification of the modeling assumptions. We have also extended our modeling efforts to 3D. The (preliminary) results of these simulations of an annular system in zero-g environment will conclude the presentation.

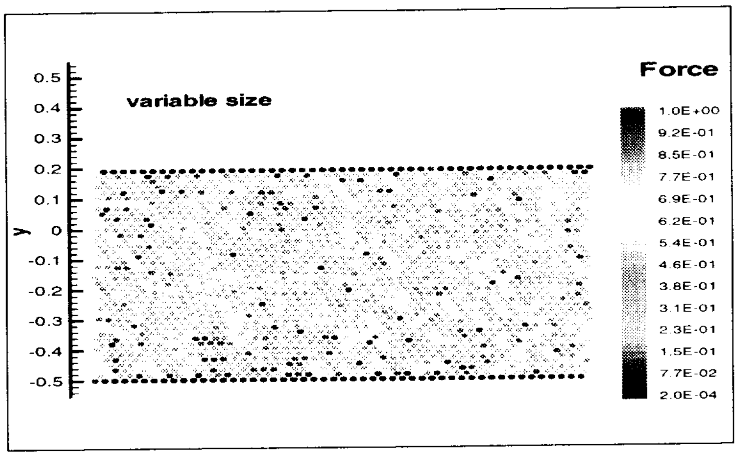


Figure 1: The (instantaneous) force experienced by the variable size particles; the volume fraction at the instant shown is approximately 0.9. The flow is driven by constant velocity motion of the upper wall in the $+x$ direction (left to right).

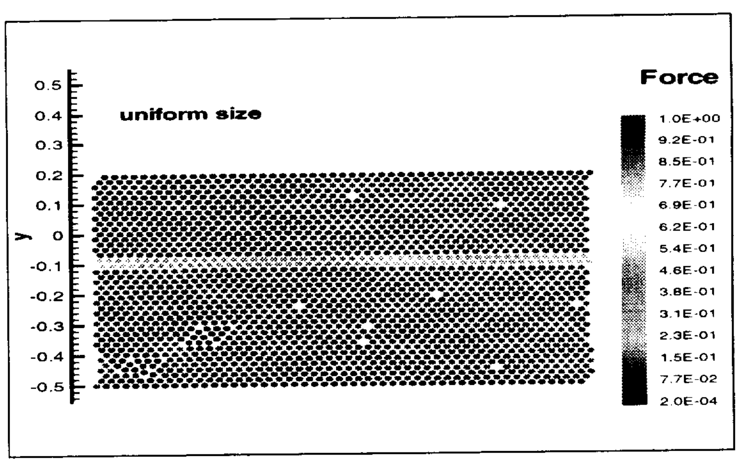


Figure 2: The force in the case of uniform size particles; all the other quantities are the same as in Fig. 1. Note formation of a shear band at $y \approx -0.1$; it should be mentioned that this particular shear band is just one of possible configurations characterizing the flow, and the manner in which the force propagates.

Dynamics of Sheared Granular Materials

By:

Lou Kondic, NJIT
Brian Utter, Duke
Robert P. Behringer, Duke

Presented at:

Sixth Microgravity Fluid Physics
and Transport Phenomena Conference
August '02

supported by NASA

Main goal

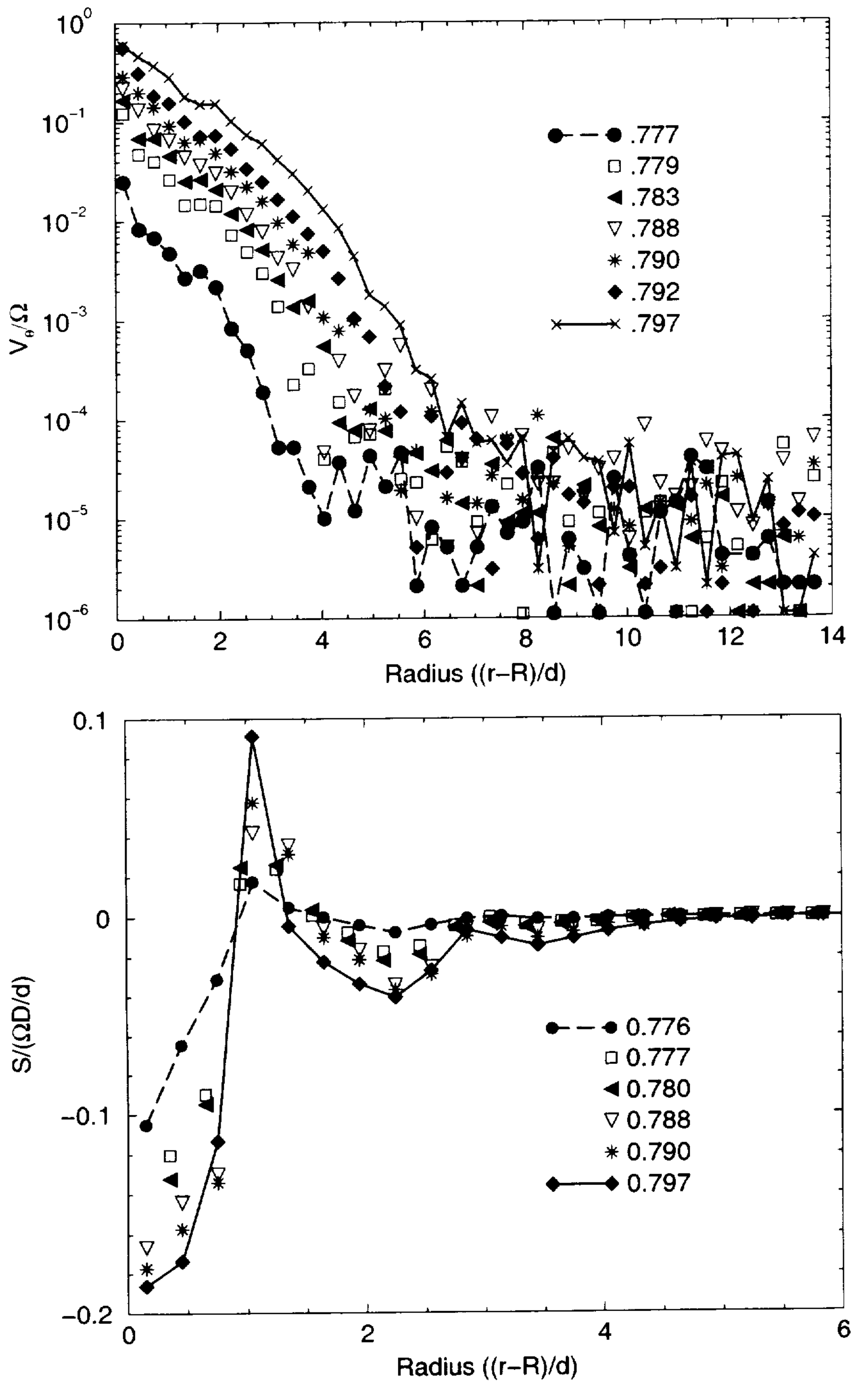
Understand the dynamics of a granular system as the volume fraction γ is modified between gas-like and solid-like
Analyze the phase transition which may occur in 3D zero-g experiment
Analogy to 2D? - see Howell et al. PRL (1999)
Discuss the parameters defining the system, in particular distribution of particle sizes

Techniques

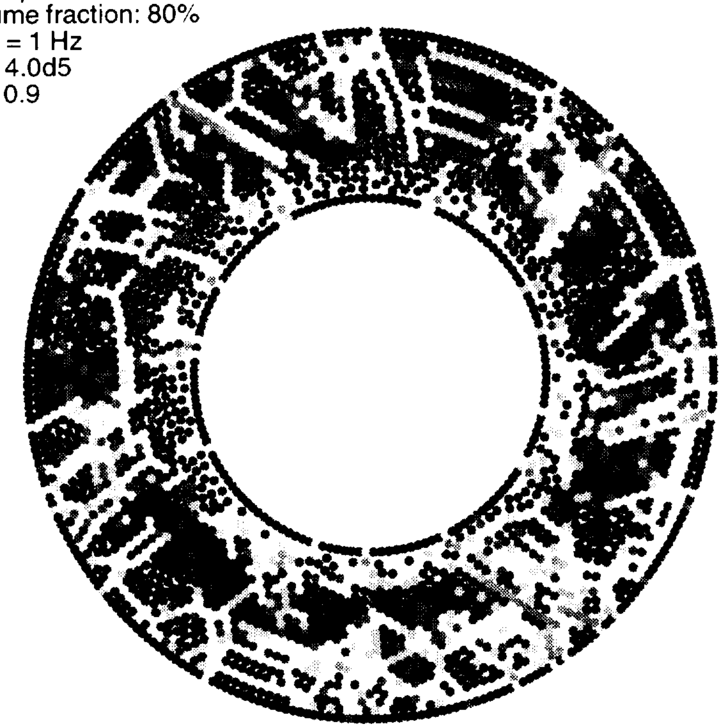
Experimental
Computational (discrete element simulations)

This talk: Simulations

Discuss expected behavior in zero g
Analyze force propagation
Also: can we thermalize the system in non-zero g and expect to reach uniform states?



(from Howell et al, PRL (1999))

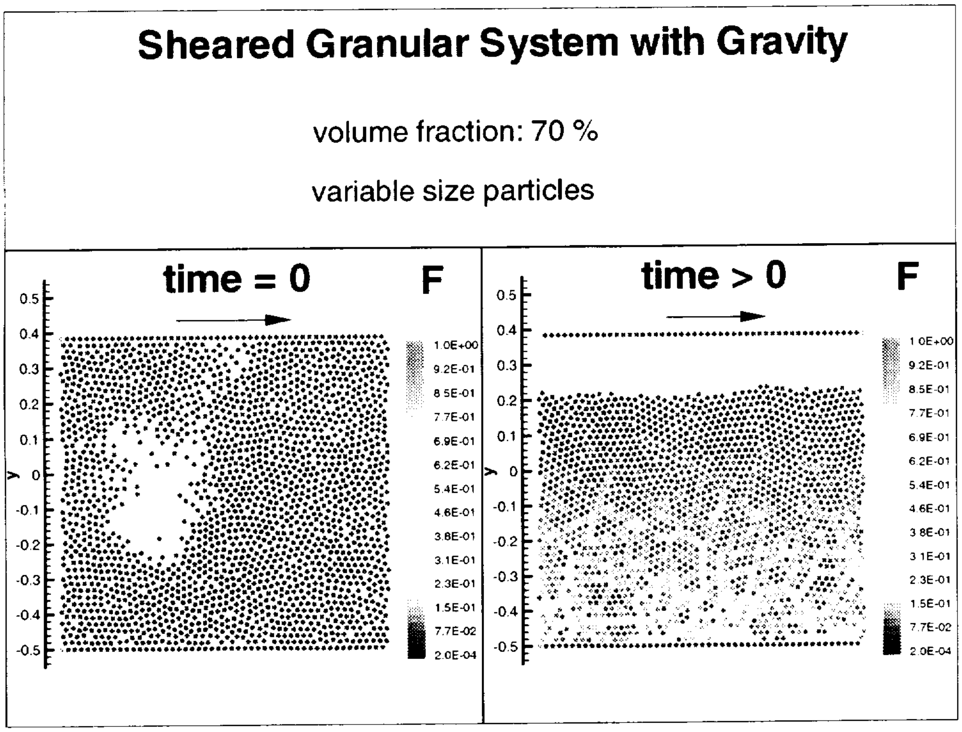


Experiment:

2D: Second-order phase transition as the volume fraction is decreased

2D: gravitational effects are reduced by using a horizontal system

3D (annular geometry): gravitational compaction does not allow to analyze dynamics close to γ_c



(an example of gravitational compaction)

Goal of Simulations

Analyze open (channel) (2D) Couette geometry to understand the basics of dynamics in 3D experiment in annular geometry and zero-g environment

Discrete element techniques

Linear force model with damping in normal and tangential directions

$$\mathbf{F}^n_{i,j} = \left[k(d - r_{i,j}) - \gamma_n \bar{m}(\mathbf{v}_{i,j} \cdot \mathbf{n})\right] \mathbf{n}$$

Tangential force

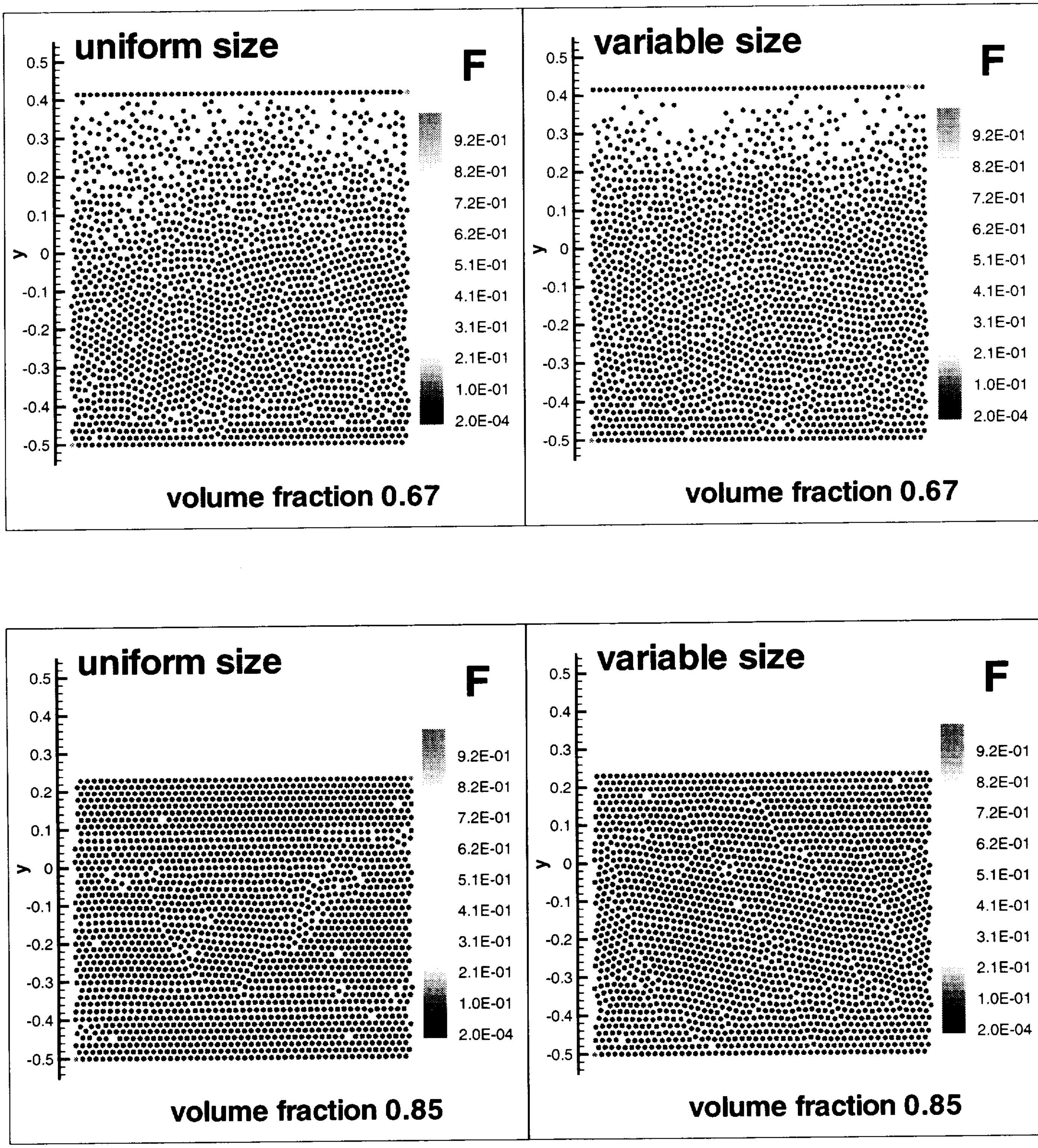
$$\mathbf{F}^t_{i,j} = min\left(-\gamma_s \bar{m} v_{rel}, \mu|\mathbf{F}_{i,j} \cdot \mathbf{n}|\right) \mathbf{s}$$
$$v_{rel} = \mathbf{v}_{i,j} \cdot \mathbf{s} + (r_i\Omega_i + r_j\Omega_j)$$
$$\mathbf{s} : \mathbf{s} \perp \mathbf{n}$$

γ_s tangentional damping
μ: Coulomb coefficient

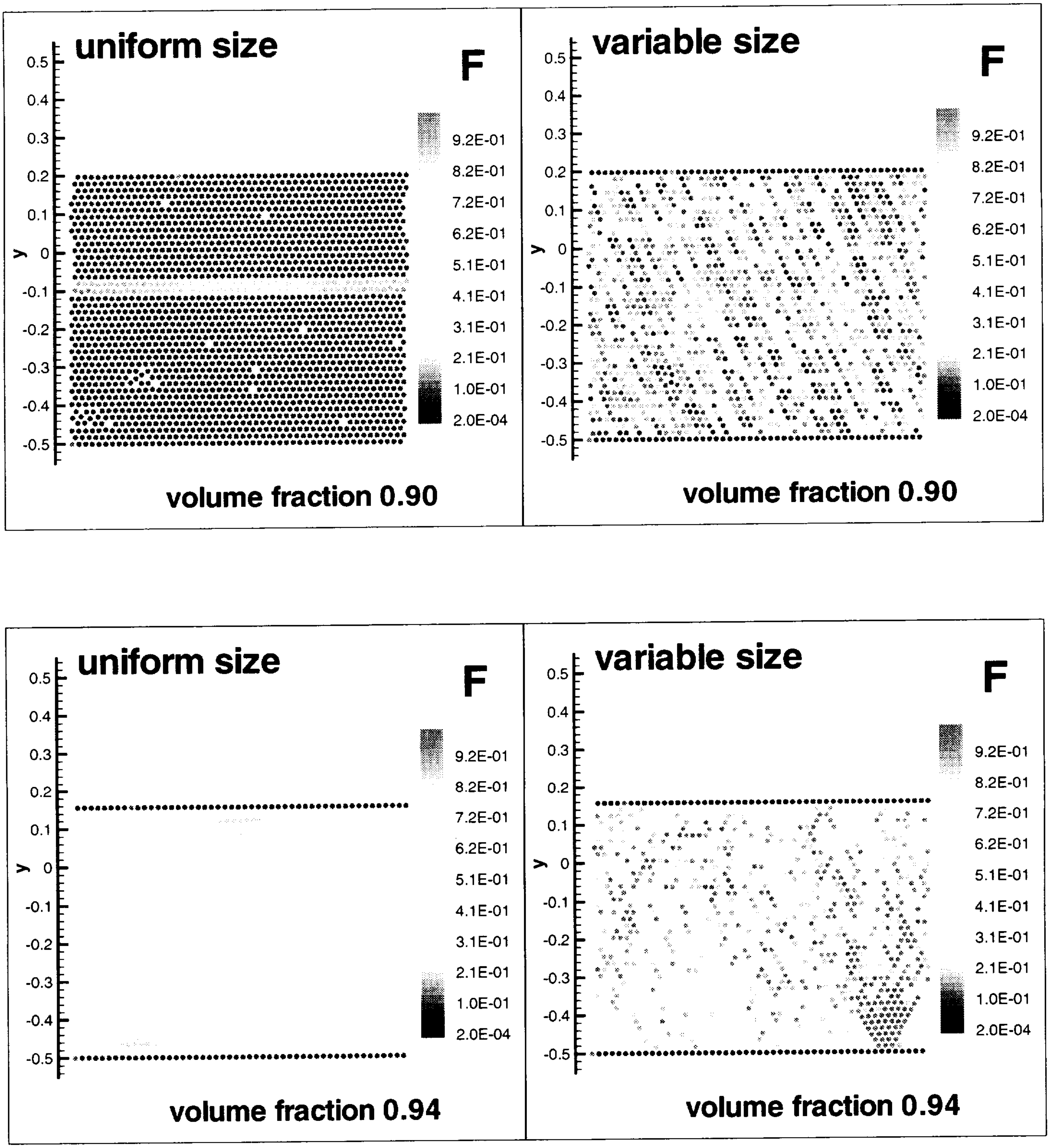
Parameters chosen appropriately for (soft) photoelastic disks, (e.g. Howell and Behringer, PRL (1999))

This talk: periodic boundaries, rough walls

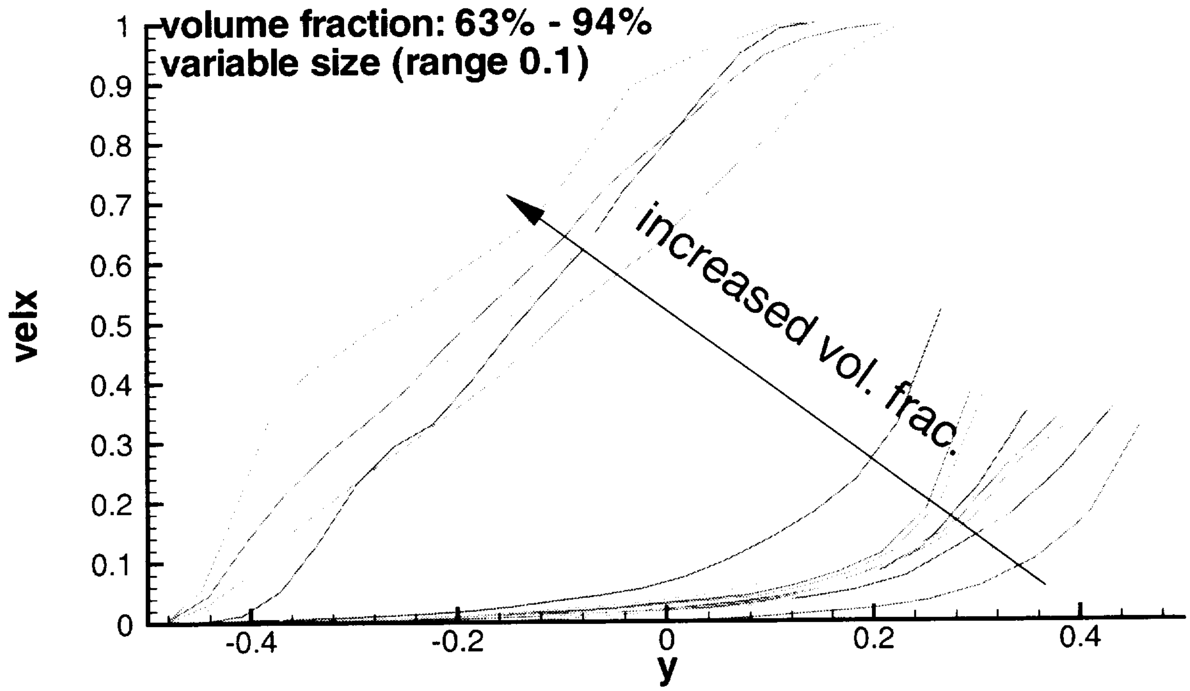
- Sheared system with slowly varying γ
- Switch on gravity as well as excitation

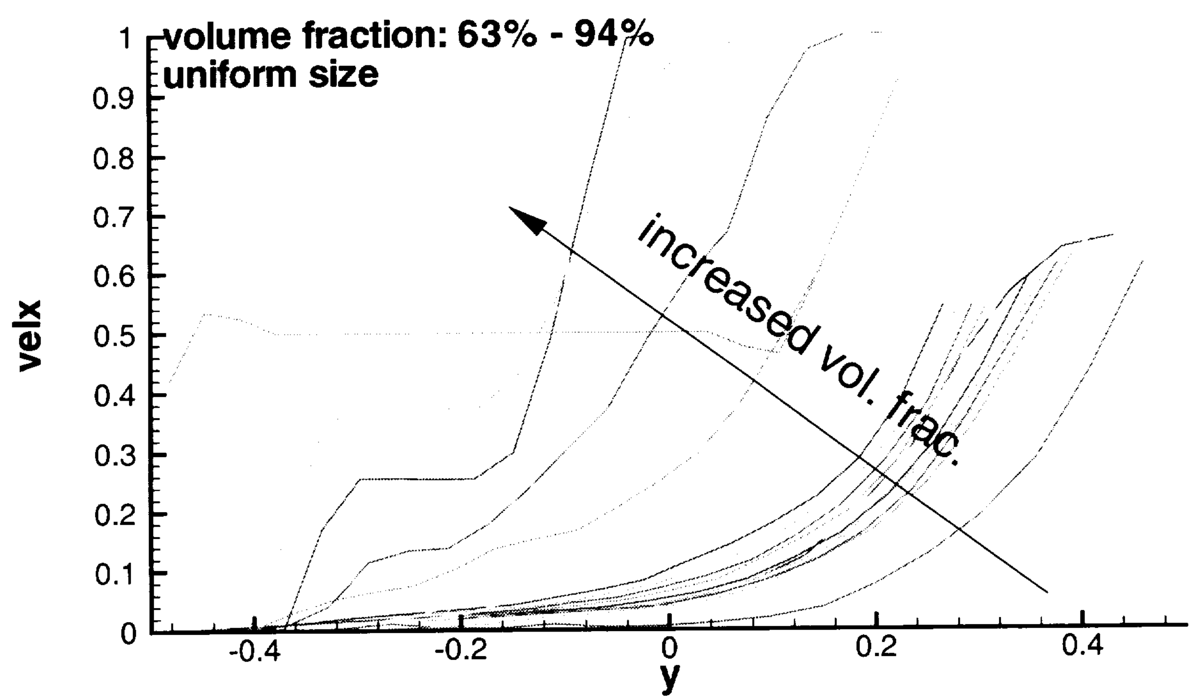


uniform size
F
0.5
0.4
0.3
0.2
0.1
y
0
-0.1
-0.2
-0.3
-0.4
-0.5
9.2E-01
8.2E-01
7.2E-01
6.2E-01
5.1E-01
4.1E-01
3.1E-01
2.1E-01
1.0E-01
2.0E-04
volume fraction 0.67
variable size
F
volume fraction 0.67
uniform size
F
volume fraction 0.85
variable size
F
volume fraction 0.85


uniform size
F
9.2E-01
8.2E-01
7.2E-01
6.2E-01
5.1E-01
4.1E-01
3.1E-01
2.1E-01
1.0E-01
2.0E-04
y
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
volume fraction 0.90
variable size
volume fraction 0.90
uniform size
volume fraction 0.94
variable size
volume fraction 0.94

Plain Couette Flow





Low volume fractions: Gas-like regime

No significant difference between monodisperse and polydisperse materials

System dilated next to the shearing wall

Energy shared between kinetic and elastic

Higher temperature and elastic energy close to the shearing wall

Rate-independent system behavior

Shearing band formation for lower γ's similarly as in radial Couette geometry

(can this shearing band be *removed* by externally imposed excitations?)

Related works

Jenkins, Richman, Phys. Fluids '85

Walton, Braun, J. Rheol., '86

Campbell, Annu. Rev. Fluid Mech. '90

Hopkins, Louge, Phys. Fluids '91

Savage, JFM '98

...

High volume fractions

From exponential to linear velocity profiles (note: linear profiles are not observed in annular geometry!)

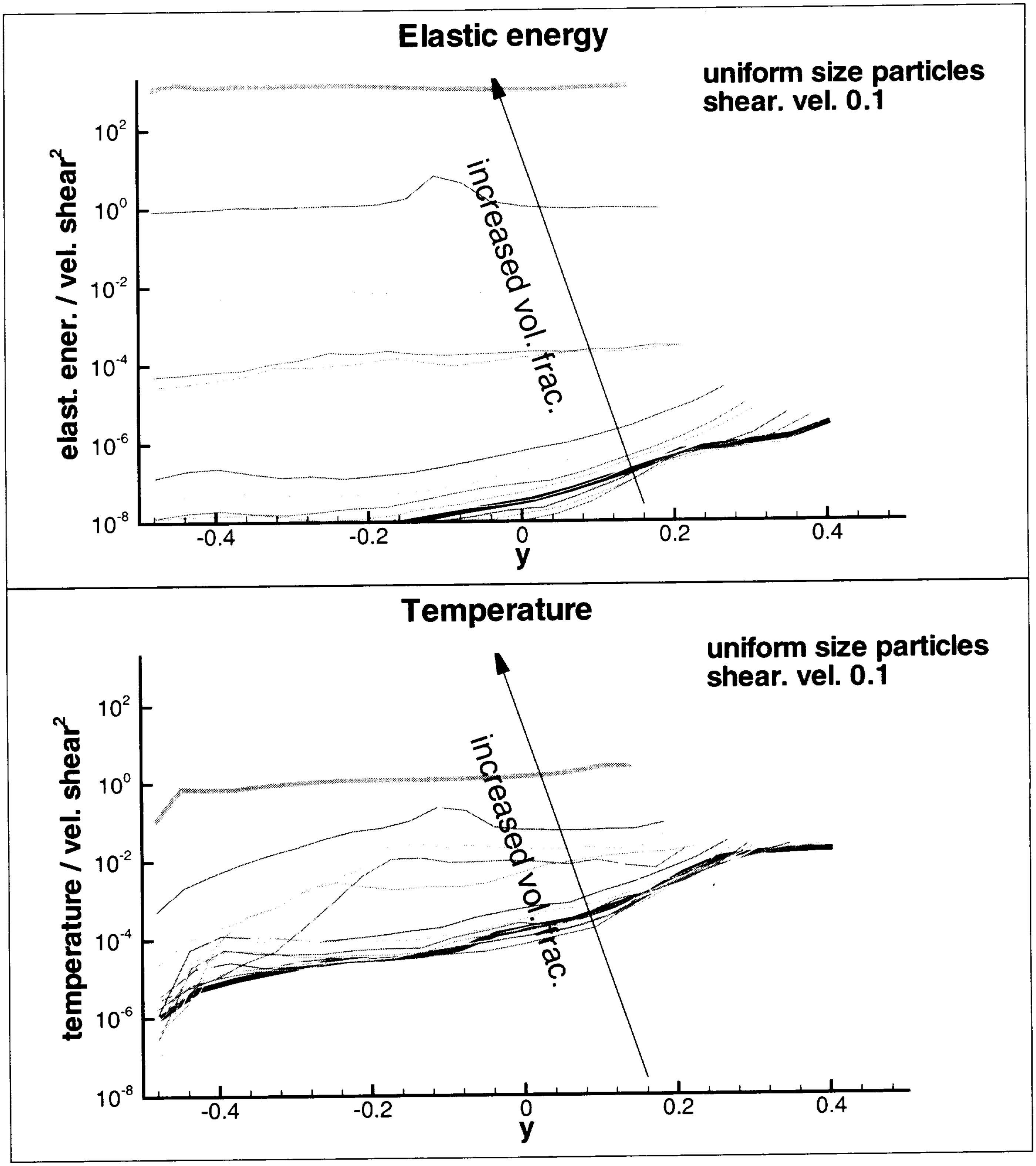
From gas-like to solid-like behavior: jamming

Significant differences between monodisperse and polydisperse systems:

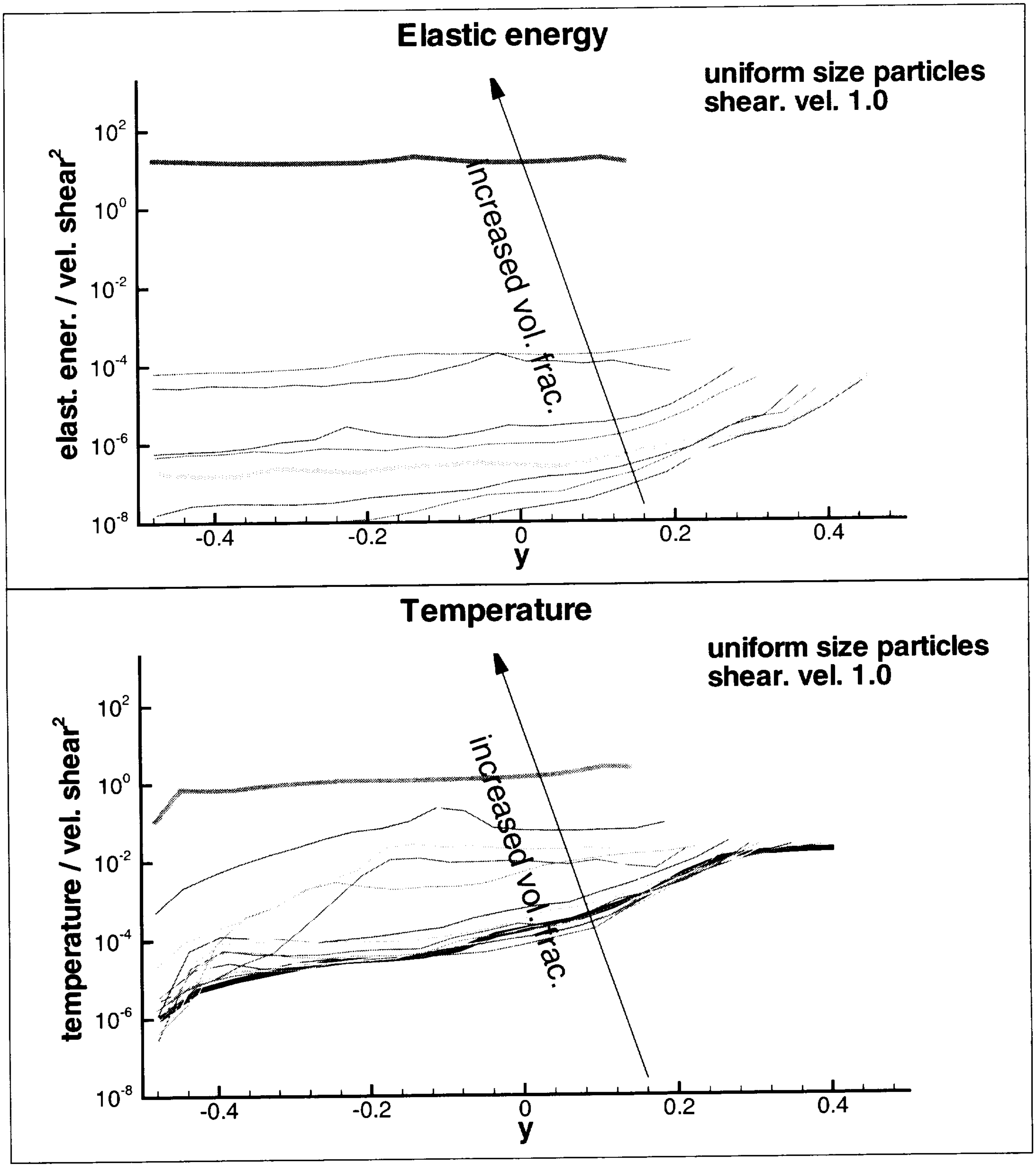
Fracture occurs for monodisperse systems

Monodisperse systems are compressed easier (crystallization) $\rightarrow$ large difference in the stored elastic energy

Rate-dependent behavior for large volume fractions



Elastic energy
uniform size particles
shear. vel. 0.1
elast. ener. / vel. shear^2
increased vol. frac.
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
-0.4
-0.2
0
0.2
0.4
y
Temperature
uniform size particles
shear. vel. 0.1
temperature / vel. shear^2
increased vol. frac.
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
-0.4
-0.2
0
0.2
0.4
y


Elastic energy
uniform size particles
shear. vel. 1.0
increased vol. frac.
elast. ener. / vel. shear^2
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
-0.4
-0.2
0
0.2
0.4
y
Temperature
uniform size particles
shear. vel. 1.0
increased vol. frac.
temperature / vel. shear^2
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
-0.4
-0.2
0
0.2
0.4
y

Gravity plus excitations

If gravity is included, compaction results $\longrightarrow$ possible phase transition cannot be observed

Question: Can we excite (thermalize) the system so to reach uniformly sheared states?

(Analogy: glasses, colloids, ...)

Consider:

Sheared system + gravity

Excitations through vibrated lower boundary

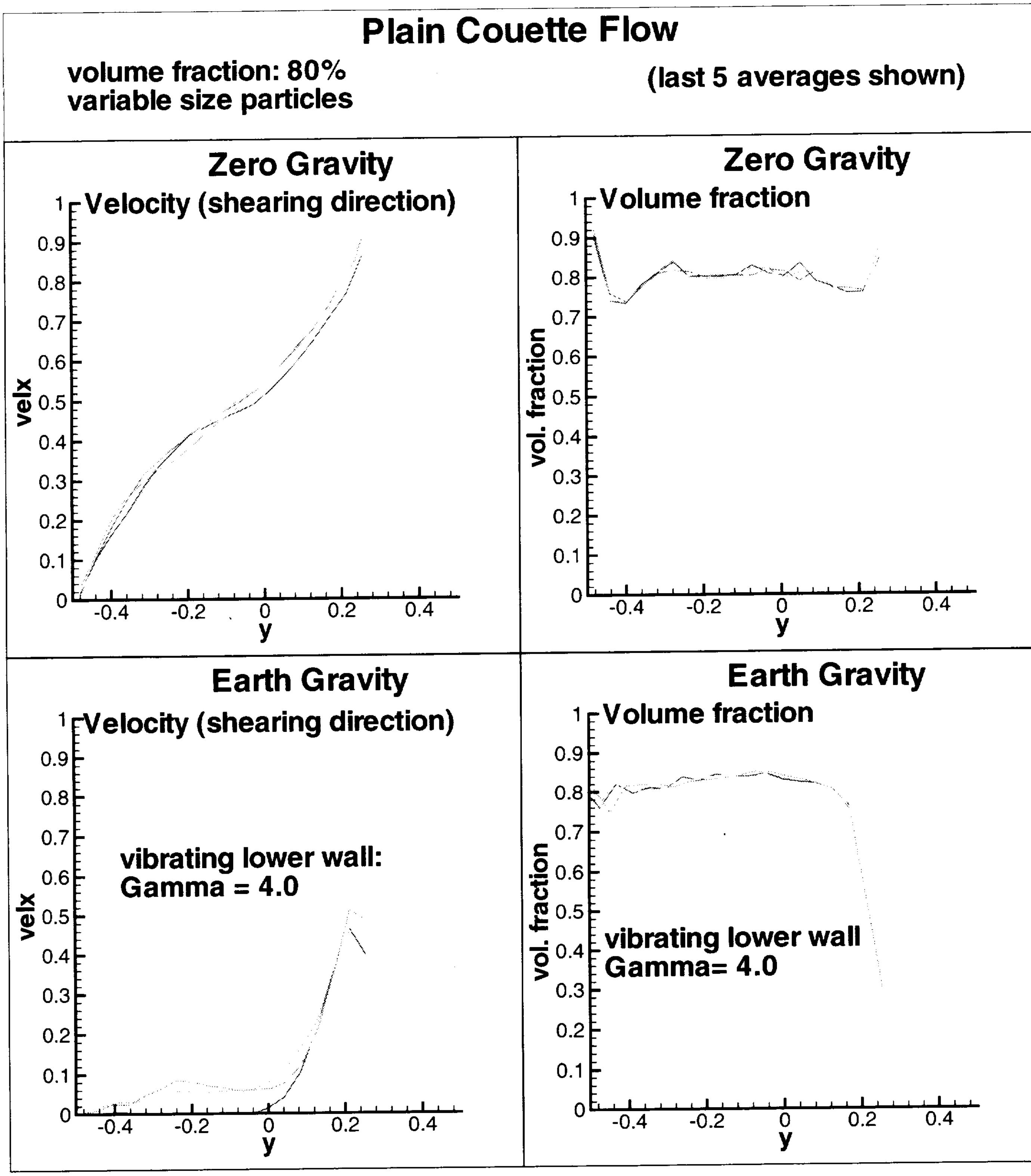
Analyze:

different modes of excitations

different Γ's

different ratios of shearing and thermalizing energy input

different volume ratios


Plain Couette Flow
volume fraction: 80%
variable size particles
(last 5 averages shown)
Zero Gravity
Velocity (shearing direction)
velx
y
Zero Gravity
Volume fraction
vol. fraction
y
Earth Gravity
Velocity (shearing direction)
vibrating lower wall:
Gamma = 4.0
velx
y
Earth Gravity
Volume fraction
vibrating lower wall
Gamma= 4.0
vol. fraction
y

Answer: It is not easy to fight Gravity!

Difficult to produce uniform and dense granular system which responds to shearing (there are also large forces resulting from excitations)

Suggestion of this study: will need to perform experiments (and simulations) in zero g to fully understand the problem

Current and Future Work

How relevant is the granular temperature? Do we need to consider a quantity that would also include elastic energy?

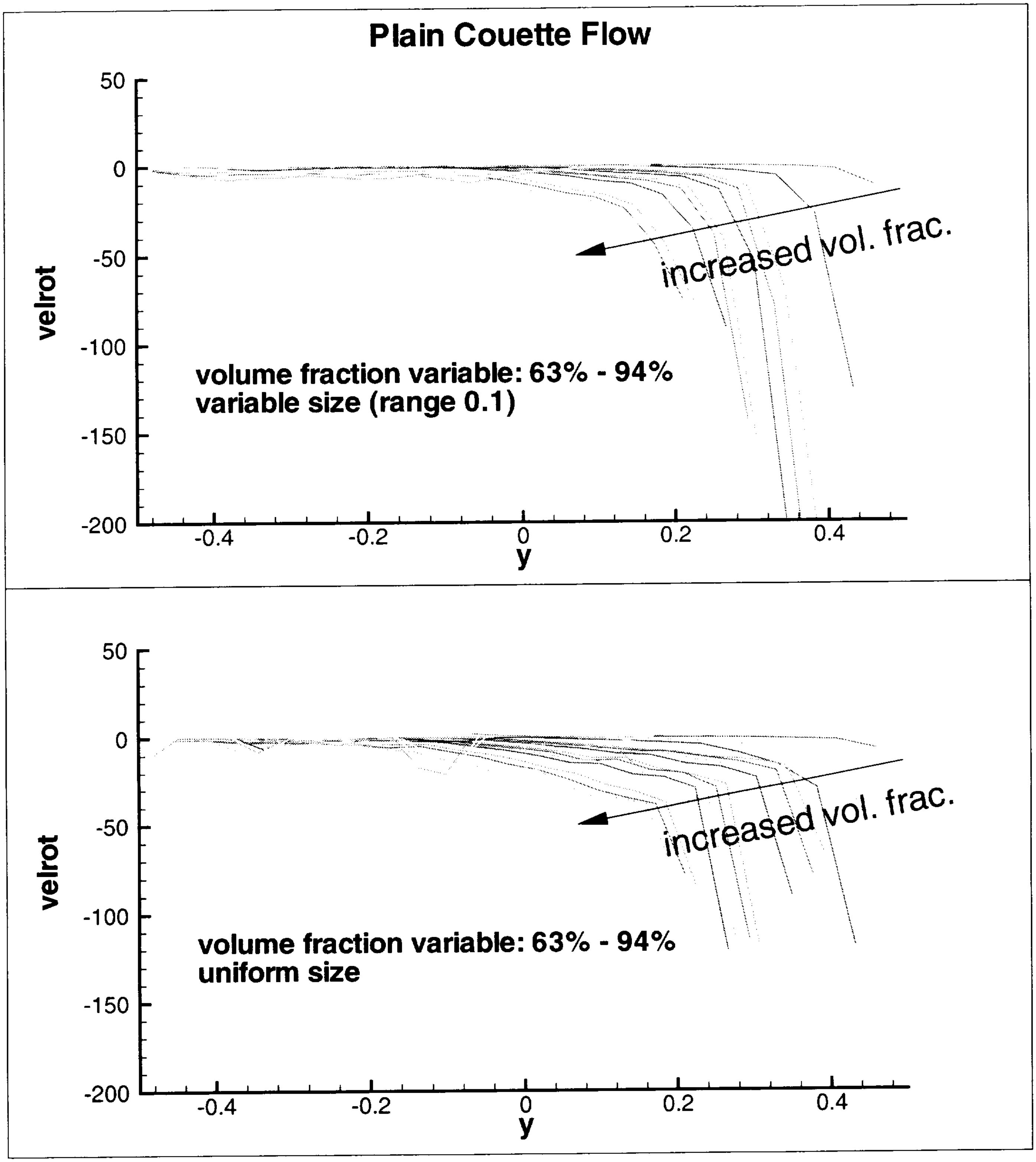
Understand better the influence of initial conditions (multiple solutions?)

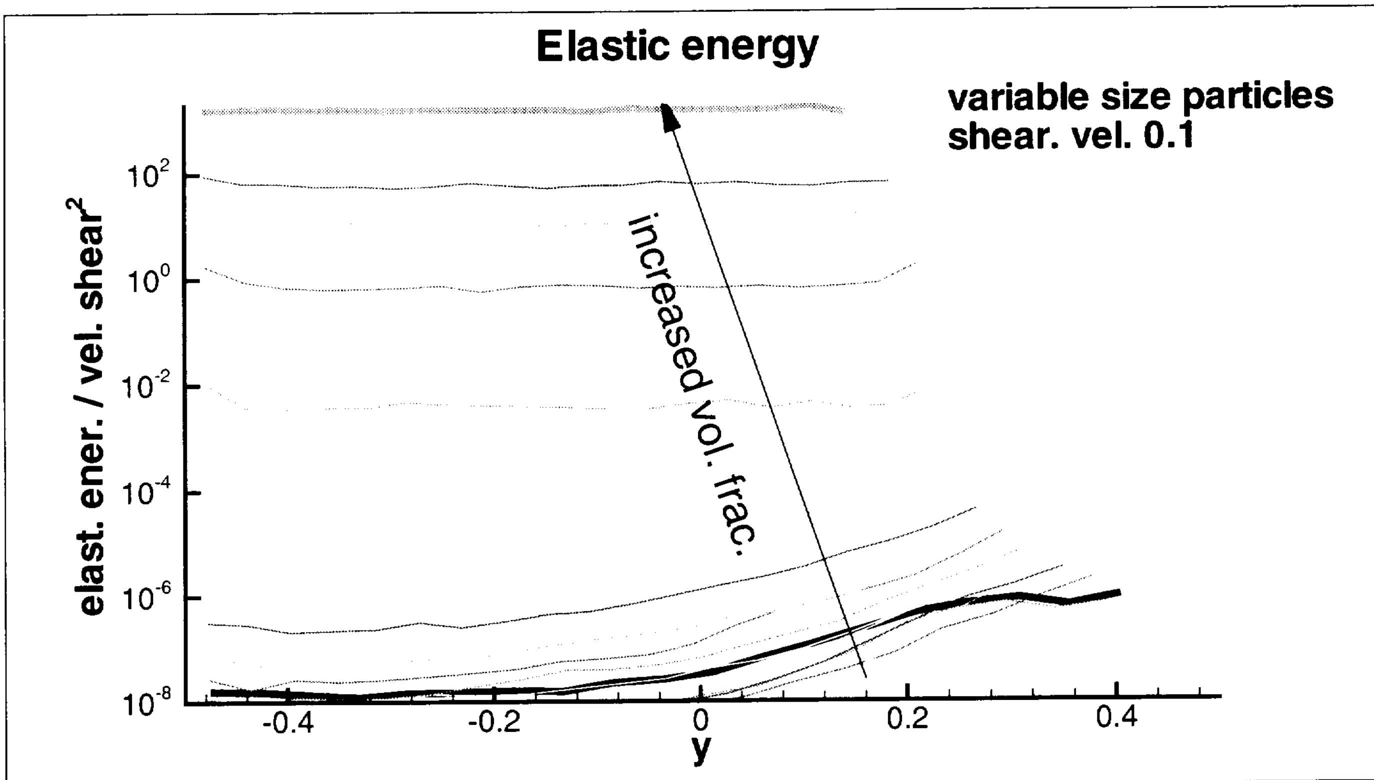
Extend to 3D and analyze the influence of material parameters

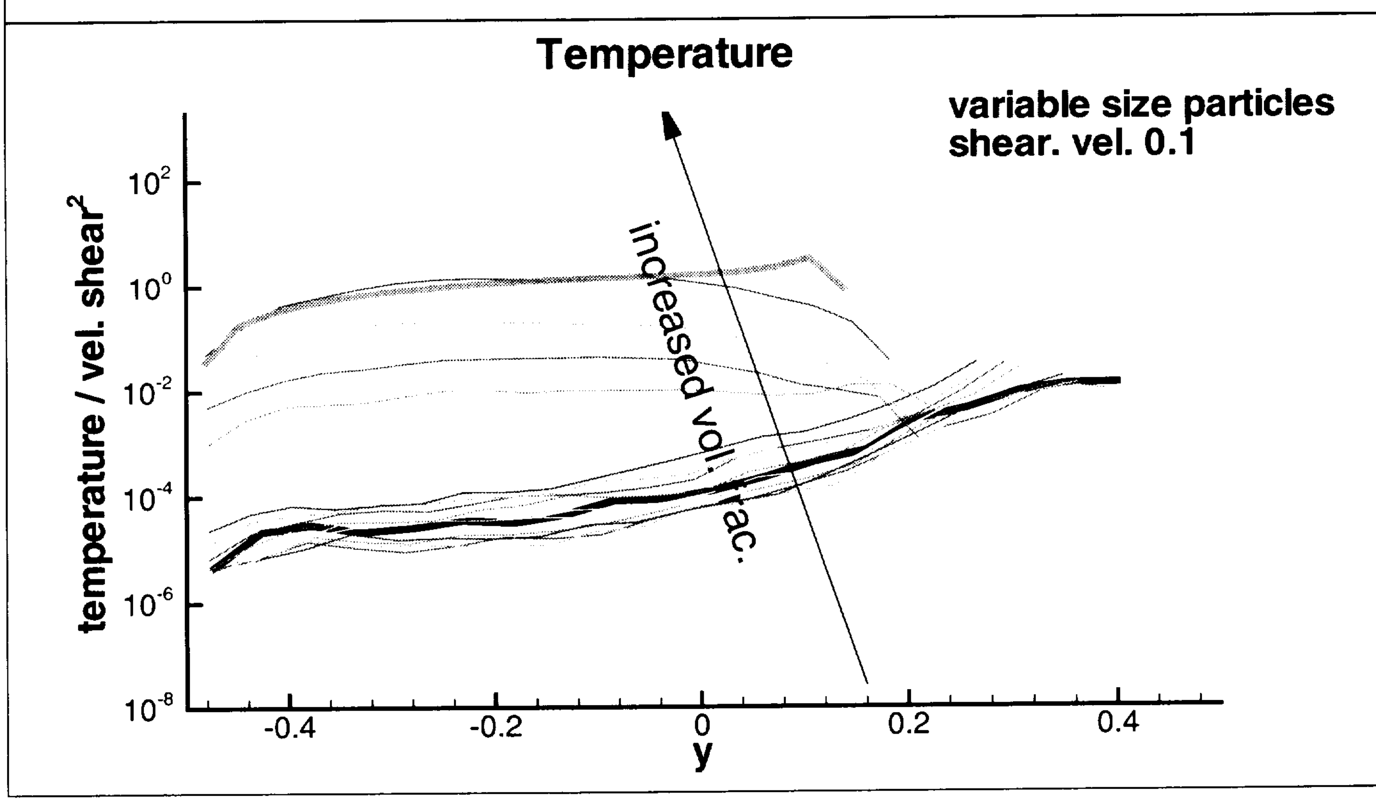
Analyze the stress distribution in space and time

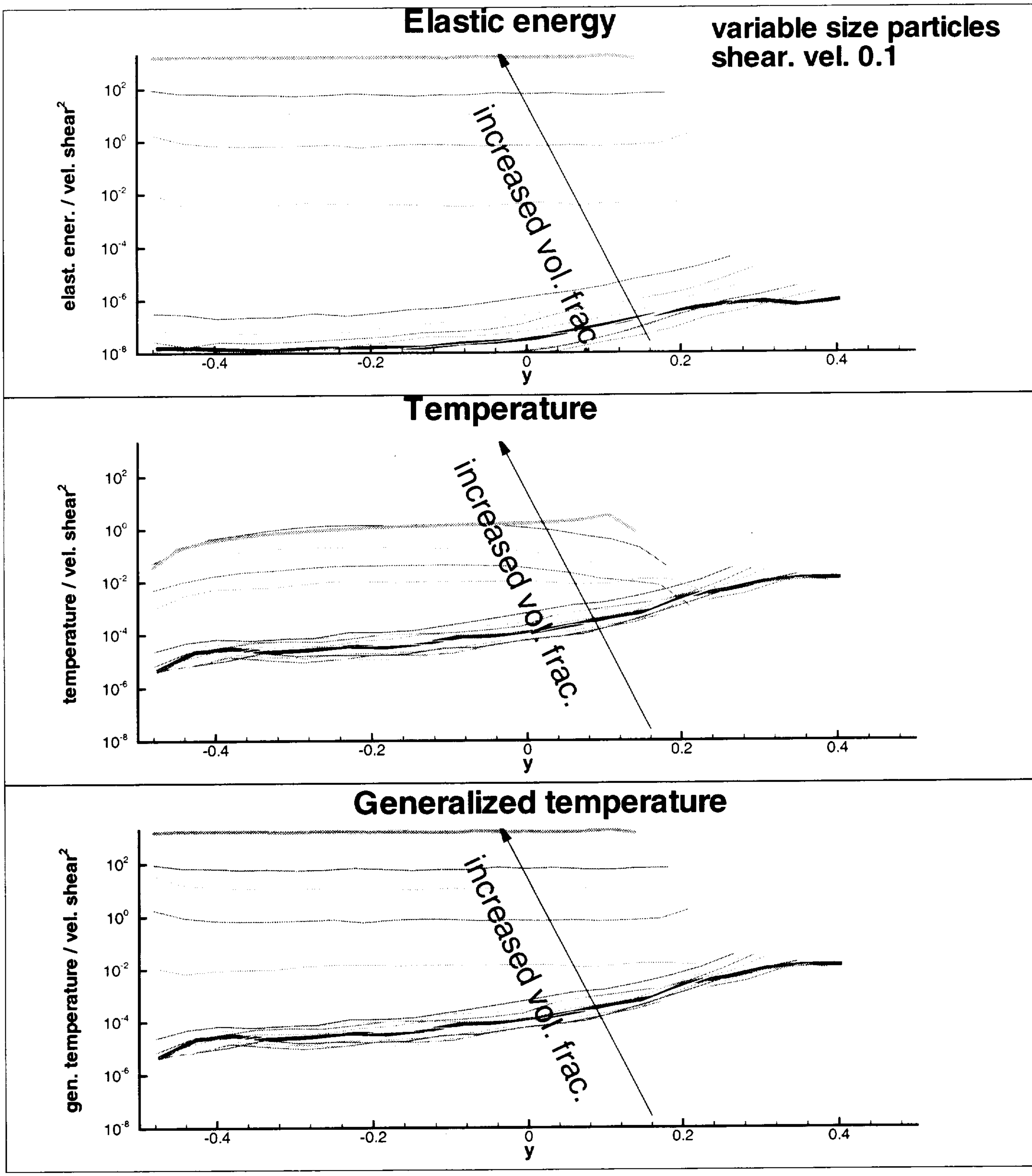
Understand the effect of geometry on the nature of the flow

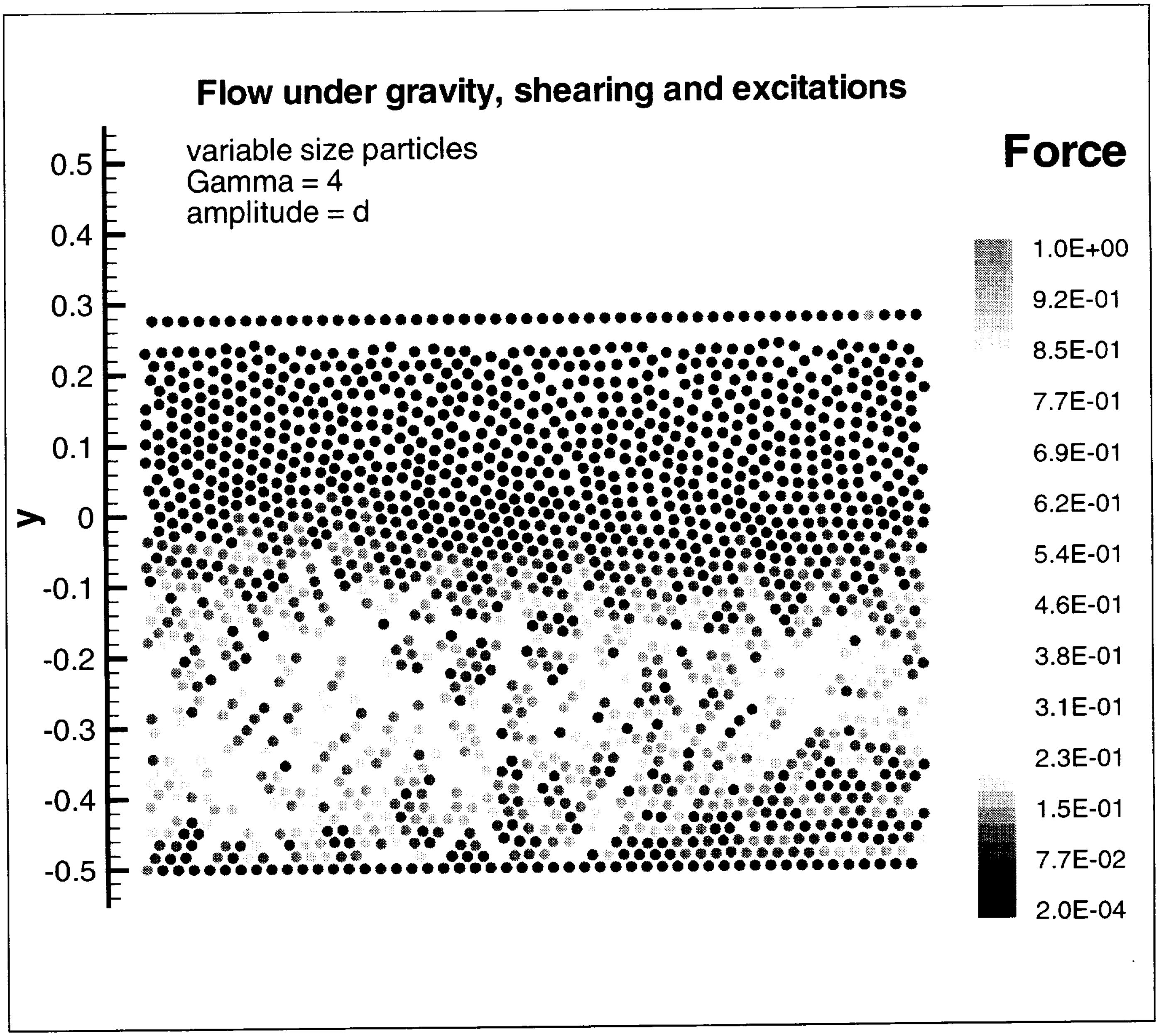
Analyze in more detail the role of external excitations in both zero and nonzero g environment


Plain Couette Flow
50
0
-50
-100
-150
-200
velrot
-0.4
-0.2
0
0.2
0.4
y
increased vol. frac.
volume fraction variable: 63% - 94%
variable size (range 0.1)
50
0
-50
-100
-150
-200
velrot
-0.4
-0.2
0
0.2
0.4
y
increased vol. frac.
volume fraction variable: 63% - 94%
uniform size


Elastic energy
variable size particles
shear. vel. 0.1
elast. ener. / vel. shear^2
increased vol. frac.
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
-0.4
-0.2
0
0.2
0.4
y


Temperature
variable size particles
shear. vel. 0.1
temperature / vel. shear^2
increased vol. frac.
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
-0.4
-0.2
0
0.2
0.4
y


Elastic energy
variable size particles
shear. vel. 0.1
elast. ener. / vel. shear^2
increased vol. frac.
y
Temperature
temperature / vel. shear^2
increased vol. frac.
y
Generalized temperature
gen. temperature / vel. shear^2
increased vol. frac.
y


Flow under gravity, shearing and excitations
variable size particles
Gamma = 4
amplitude = d
Force
1.0E+00
9.2E-01
8.5E-01
7.7E-01
6.9E-01
6.2E-01
5.4E-01
4.6E-01
3.8E-01
3.1E-01
2.3E-01
1.5E-01
7.7E-02
2.0E-04
y
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5