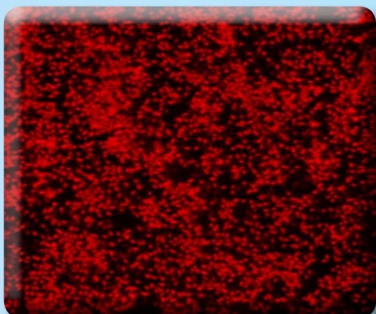
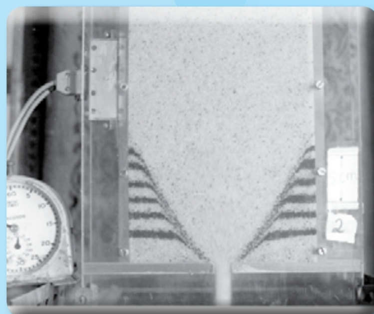
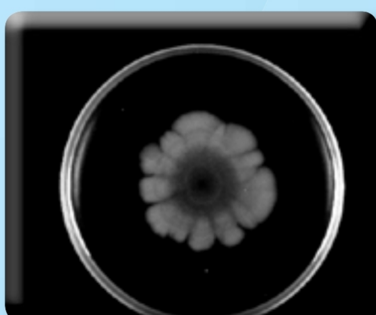
International Union of Theoretical and Applied Mechanics

IUTAM Symposium on MOBILE PARTICULATE SYSTEMS: Kinematics, Rheology and Complex Phenomena

January 23 - 27, 2012




Organised by

Indian Institute of Science, Bangalore 560 012 INDIA

IUTAM Symposium on

MOBILE PARTICULATE SYSTEMS: Kinematics, Rheology and Complex Phenomena

Bangalore, India
January 23 - 27, 2012

Organised by

Indian Institute of Science, Bangalore

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Welcome Message

On behalf of my colleagues in the organizing committee, I extend a warm welcome to all the participants of the IUTAM Symposium on Mobile particle systems. We thank all the participants, many having travelled long distances, for attending this symposium.

This symposium follows a series of meetings held under the aegis of the IUTAM on the broad area of particle and particle-fluid systems, but each with a different emphasis. In this symposium, we have brought together researchers and experts from diverse disciplines with the aim of furthering our understanding of the kinematics, rheology and dynamics of particle and particle-fluid flows. We believe we have gathered a very competent group of researchers, with a judicious mix of young and senior, well recognized scholars.

The sessions in the symposium are classified into five rough areas: slow granular flows, rapid granular flows, granular flows in the intermediate regime, dynamics and rheology of suspensions, turbulent gas-particle flows, and living suspensions. Some of the presentations go beyond these categories, but are still substantively connected to them.

We hope that the participants will enjoy the symposium, and also get a chance to explore the city of Bangalore and its invirons.

When we started, little did we realize that organizing a symposium is ninety percent logistics, and only the other half is academics (apologies to Yogi Berra). We have put in our best efforts, and are confident that in the end it will be worthwhile. Needless to say, we could not have managed it without the tremendous help and enthusiasm from the student volunteers, and the support from the Indian Institute of Science and our other sponsors – we are grateful to them all.

Prabhu Nott

General Information

- **Venue**
  The Lalit Ashok Hotel,
  Kumara Krupa High Grounds,
  Bangalore, India

- **Registration**
  Please register on January 23, 2012 between 08:00 am and 08:45 am at the symposium venue and collect the conference kit.

- **Name Badges**
  Name badges will be issued at the registration desk. Please display your badge when requested. Entry to auditorium, food areas, etc. requires display of badge.

- **Accommodation**
  Accommodation for student participants has been arranged at the Guest House, Central Power Research Institute (CPRI) Bangalore.

- **Speaker Check-In Information**
  Participants are requested to load their presentation file well ahead of the start of the session. Student volunteers will help you in the process. Kindly preview your slides before the presentation.

- **Mobile Phone Policy**
  Kindly switch your mobile phone off while inside the auditorium.

Technical Programme

Day 1: January 23, 2012

08 : 00 - 08 : 45	Registration	
08 : 45 - 09 : 15	Introductory remarks	

Rheology and dynamics of suspensions

09 : 15 - 10 : 00	J. Hinch	Fluctuations in the velocities of sedimenting particles
10 : 00 - 10 : 30	M. L. Ekiel-Jeżewska	Clusters of particles settling under gravity in a viscous fluid
10 : 30 - 11 : 00	Coffee break	
11 : 00 - 11 : 30	A. Ramachandran	Demonstration of secondary currents in the pressure-driven flow of a concentrated suspension through a square conduit
11 : 30 - 12 : 00	A. Singh	Radial segregation of settling suspension in horizontally rotating cylinder
12 : 00 - 12 : 30	M. S. Tirumkudulu	Ultimate strength of a colloidal packing saturated with a solvent
12 : 30 - 14 : 00	Lunch	
14 : 00 - 14 : 30	O. Pouliquen	Rheology of very dense suspensions
14 : 30 - 15 : 00	G. Ovarlez	Local behavior of dense suspensions of noncolloidal particles
15 : 00 - 15 : 30	A. Lindner	Flow of dense granular suspensions: an experimental study.
15 : 30 - 16 : 00	Coffee break	
16 : 00 - 16 : 30	J. F. Morris	Inertial effects upon rheology, migration, and segregation in suspensions
16 : 30 - 17 : 00	G. Leal	The role of copolymer surfactants in determining the polydispersity of drop size distribution and copolymer concentration in disperse phase polymer blends

Day 2: January 24, 2012

Slow granular flows

08 : 45 - 09 : 30	J. D. Goddard	Dissipative potentials in the mechanics of particulate media
09 : 30 - 10 : 00	P. R. Nott	Kinematics and stress in dense granular materials sheared in a cylindrical Couette device
10 : 00 - 10 : 30	F. Radjai	Fabric states and plastic behavior of granular materials
10 : 30 - 11 : 00	Coffee break	
11 : 00 - 11 : 30	K. Kamrin	Local and nonlocal models for dense granular flow
11 : 30 - 12 : 00	T. G. Murthy	Experimental studies of particle shape effects on slow flow in a dense granular ensemble
12 : 00 - 12 : 30	X. Li	Statistical characterisation of microstructure and particle-interactions
12 : 30 - 14 : 00	Lunch	
14 : 00 - 14 : 30	D. Khakhar	Rheology and segregation of granular mixtures in dense flow
14 : 30 - 15 : 00	K. Hill	Segregation of binary mixtures: competing effects of gravity and shear rate gradients
15 : 00 - 15 : 30	É. Guazzelli	Dense suspension rheology: normal stresses and migration
15 : 30 - 16 : 00	Coffee break	
16 : 00 - 16 : 30	J. A. Dijksman	Particle diffusion in the bulk of slow granular flows
16 : 30 - 17 : 00	A. V. Orpe	Interstitial fluid effects on the dynamics of dense granular flows

Day 3: January 25, 2012

Granular flows in the intermediate regime

08 : 45 - 09 : 30	S. Sundaresan	Rheology of dense granular flows: regime bridging and implications for kinetic theory
09 : 30 - 10 : 00	J. C. Ruiz-Suárez	Falling inside a superlight granular medium
10 : 00 - 10 : 30	N. Gray	Particle size segregation and spontaneous levee formation in geophysical mass flows
10 : 30 - 11 : 00	Coffee break	
11 : 00 - 11 : 30	R. H. Davis	Collisions of wet particles
11 : 30 - 12 : 00	I. Sharma	Stability of granular asteroids
12 : 00 - 12 : 30	T. Pöeschel	Packing Structure of Granular Systems
12 : 30 - 14 : 00	Lunch	

Rapid granular flows

14 : 00 - 14 : 45	V. Kumaran	Transition in a dense granular flow
14 : 45 - 15 : 15	T. Börzsönyi	Orientational order and alignment of elongated particles induced by shear
15 : 15 - 15 : 45	N. M. Vriend	The second normal-stress difference in avalanching granular flows
15 : 45 - 16 : 15	Coffee break	
16 : 15 - 16 : 45	H. Hayakawa	Nonlinear analysis for a sheared granular flow: relaxation to a steady state and response around a steady state
16 : 45 - 17 : 15	S. Luding	From particles to continuum theory: shear-bands, jamming and dilatancy

Day 4: January 26, 2012

Turbulent fluid-particle flows

08 : 45 - 09 : 30	M. Reeks	Segregation of particles in incompressible random flows:singularities, intermittency and random uncorrelated motion
09 : 30 - 10 : 00	T. Tanaka	Numerical model for the motion of a large object in dense gas-solid flows
10 : 00 - 10 : 30	P. S. Goswami	Particle dynamics in a turbulent particle-gas suspension at high Stokes number
10 : 30 - 11 : 00	S. Roy	Dynamic flow structure in multiphase systems using single radio-labelled particle tracking
11 : 00 - 12 : 30	Coffee break and **Poster presentation**	
12 : 30 - 14 : 00	Lunch	

Day 5: January 27, 2012

Living suspensions

08 : 45 - 09 : 30	S. Ramaswamy	Chemotactic catalytic colloids
09 : 30 - 10 : 00	M. D. Graham	Hydrodynamic coordination of bacterial motions: from bundles to biomixing
10 : 00 - 10 : 30	S. Rafaï	Active suspensions under flow
10 : 30 - 11 : 00	Coffee break	
11 : 00 - 11 : 30	G. Subramanian	Pair-correlations in a bacterial suspension
11 : 30 - 12 : 00	P. Peyla	Rheology of active suspensions. Active rotors
12 : 00 - 12 : 30	D. Saintillan	The dynamics of active suspensions: effects of confinement and of concentration
12 : 30 - 14 : 00	Lunch	
14 : 00 - 14 : 30	J. Brady	Reaction-induced motion: chemical swimming, sailing and surfing
14 : 30 - 15 : 00	A. S. Sangani	Evaluation of proposed mechanisms for ciliary beating of eukaryotic cells
15 : 00 - 15 : 30	R. Prabhakar	Measurements of extensional viscosities of suspensions of motile microbes
15 : 30 - 15 : 45	Valedictory remarks	
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Rheology and dynamics of suspensions

Fluctuations in the velocities of sedimenting particles

John Hinch

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The sedimentation velocities of individual particles in a suspension fluctuate with the constantly changing configuration of the particles resulting from long-range multi-particle interactions. Until recently there was a paradox with the magnitude of the fluctuations predicted by theory and numerical simulations to increase with the size of the container, whereas experiments saw no such dependency. Insight into the paradox has come from careful experiments accompanied by numerical simulations, both studying the variation in time and position of the fluctuations and the small vertical variations of the concentration of the particles.

References

[1] Fluctuations and instability in sedimentation, Elisabeth Guazzelli and John Hinch, Annual Reviews in Fluid Mechanics **43**, 97 (2011).

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Clusters of particles settling under gravity in a viscous fluid

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We investigate clusters made of a small number of particles settling under gravity in a viscous fluid. The particles do not touch each other and can move relative to each other. A family of clusters is found with periodic oscillations of all the settling particles. The dynamics is analysed in the point-particle approximation. The results are used to explain how a spherical cloud, made of a large number of particles distributed at random, evolves and destabilizes.

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Demonstration of secondary currents in the pressure-driven flow of a concentrated suspension through a square conduit

Adam Zrehen and Arun Ramachandran

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It was shown theoretically by Ramachandran and Leighton [2] that the pressure-driven flow of concentrated suspensions of non-colloidal particles through non-axisymmetric conduits may not be unidirectional, and that the base flow along the axis of the conduits in the flow direction should be accompanied by a secondary flow driven by second normal stress differences. This work confirms the existence of these secondary flows by carrying out pressure-driven suspension flow experiments through a square (non-axisymmetric) duct. By tracking the motion of a thin stream of a contrastingly-dyed suspension introduced into the bulk flow of another, it is demonstrated that the suspension flows out of the sidewalls of the geometry towards the corners of the square cross-section, and then flows towards the center (see figure 1 for numerical calculation). This distortion of the interface was found to be qualitatively consistent with the calculations based on the suspension balance model of Nott and Brady [1] coupled with the constitutive equations of Zarraga and Leighton [3].

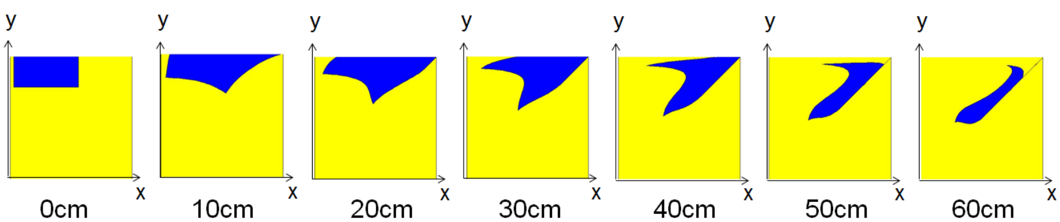

Figure 1: The axial progression of a patch of a non-colloidal suspension (blue) in the bulk flow of another (yellow), as predicted by the suspension balance model of Nott and Brady [1] and the constitutive equations of Zarraga and Leighton [3]. The cross-sectional co-ordinates are x and y, and the flow is into the plane of the paper. The calculation is performed in the first quadrant of the square only (the origin is, therefore, the center of the square).

Secondary currents have been historically neglected in suspension-flow calculations, in spite of the fact that they are predicted to have a stronger and often, counterintuitive influence on concentration distributions as compared to the traditionally-considered effect of shear-induced migration. This paper lends support to the idea that the impact of secondary currents is not negligible, and that such currents may actually be the dominant mechanism that determines particle distribution in suspension flows. This work also has strong implications for co-extrusion of non-colloidal suspensions in non-axisymmetric geometries.

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[2] Ramachandran, A. and D. T. Leighton, J. Fluid Mech. **603**, 207 (2008).

[3] Zarraga, I. E., D. A. Hill and D. T. Leighton, J. Rheol. **44**, 185-220 (2000).

Radial segregation of settling suspension in horizontally rotating cylinder

Akshat Jain[1], Anugrah Singh[1] and John F Brady[2]

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Suspension of solid particles in viscous fluid rotating in a horizontal drum or cylinder is often encountered in many mixing and segregation devices. In mixing application, homogeneous dispersion of particles is desired, while on the other hand phenomena of segregation provide an effective way to separate particles caused simply by rotation of cylinder [1]. A great deal of experimental and theoretical work has been done in the past to understand the axial and radial patterns in mono- dispersed neutrally buoyant suspension in fully filled cylinder [2-3] but there are very limited studies on the dynamics of settling suspensions in rotating cylinder [4]. We report experimental and simulation studies on the radial segregation of non-neutrally buoyant suspension in rotating cylinder. It is observed that the interplay between hydrodynamic and gravitational forces on the particles leads to instabilities resulting into a segregation pattern in which the heavier particles occupy the central region and the lighter particles are confined around the heavier particles. The final pattern is independent of initial configuration of the particles. The experiments were conducted by taking equal volume percentage of heavier (steel balls) and lighter (glass beads) particles in glycerol-water mixture. The cylinder was rotated at very low speed to keep the Reynolds number small. Figure 1 (a) shows the initial configuration of particles. The particles that appear to be solid black are the steel beads and the lighter ones are the glass beads. The final steady state configuration is shown in figure 1(b) where the segregation pattern is clearly observed with heavier particles surrounded by lighter ones. The Stokesian dynamics simulations were performed for similar conditions as mentioned above. Figure 2(a) shows the initial distribution of particles in the cylinder and figure 2(b) shows the final segregation pattern. It is clear that the simulations also display segregation of heavy particles in the inner core surrounded by the light particles. We have also conducted simulations for different ratio of particle densities. It was observed that the segregation of heavier particles increases as we increase the density ratio. This can be explained on the basis of difference in trajectories of a light and a heavy particle. The heavier particles have shorter trajectories as compared to the lighter ones; which allows these particles to separate from the lighter ones. Lighter particles prefer to stay is a highly mobilized region. As we go on decreasing the density ratio, the difference in trajectories of heavy and light particle reduces and so is the decrease in segregation.

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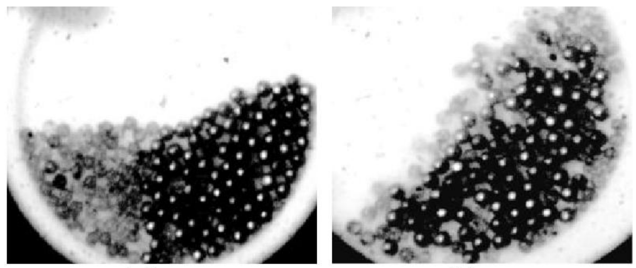
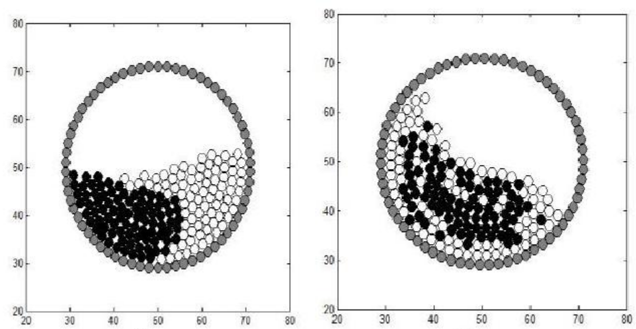


(a) (b)

Figure 1: Initial distribution (a) and final configuration (b) of particles in experiments.



(a) (b)

Figure 2: Initial distribution (a) and final configuration (b) of particles in Stokesian dynamics simulations.

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Ultimate strength of a colloidal packing saturated with a solvent

Mahesh S Tirumkudulu and Arijit Sarkar

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The consolidation of colloidal particles in drying colloidal dispersions is influenced by various factors such as particle size and shape, and inter-particle potential. The capillary pressure induced by the menisci, formed between the top layer of particles in the packed bed, compresses the bed of particles while the constraints imposed by the boundaries result in tensile stresses in the packing. Presence of flaws or defects in the bed determines its ultimate strength under such circumstances. In this study, we determine the asymptotic stress distribution around a flaw in a two dimensional colloidal packing saturated with liquid and compare the results with those obtained from the full numerical solution of the problem. Using the Griffiths criterion for equilibrium cracks, we relate the critical capillary pressure at equilibrium to the crack size and the mechanical properties of the packed bed. The analysis also gives the maximum allowable flaw size for obtaining a crack free packing.

Experiments performed to test the above predictions show that the stress required to fracture a cylindrical colloidal packing saturated with solvent under axial tension varies inversely with the three-half powers of the diameter. The predicted critical stress required to initiate cracks from flaws shows the same scaling with flaw size. Close inspection of the failed sections of the packing revealed flaws entrapped during the drying process. The maximum capillary pressure sets the critical flaw size below which the crack will not nucleate, thereby giving the ultimate strength of the colloidal packing. The experiments show that if the flaw size can be restricted below the critical value, large colloidal packings free of cracks can be synthesized.

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Rheology of very dense suspensions

Francois Boyer, Elisabeth Guazzelli, and Olivier Pouliquen

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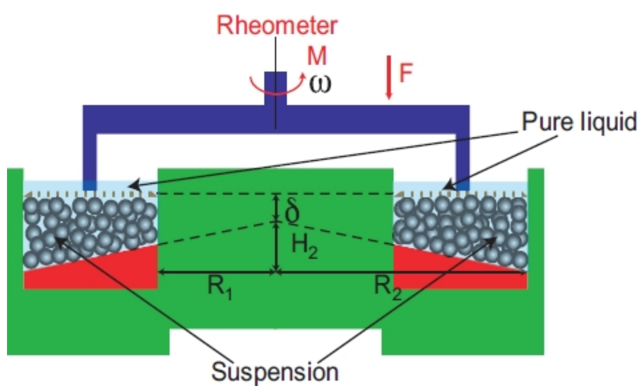
The rheology of suspensions of rigid particles close to the jamming transition is studied using a non conventional rheological method inspired by recent studies in dry granular media. A shear cell has been developed, in which the granular pressure is controlled, the volume fraction being free to adjust. Using this new setup, we show that suspensions can be described by a visco-plastic frictional rheology, providing a link with the rheology of dry granular media. This configuration also circumvents the divergences observed in volume fraction imposed rheology at the jamming transition and provides precise measurements of the constitutive equations very close to the jam- ming transition. The link between this point of view and the classical empirical models proposed for suspensions will be discussed.

This work is part of Francois Boyer's Phd.



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[1] F. Boyer, E. Guazzelli, O. Pouliquen, Physical Review Letter **107**, 188301 (2011).

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Local behavior of dense suspensions of noncolloidal particles

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Dense suspensions of noncolloidal particles display a rich non-Newtonian behavior (yield stress, shear thickening, normal stress differences...), which is not yet fully understood. In particular, its link with the possible existence of direct contacts between the particles remains unclear.

We investigate the behavior of dense suspensions of monodisperse spherical particles [13] in a wide gap Couette geometry. We measure the torque/rotational velocity relationship for various shear histories. We also measure the velocity and particle volume fraction profiles thanks to MRI techniques. At the macroscopic scale, the systems display a torque plateau at low imposed shear rate, which is interpreted as a yield stress. They also show an irreversible discontinuous shear thickening behavior at moderate macroscopic shear rate. However, thanks to the local observations, we show that the intrinsic behavior is characterized by viscous and inertial behaviors only.

The macroscopic yield stress is associated with flow heterogeneity (shear banding): the material splits between a non flowing region and a region flowing at a shear rate higher than a critical value. In this last region, the local shear stress/shear rate relationship is shown to be linear: the material has a purely viscous behavior. We show that the flow instability is due to competition between slight sedimentation, which tends to create a contact network, and shear-induced resuspension.

The discontinuous macroscopic shear thickening is associated with very rapid shear-induced migration. At steady state, the material is heterogeneous. However, the combination of macroscopic and local measurements allows us to derive the local behavior of a homogeneous material; we then evidence a transition from a viscous ($\tau\alpha\dot{\gamma}$) to inertial ($\tau\alpha\dot{\gamma}^2$) local behavior. Migration is shown to be slow in the viscous regime, and rapid in the inertial regime. The macroscopic discontinuous shear thickening thus appears as a direct consequence of the existence of the intrinsic continuous shear thickening behavior. We finally discuss the volume fraction dependence of the locally observed behavior, and point out the role of direct contact forces in the observed behavior.

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Flow of dense granular suspensions: an experimental study.

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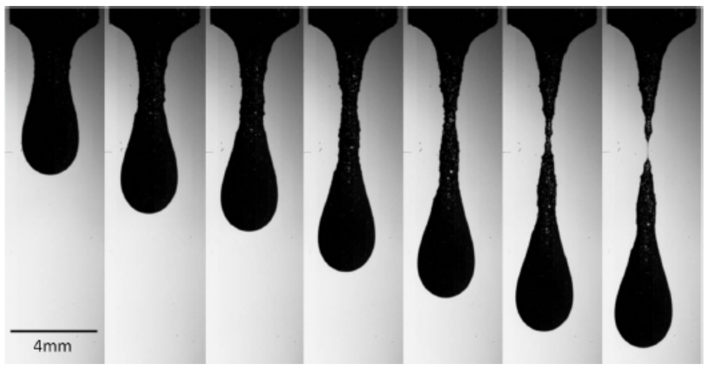

Figure 1: Detachment of a drop of a granular suspension ($\phi = 40\%$, grain diameter 140 μm.)

We study experimentally the flow of dense granular suspensions. The suspensions are made of monodisperse, spherical, non-Brownian polystyrene beads immersed in density matched silicon oil. The volume fraction ϕ can be varied from 30 to 61%. We investigate the flow behaviour of these dense granular suspensions by the use of two complementary geometries: shear flow on an inclined plane and elongation flow during the detachment of a suspension droplet. We show that the inclined plane is a useful rheometer suited to explore the continuous transition from an effective viscous flow (high thicknesses) to dense "pseudo-granular" flow (low thicknesses). A mesoscopic length scale separates the two flow regimes and diverges when the volume fraction approaches the jamming limit [2]. This set-up allows for measuring the viscosity directly up to volume fractions as large as 61%, which is impossible with a classical rheometer [1]. In the case of the "pinch-off" experiments, we show that the elongation viscosity is identical to the one measured on an equivalent pure viscous liquid. Nevertheless, the final detachment regime is accelerated by the presence of grains. Moreover, we find a dynamical process independent of the grain concentration, but slightly dependent on the grain size [3].

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Microstructural theory and rheology in very concentrated Brownian suspensions

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A microstructural theory for concentrated Brownian colloidal suspensions is developed and applied to predict the macroscopic shear rheology, as well as active microrheology, of these mixtures. The discussion will focus on the shear-flow problem for hard spheres, but will outline the results for shear flow of suspensions of particles interacting through soft repulsive potentials, as well as active microrheology (where one particle is pulled through an otherwise quiescent bath). For the first time, a theory is available which applies for solid volume fractions up to $\phi = 0.5$, and for near equilibrium to hydrodynamically dominated conditions, i.e. over a very wide range of the Peclet number, $Pe = 6\pi\eta\dot{\gamma}a^3/kT$; here η is the fluid viscosity, $\dot{\gamma}$ is the shear rate, a is the particle radius, k is the Boltzmann constant and T is the absolute temperature.

The theory is based upon the Smoluchowski equation for the configuration of the dispersion, reduced to the pair level to describe the pair distribution function g(r). The novelty lies in de- veloping the pair Smoluchowski equation as an integro-differential equation, in which the integral aspect arises in order to capture the many-body nature of the problem. The integrals appear as coefficients which represent self-consistently two crucial aspects of the bath particles: first is the forcing of pairs toward contact by the bath, and second is the tendency for a third particle to be in the space intervening between the pair. The forcing toward contact results in the well-known flow-driven accumulation of pair probability at contact, while the fact that a particle may intervene propagates the correlation to large distances. These features are sufficient to capture the role of excluded volume in a hard-sphere suspension, showing not only correlation at contact but also long-range correlation in the form of a next-nearest neighbor ring. The results of the theory agree well with slight perturbations from equilibrium structure, and thus reproduce integral equation approaches in the limit of very small Pe, and agree with microstructure obtained by sampling from Accelerated Stokesian Dynamics simulation for $1 < Pe < 200$. It is shown that the inclusion of a shear-induced diffusion is essential to the theory for hard-sphere suspensions. Imposition of flow results in a progressively more anisotropic structure near contact of the pair as Pe increases, and the viscosity and normal stresses respond to the microstructural changes.The shear thinning and thickening of the suspension viscosity are qualitatively in agreement with simulation and experi- mental observations, with satisfactory quantitative agreement. Similar levels of agreement are seen for the normal stress differences.

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The role of copolymer surfactants in determining the polydispersity of drop size distribution and copolymer concentration in disperse phase polymer blends

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We summarize recent work to understand the role of copolymer surfactants in determining the drop size distribution and the polydispersity of copolymer coverage on the drops in a disperse phase polymer blend. In the first part of the work, we discuss the roles of Marangoni effects and of steric repulsion in inhibiting coalescence, and hence controlling the drop size distribution. This is done by utilizing data on a symmetric system, with the two bulk phase polymers having equal viscosities and the two parts of the diblock copolymer having either the same molecular weights or the same degree of polymerization. In the second part, we consider drop breakup and its role in determining the polydispersity of copolymer coverage in the blend.

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Slow granular flows

Dissipative potentials in the mechanics of particulate media

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This paper is concerned with the usage of generalized dissipation functions or “dissipative potentials” in various theories of viscoplasticity, with special emphasis on the application to fluid-particle suspensions and granular media. As generalizations of the classical Rayleigh dissipation function, such functions have been employed in plasticity theories at least as far back as the early work of Melan [3, 5], and have been generalized to Cosserat continua [4]. A cursory survey is given of select applications of such models to the plasticity of granular materials.

Physical justifications for the existence of dissipative potentials are often based on the as- sumption of maximum dissipation (or entropy generation) [6], which is plausible for Stokesian suspensions but less than evident for granular materials generally. By contrast, in remarkable work that seems to have been largely ignored, Edelen [1, 2] has proposed a purely mathematical construct giving general force-dependent velocity (or thermodynamic “flux”) as the gradient of a dissipative potential plus a non-dissipative term that represents Ziegler’s “thermodynamically orthogonal” flux and the “gyroscopic” effects that are usually ruled out of Onsager-type theories.

The present work provides an elementary derivation of Edelen’s results by means of conventional vector calculus, and at the same time expores the possibility of representing kinematic constraints such as granular dilatancy in terms of the non-dissipative terms in the Ziegler- Edelen formulae.

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The kinematics and stress in a dense, slowly sheared granular column

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The stress in a column of granular material confined by vertical walls has been of interest since the mid-nineteenth century, when food grains began to be stored in tall silos. It was realized quite early that, unlike in liquid columns, the normal stress at the base of a static granular column does not increase linearly with the head of material. Apart from its importance in the design of silos, the stress in sheared granular columns is also of interest from the standpoint of rheometry – rheological properties of liquids are often measured in a cylindrical Couette device, as they are readily obtained from the stress and strain rate in such viscometric flows. However, very few studies have attempted to determine the rheology of dense granular materials using this device, as the kinematics and stress in granular materials have a more complex relationship. Here, we present measurements of the stress as a function of vertical position in a column of granular material sheared in a cylindrical Couette device. We find that the stress profile differs fundamentally from that of fluids, from the predictions of plasticity theories, and from intuitive expectation. We show that gravity and the confining walls play important roles. We argue that the anomalous stress profile is due to an anisotropic fabric caused by the combined action of gravity and shear.

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Fabric states and plastic behavior of granular materials

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The plastic behavior of granular materials is governed by unilateral contact interactions and steric exclusions. These features are thus essential in modeling the internal friction, dilatancy and fabric states. We present a general framework for fabric evolution with the guiding idea that a physical plastic model of granular materials should be based in the first place on low-order parameters pertaining to the granular microstructure but accounting more or less strictly for steric exclusions as well as the mechanical equilibrium of the particles. We introduce a fabric tensor that, by combining the coordination number and fabric anisotropy, allows for a simple tensorial representation of the fabric states by means of Mohr circles. We discuss how low-order fabrics are induced by homogeneous shearing. Finally, a model is introduced for the evolution of fabric states with the strain-rate tensor. This model predicts the existence of a steady state, which provides in this way a geometrical interpretation of the critical state as a "saturated or "jammed state, and an exponential evolution of the fabric variables during transients. It also predicts the range of accessible fabric states and an upper bound on the fabric anisotropy. By means of numerical simulations, we show that this model fits correctly the data the under complex loading paths.

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Local and nonlocal models for dense granular flow

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Dense granular materials such gravel and sand compose a family of heterogeneous media with a number of modeling challenges. While discrete element approaches have been useful and have had success in reproducing experimental results, a feasible and broadly applicable continuum law for granular flow is much desired, that can predict stress and flow fields in arbitrary geometries. This talk uses data from experiments and discrete element simulations to determine a common size-scale for RVE behavior in common granular materials, and synthesizes a meso-scale elasto-plasticity law for steady flow. The law is tested and verified in a number of geometries by comparing against known data. For reasons to be explained, the law is less sufficient in slowly sheared regions, where a verifiable nonlocal constitutive behavior can emerge. Nonlocal effects cause the actual flow to differ from the local law in several ways: (1) Slowly driven shear-bands have a non-vanishing width scaled by the particle size; (2) In the presence of a stress gradient, material undergoing stresses less than the yield criterion can still flow; (3) The flow-rate in slowly sheared regions is independent of the size of the stress, in sharp contrast with the local law. We address these issues by adding a nonlocal enhancement term to our law, which enables us to capture all of these effects. This term is inspired by theoretical work on nonlocal fluidity in the emulsions community. We demonstrate the merits of the extended law by testing its predictions against multiple DEM simulations in multiple geometries.

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Experimental studies of slow flow past obstacles in a dense granular ensemble

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Slow flows in granular materials are predominantly characterized by a high solid fraction and force transfer through sustained inter-particle contact. Slow flows past obstacles have interesting kinematics, and have applications in many problems including shallow foundations, mixing, deformation processes such as drilling etc. Intrusion of objects into a granular ensemble can also be studied as the flow of a granular ensemble past an obstacle.

An experimental study has been made in order to understand the velocity and deformation fields in a model granular ensemble of sand flowing past a flat punch. Under nominal plane strain conditions obtainable in a lab, an ensemble of rounded sand particles was used to study the extent and characteristics of the deformation field around a stationary obstacle (i.e. a flat punch). High-speed and high-resolution images were obtained during the traverse of the granular ensemble. These images were analyzed using a hybrid piv-ptv and optical flow algorithm. Kinematics of the deformation such as the velocity field, strain-rate field and the accumulated strain were discernible through these image analysis results.

Interesting features of deformation in the granular ensemble have been identified, such as "a zone of participation", "a dead wedge", initiation and propagation of shear bands etc have been identified in this deformation field. Severe jumps in the velocity of the granular medium renders a deformation field akin to the velocity fields observed during indentation of solids. Comparison of these results to existing analytical and numerical solutions of this problem have also been made.

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Statistical characterisation of microstructure and particle-interactions

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With fast development in laboratory measurement techniques and numerical simulation methods, particle-scale information becomes assessable. This consequently poses new challenge of processing the massive amount of particle-scale information, which is often directional data. The directional statistic theory established for orientations [1] has been revisited and generalized to vector-valued data. Their directional probability density distribution and the average values along each direction are approximated by polynomials in unit directional vector n with tensorial coefficients. The coefficients could be determined by applying the least square error criterion, and serve as macro-scale statistical characterisation of these micro-scale directional data [2].

The approach has been applied to study the stress state of a granular material. Starting from the micro-structural expression of the stress tensor, analyses have been carried out on the statistical characterisation of micro-structure and particle-interactions based on data obtained from discrete element simulations. It has been shown that good approximation could be achieved by a few limited terms. In two dimensional conditions, we derived

$$\sigma_{ij} = \frac{\omega N}{2V}\zeta v_0 f_0[(1+C)\delta_{ij} + G^f_{ji} + G^v_{ij} + \frac{1}{2}D^c_{ij}] \tag{1}$$

where ω is the coordination number, N is the number of particles, V is the material volume. The parameter ζ reflects the statistic dependence between contact vectors and contact forces, and the parameter C is due to the contribution from the joint products of deviatoric stress tensors. v_0 and f_0 represent the directional average of the mean contact vector and contact force along each direction. D^c_{ij}, G^v_{ij}, G^f_{ji} are direction tensors characterizing the directional dependence of contact normal density, mean contact vector and mean contact force. It explicitly expressed the stress tensor in terms of direction tensors characterizing contact normal density and contact forces. It is equivalent to the stress-force-fabric relationship in proportional loading following the same set of assumption [3]. But based on directional statistical theory, all the assumptions have been examined. Also the new derived stress-force-fabric relationship is valid for non-proportional loading with additional capacity in predicting principal stress direction.

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Rheology and segregation of granular mixtures in dense flow

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We investigate the rheology of granular mixtures, comprising particles of different size and density, in a flow on a rough inclined plane by means of Discrete Element Method (DEM) based simulations. Steady flows at relative high particle volume fractions (ϕ ¿ 0.5) are considered for different density ratios, size ratios and inclination angles. A new model based on the viscoplastic model of Jop et al. (Nature, **441**, 727, 2006) is shown to describe the rheology of the mixtures quite well. Segregation of particles is analyzed by considering the sedimentation of single particles in the flow. We find that modified versions of Stokes Law and Archimedes principle may be used to obtain the drag force and buoyancy experienced by a sedimenting particle. A continuum model is developed to predict the equilibrium segregation in the flow and compared to simulation results.

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Segregation of binary mixtures: competing effects of gravity and shear rate gradients

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It is well-known that a mixture of different sized particles will segregate in a gravitational field. However, it has only recently been shown that a gradient of shear rate alone can drive segregation in dense sheared systems [1]. In contrast with sparse energetic granular materials, in dense sheared systems, large particles segregate to the regions with higher shear rates. We develop a model for shear-induced segregation in dense mixtures of different sized particles. The model is comprised of two primary parts. The first involves the tendency of a gradient in kinetic stress – stress associated with velocity fluctuation correlations – to drive all particles toward regions of low shear rate. The second is essentially a kinetic sieving effect in which small particles are more likely to find voids into which they can travel than large particles. The two features together segregate small particles to regions of low shear rate and squeeze large particles in the opposite direction. We validate this model via 3D Discrete Element Method (DEM) simulations in a vertical chute. We then combine this theory for segregation via kinetic stress gradients [2] with a theory for gravity-driven segregation of granular materials (first proposed by Gray and Thornton, [3]) to study how these competing segregation mechanisms can give rise to a variety of trends that have been observed in dense sheared granular flows.

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Dense suspension rheology: normal stresses and migration

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Dense or highly concentrated particulate systems are very common in several engineering fields such as civil engineering, food or pharmaceutical industry as well as in geophysical situations such as debris flows, sediment transport, and submarine avalanches. The major difficulty of dense particulate flows is that the grains interact both by hydrodynamics interactions through the liquid and by mechanical contact. These systems thus belong to an intermediate regime between pure suspensions and granular flows.

Dense suspension rheology exhibits a number of non-Newtonian behaviours. We focus on the appearance of normal stress differences and present two new experimental determinations of these differences using rotating-rod rheometry and tilted-trough flow [1, 2]. We also discuss particle migration from regions of high to low shear-rate which can occur in these flow geometries.

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Particle diffusion in the bulk of slow granular flows

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Granular flows have been successfully modeled by the inertial number theory [1]. This mean field model provides insight into which timescale sets the flow dynamics for granular flows. However, there are several shortcomings to this model; for example, it fails at describing slow granular flows. Indeed, there is as yet very little insight in the microscopics of slow granular flows.

Here we report on direct measurements of microscopic particle dynamics in the bulk of a slow, dense granular flow. To image the bulk of the granular flow, we use an index matched scanning technique [2]. We measure the trajectories and diffusion of all particles for a wide range of strain rates in a split bottom cell. This setup has been shown to provide smooth and continuous shear bands [3, 4]. Crucially, we can probe the dependence of the particle diffusion on the local pressure. With dimensional analysis, we explicit the family of timescales associated with particle dynamics. We show that in order to capture the diffusive particle behavior within the bulk, one needs the local inertial number, but also a new dimensionless number that we call the layer number [5].

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Interstitial fluid effects on the dynamics of dense granular flows

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The dynamics of gravity driven dense granular flows are investigated in a rotating cylinder assembly for different flow rates and in presence of interstitial fluids of varying viscosities. Exper- iments are performed in a cylinder half-filled with a model granular material - glass beads of size 1 mm with the remainder filled with an interstitial fluid. All the measurements are carried out at the center of the cylinder where the flow is fully developed. The flow is imaged using a high speed camera, the particle positions are identified very accurately and tracked over long durations to obtain mean and fluctuating properties. One of the liquids is chosen to have the same refractive index as the particles to allow imaging in the bulk away from the end walls. A small amount of fluorescent dye is added and slices of granular flow at different distances from the end walls are visualized using a thin laser sheet.

The mean velocity near the wall shows near-linear behavior across the entire flowing layer for all cases studied. With air as the interstitial fluid, the mean velocity decays exponentially with depth in a small region near the base. Increasing the interstitial viscosity leads to a shrinkage of this region. Qualitatively similar profiles are obtained at different distances from the wall with the magnitude increasing upto a distance of 15 d. The r.m.s. velocity profiles show similar trends. The flowing layer thickness and the dynamic angle of repose near the wall increases monotonically with increasing flow rates and increasing interstitial liquid viscosity. The angles decrease while flowing layer thickness increase with distance from the wall upto a distance of 15 d. The experimental data is compared with the predictions of the models by Khakhar et al. [1] and Jop et al. [2].

Acknowledgments

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Granular flows in the intermediate regime

Rheology of dense granular flows: regime bridging and implications for kinetic theory

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Using the discrete element method, simulations of simple shear flow of dense assemblies of soft, frictional particles have been carried out over a range of shear rates and volume fractions in order to characterize the rheology of granular flows in the inertial, quasi-static, and intermediate regimes. In agreement with previous results for frictionless spheres [1], the pressure in each regime is found to obey an asymptotic power law relation with shear rate. These relations are then used to construct a blended pressure model bridging the three regimes. Additionally, we model the shear stress ratio variation using two dimensionless groups: 1) the inertia number [2], which collapses inertial regime data at different volume fractions and shear rates, and 2) the ratio of the particle binary collision time to the macroscopic deformation timescale, which further corrects for the departure from inertial behavior. The pressure and shear stress ratio relations form a rheological model that, in the hard-sphere limit, can be written as a modified kinetic theory for dense granular flows. The primary features of this kinetic theory are the inclusion of (1) a critical volume fraction that depends on the interparticle friction coefficient and (2) a 'chain-length' correction factor to the energy dissipation equation to account for multi-body interactions [3], and (c) a correction factor to the shear stress equation to account for the development of a yield stress at close packing.

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Falling inside a superlight granular medium

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Daily experience tells us that a projectile impacting into a granular medium, invariably stops at some finite depth. Chain forces acting against the projectile and the energy dissipation due to friction are responsible for such stopping effect. Here we challenge such phenomenon by doing penetration experiments and Molecular Dynamics Simulations in 2 and 3D superlight granular systems. Two counterintuitive behaviours are observed: 1) above a critical mass, a projectile impacting into a granular medium endlessly sinks with a terminal velocity as if the medium were a simple fluid [1]; 2) several projectiles fall through the medium in a collective way following a cooperative dynamics, whose complexity resembles flocking phenomena in living systems [2]. We claim that the observed dynamics might give a clue for advancing the idea that hydrodynamics have an important role in granular systems.

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Particle size segregation and spontaneous levee formation in geophysical mass flows

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Hazardous geophysical mass flows, such as snow avalanches, debris-flows and pyroclastic flows, often spontaneously develop large particle rich levees that channelize the flow and enhance their run-out. Measurements of the surface velocity near an advancing flow front have been made at the United States Geological Survey (USGS) debris-flow flume, where $10m^3$ of water saturated sand and gravel are allowed to flow down an $80m$ chute onto a run-out pad. In the run-out phase the flow front is approximately invariant in shape and advances at almost constant speed. By tracking the motion of surface tracers and using a simple kinematic model, it was possible to infer bulk motion as incoming material is sheared towards the front, over-run and shouldered to the side. At the heart of the levee formation process is a subtle segregation-mobility feedback effect. Simple models for particle segregation and the depth- averaged motion of granular avalanches are described and one of the first attempts is made to couple these two types of models together. This process proves to be non-trivial, yielding considerable complexity as well as pathologies that require additional physics to be included.

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Collisions of wet particles

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Collisions of wet particles occur in natural phenomena such as avalanches, mudslides, and pollen capture. They are also important in industrial processes such as agglomeration, fluidization, and wet granular flow. Early work extended the Hertz theory for dry, elastic collisions to head-on, wet collisions between two spherical particles or a particle and a surface. It was called "elastohydrodynamics," due to the coupling between the elastic deformation of the approaching surfaces and the hydrodynamic pressure to squeeze the viscous fluid out from between them [1]. A key finding is the critical Stokes number, below which sticking occurs due to viscous dissipation and above which bouncing occurs (but with a reduced coefficient of restitution compared to dry collisions, due to the loss of a portion of the particle kinetic energy to viscous dissipation). The Stokes number is a ratio of particle inertia to viscous forces, $St = mv_0/(6\pi\mu a^2)$, where m is the reduced mass of the particles, a their reduced radius, v_0 their relative impact velocity, and μ the fluid viscosity.

In this presentation, we extend the earlier work to first consider head-on, wet collisions of three spherical particles, using a pendulum apparatus called the Stokes' cradle [2]. It is similar to the desk-top toy, Newton's cradle, except only three spheres are used and the two target spheres are coated with a thin layer of viscous liquid. Four different outcomes are possible (depending on which adjacent pairs stick together and which separate after collisions), and all four outcomes have been achieved by varying the impact velocity and liquid-layer thickness.

We next consider oblique collisions between wet particles [3]. Here, three different outcomes are observed: (1) "Stick" at small Stokes numbers, where the particles stick together due to viscous forces, (2) "Bounce" at large Stokes numbers, where the particles rebound apart due to elastic deformation, and (3) "Stick-Rotate-Separate" at intermediate Stokes numbers and large impact angles, where the particles initially stick together, rotate as a doublet, and then separate due to "centrifugal" forces. For both problems, modeling as well as experimental results are presented.

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Stability of granular asteroids

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Recent observations [1] have suggested that several of the near-Earth asteroids may be granular aggregates held together by self-gravity alone. This poses new challenges when attempting to un- derstand their origins and/or developing threat-mitigation strategies. As in fluids [2], gravitating ellipsoidal granular aggregates are unable to support all manners of spins and shapes. This fact may help us relate asteroids observational data to their internal structure. Equilibrium shapes and dynamical evolution into these shapes of these objects were investigated in [3]. The granular aggregates were modeled as rigidperfectly-plastic materials obeying a Drucker-Prager yield crite- rion and following an appropriate flow rule. Here we further constrain the possible shapes of these objects by investigating the stability of the proposed equilibrium regions.

As opposed to fluids, the transition of granular materials from solid-like to fluid-like behavior is often modeled via non-smooth constitutive laws. Thus, the material moves in and out of equilibrium also in a non-smooth manner, as, for example, in the case of a dry Coulomb slider. This precludes application of standard spectral stability methods. Furthermore, the fact that asteroids are freely rotating bodies demands extra care during a stability analysis. This leads us to explore the energy criterion of stability that tests stability by bounding the excess kinetic energy. We extend the energy criterion to freely-rotating systems comprising of pressure-dependent non-smooth materials. The criterion so developed is then applied to test stability of granular asteroids. Finally, the results are illustrated in the context of several known near-Earth asteroids.

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Packing structure of granular systems

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We investigate the ballistic deposition of granular particles and agglomerates of particles using a modified Fischer-Bölsterli Algorithm [1]. In the case of the unconfined deposition of particles from a circular dropping area on a flat plate, a heap is formed. Very large heaps are found to contain three new geometrical characteristics not observed before: they may have two external angles of repose, an internal angle of repose, and four distinct packing fraction (density) regions. Such characteristics are shown to be directly correlated with the size of the dropping zone. In addition, we also describe how noise during the deposition affects the final heap structure [2].

The algorithm may be also applied to investigate the structural evolution of a nanopowder by repeated dispersion and settling which can lead to characteristic fractal substructures with robust statistical properties [3]. The agglomerate is cut into fragments of a characteristic size ℓ, which then are settling under gravity. Repeating this procedure converges to a loosely packed structure, the properties of which are investigated: (a) The final packing density is independent of the initialization, (b) the short-range correlation function is independent of the fragment size, and (c) the structure is fractal up to the fragmentation scale ℓ.

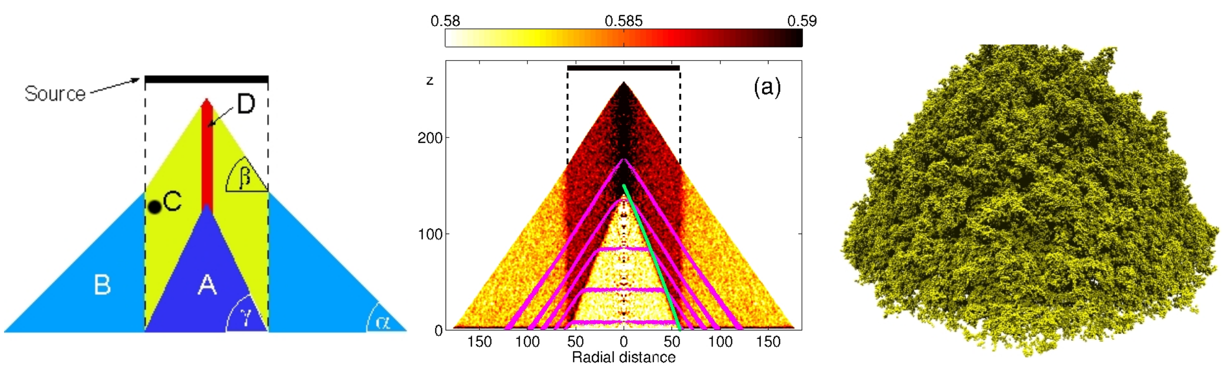

Figure 1: Large heaps from area sources reveal 4 zones of different density and 3 characteristic angles (left and middle). Fractal sediment of nano-particles (right)

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Rapid granular flows

Transition in a dense granular flow.

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The effect of base roughness on the flow down an inclined plane is studied using the discrete element method (DEM), in which the interaction force between particles is modeled using a spring-dashpot model in which the force due to deformation consists of a spring force proportional to the relative displacement of the surface of contact between the both parallel and perpendicular to the surfaces, and a damping force proportional to the relative velocity. The simulations are carried out using the open source code, LAMMPS (Large-scale Atomic Molecular Massively Parallel Simulator). The base consists of a random configuration of frozen particles, and the base roughness is varied by varying the ratio of the diameters of the frozen and moving particles. As the base particle diameter is decreased, a discontinuous change is observed in both the relative arrangement of particles and in the flow dynamics at a critical base particle diameter. Above the transition particle diameter, the relative particle arrangement is disordered, the flow is less dense (volume fraction 0.59 or less), whereas below the transition diameter, the particles flow in the form of layers sliding past each other, with hexagonal ordering within the layers, and the flow is more dense (volume fraction in the range 0.62-0.64). In both regimes, it is found that Bagnold law is valid, and the stress is proportional to the square of the strain rate. However, the Bagnold coefficients (ratio of stress and square of strain rate) are higher, by more than an order of magnitude, in the disordered state in comparison to the ordered state. The physical basis for the transition will be discussed using both theories for flow instabilities in homogeneous fluids, as well as the instability of a layered flowing structure.

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Orientational order and alignment of elongated particles induced by shear

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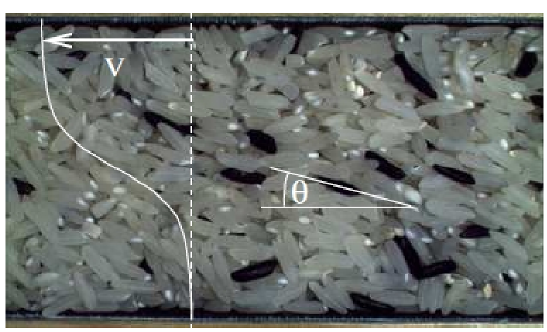
Flow of large ensembles of elongated objects — often observed in nature or industry — usually induces pronounced alignment of the building blocks. This phenomenon is found at all length scales, in log jams on rivers, in seeds, nanorods, viruses, and even at molecular scales in nematic liquid crystals. On one hand, such alignment processes are poorly characterized for macroscopic objects, even though granular flows have been extensively studied in the last two decades. On the other hand, shear alignment and collective reorientation dynamics is well documented and exploited at molecular scale (for nematic liquid crystals) and can be described quantitatively by continuum theory. Here we show that shear alignment of ensembles of macroscopic particles is very similar to molecular systems, despite the completely different types of particle interactions. We demonstrate that for dry elongated grains the preferred orientation forms a small angle θ with the streamlines (*see the image below*), independent of shear rate across three decades. This angle decreases with increasing aspect ratio of the particles. The shear-induced alignment results in a considerable reduction of the effective friction of the granular material.



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The second normal-stress difference in avalanching granular flows

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Granular avalanches on an open slope form channels, where a flowing region is bounded by quasi- static levees. Current theories are inaccurate for these flows because they contain static and flowing regions at depths close to h_{stop} [1]. The dimensions of the unconfined channels and the relations between the flowing and static regions provide insight on the rheology of the flow [2]. Previous work [3] highlighted laboratory experiments of unconfined shallow granular flows featuring a curved free surface in the flowing regions, bounded by static margins exerting lateral stresses on the flow. As the velocity profile and the height of the margins are self-similar, the rheological parameters cannot be uniquely determined, since the lateral stresses and flow depth both effect the velocity.

The current study investigates the characteristics of a flowing granular material down a low-angle V-shaped inclined plane under the action of gravity. The long-wave (shallow water) approximation relates the geometry of the flow directly to the slight V-shaped angle and therefore the depth dependence of the velocity can be decoupled from the lateral stresses.

Carefully performed laboratory experiments (panel a) show that the surface of the flow, steady both in time and down the slope, has significant curvature caused by second normal-stress differ- ences, similar to those observed in non-Newtonian fluids such as granular suspensions [4]. The curved top surface may be up to 30 % higher than the margins of the flowing region. The DEM simulations (panel b) show a similar surface profile, but also reveal details about the internal flow structure featuring a down-welling region in the middle and up-welling of material along the edges. Theoretical calculations involving a new granular theory explaining surface curvature across a slope on a flat surface [5] may be easily adapted to include the V-shape geometry. Experiments and numerical simulations validate the new theoretical model relating the height and velocity of the flow directly to the V-shape angle.

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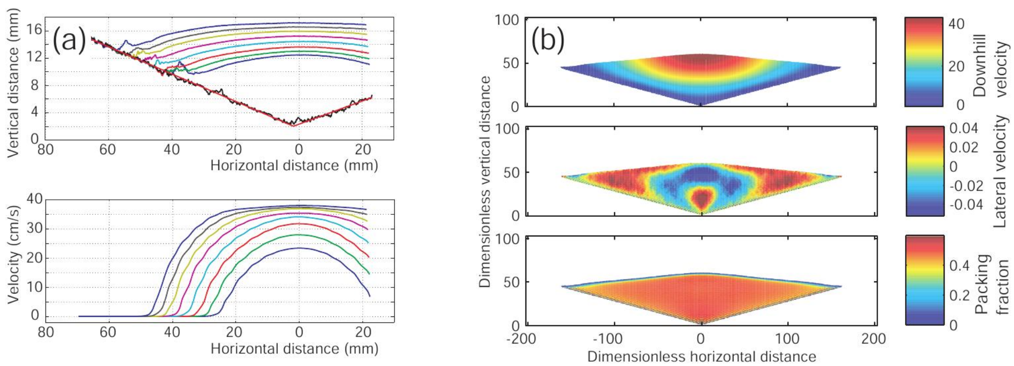

Figure 1: Steady granular flow down a V-shaped channel: (a) experiments with V-angle 11 degrees and slope angle 32 degrees. Surface heights and velocities for different flow rates, (b) velocity and density cross-sections from DEM simulations of a 15 degree V-angle on a 35 degree chute.

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Nonlinear analysis for a sheared granular flow: relaxation to a steady state and response around a steady state

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Granular flow under a plane shear is the simplest and the most appropriate situation to understand *unusual* nature of granular hydrodynamics. In this talk, we present the current achievement through our stuy on the shared flow for moderate dense granular gases. This talk consists of the following three parts.

In the first part, we briefly verify the validity of a set of granular hydrodynamic equations derived from the granular kinetic theory e.g.[1] from the direct comparsion with the result of molecular dynamics simulation.[2] It is rather surprised that the granular hydrodynamics can reproduce shear band formation even if very dense region exists.

In the second part, which is the main part of this talk, we develop the weakly nonlinear anaysis of a two dimensional sheared granular flow after a uniform sheared state becomes unstable.[3] Here, we have derived the TDGL equation starting from a set of granular hydrodynamic equations. Through our analysis the appearance of a nonlinear state is characterized by a supercritical bifurcation in the dilute case but by a subcritical bifurcation for denser case.

In the last part, we discuss the response theory around a NESS of sheared granular flow based on the adiabatic approximation and the complete counting statistics.[4] Through this analysis, we demonstrate what the essential differences is between the response theory around an equilibrium state and the response theory around a NESS. It is remarkable that the response theory around a NESS depends on the protocol, i.e. the path of the changing the shear rate.

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From particles to continuum theory: shear-bands, jamming and dilatancy

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From molecular dynamics simulations of many atoms or particles, one can extract scalar fields like density or temperature, as well as velocity, i.e. vectorial fields, or tensors like stress, strain, and structure (fabric). Given sufficiently good statistics the data can have a quality that allows to derive constitutive relations about the rheology and flow behavior of complex fluids (like atoms confined in nano-geometry, or granular particle systems) that behave strongly non-Newtonian, with particular relaxation behavior, anisotropy etc. With attractive forces involved, this leads to cohesion added on top of the already non-trivial dynamics of granular matter. Dependent on the energy input (shear-rate), the particles can flow like a fluid, jam and un-jam, or be solid with a very interesting anisotropic structure (contact-and force-networks). The interplay between strain, stress and anisotropy leads to dilatancy and an interesting memory of the packing: the evolution of anisotropy is independent from anisotropy of stress, both in evolution rates as well as in direction, i.e., tensorial eigen-system orientations.

The presentation will show the basic approach to coarse graining following the ideas of Isaac Goldhirsch [3] towards the micro-to-macro transition towards constitutive relations obtained from micro/atomistic/particle simulations. Examples involve the split-bottom ring shear cell and inclined plane avalanche flows.

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Turbulent fluid-particle flows

Segregation of particles in incompressible random flows: singularities, intermittency and random uncorrelated motion

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The transport of particles/droplets dispersed in turbulent flows is of crucial importance to a wide range of natural and engineering processes. In this theoretical and numerical study, we focus on the transport of heavy particles in an incompressible gas flow and exploit a Full Lagrangian method to measure the statistical properties of the particle segregation. While doing so, we are able to analyse some particular features of this ongoing process, and in particular to study the statistics of singularities in the particle concentration field and the recently observed Random Uncorrelated Motion (RUM): the velocity of particles with large inertia brought into close proximity may be strongly decorrelated not only with the flow but one with another.

In our recent work (IJzermans et al, 2009 and 2010), we have studied the segregation of heavy particles in turbulence by calculating the rate-of-compression of the particle phase in a kinematic simulation. Particles are advected by Stokes drag in a flow field composed of 200 random Fourier modes. The volume occupied by the particles centred around a position x at time t is denoted by J = det(J_{ij}), where $J_{ij} = \partial x_i x_0 / \partial x_{o,j}$, where x_0 denotes the initial position of the particle. The particle-averaged compressibility, $\zeta = d < ln|J| >= dt$, gives a measure for the change of the total volume occupied by the particle phase. Numerical results showed that the particleaveraged rate-of-compression decreases continuously if the value of the Stokes number (the dimensionless particle relaxation time) is below a threshold value, $St_c r$, indicating that the segregation of these particles continues indefinitely. We find that the probability density function of $ln|J|$, the compression, tends to a Gaussian distribution for $St \sim 1$ when $t \to \infty$. We believe the explanation for Gaussianity is similar to that for the occurrence of a Gaussian distribution of displacement (Taylor, 1922), with $\zeta'(t)$, the fluctuating value of $\zeta(t)$ about its mean. However, we find that that such PDF shows a significant skewness towards negative compression (segregation), i.e. singularities in the flow are likely to play a significant role in determining the statistics of the segregation in these long term limit

By counting events for which $|J(t)| = 0$, we can calculate the distribution of singularities over a fixed interval of time respectively for a set of St numbers. As shown in Figure 1 for $St = 1$, excluding the influence of an initial transient when no singularities are observed, the histogram that represents the discrete probability distribution is well approximated by a Poisson distribution that describes the probability of the

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occurrence of an event (singularity) in a specified time span $[0; \Delta t]$ as $\sim \lambda \Delta t = \Lambda$; λ is the rate constant for the occurrence of singularities. The Poisson process implies that starting from some initial fully mixed equilibrium distribution, the decay in the number of particles that have not experienced a singularity is $\sim exp(-\lambda t)$.

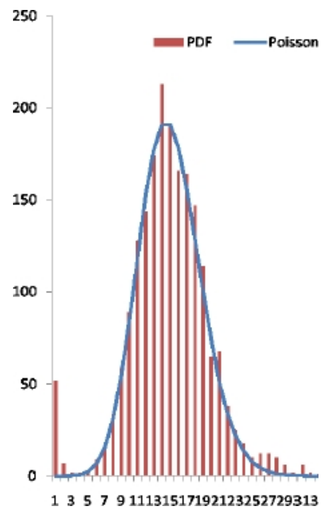

Figure 1: Comparison between theory and experimental data.

Finally, we discuss our work in relation to that of Falkovich & Pumir, 2007 and Wilkinson *et al*, 2007 and conclude that the occurrence of singularities is related to the formation of caustics and sling effect respectively, since it corresponds to the folding of the particle velocity field in phase space. We believe that RUM and singularities are intrinsically related and we are currently working to find a suitable way to demonstrate such theory from a mathematical and numerical point of view.

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Numerical model for the motion of a large object in dense gas-solid flows

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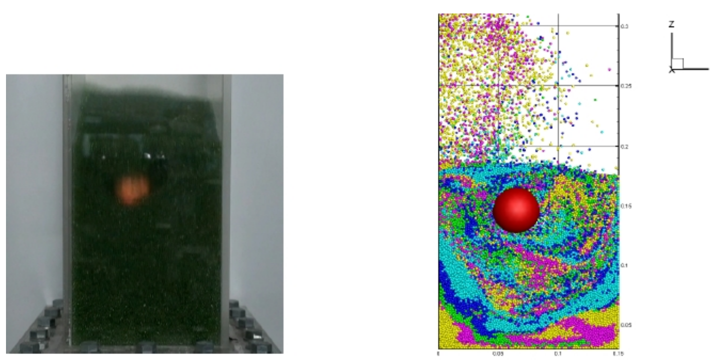
Tsuji et al. [1] proposed a DEM-CFD coupling method in which DEM for the simulation of particles motion is coupled with locally averaged Navier-Stokes equation to simulate the flow in gas-fluidized bed, and well predicted the formation of bubbles observed in the experiment. In this coupling method, the space resolution of fluid motion is taken to be larger than the particle size but smaller than the meso-scale structures such as bubbles formed in gas-fluidized bed. In many practical applications of fluidized bed, solid objects much larger than the particles of fluidized medium exist in the beds. These systems can not be treated by the original DEM-CFD coupling method and require a new model for the large objects.

In the present study, we propose a numerical model which expresses the motion of a large object in fluidized bed based on the DEM-CFD coupling method. The model is highly inspired by the volume penalization method and the interaction force between the fluid and large object is expressed by assuming that the large object is composed of dense small virtual particles. In this study, the motion of a sphere in a bubbling fluidized bed is numerically simulated by using the present model and the results are compared with the corresponding experiments. It was found that the present model well expresses the behavior of the sphere observed in the experiment (FIG. 1).



(a) Experiment (b) Simulation

Figure 1: Snapshots of the motion of a large sphere in gas-fluidized bed.

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Particle dynamics in a turbulent particle-gas suspension at high Stokes number

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The 'fluctuating force' model has been developed to capture the effect of turbulent fluid velocity fluctuations on the particle phase in a turbulent gas-solid suspension in the limit of high Stokes number, where the particle relaxation time is large compared to the correlation time for the fluid velocity fluctuations. The force exerted by the turbulent fluid velocity fluctuations, considered as anisotropic Gaussian white noise, is incorporated in the equation of motion of the particles. The noise amplitude is determined from the time correlations of the spatially varying and nonisotropic turbulent fluid velocity fluctuations obtained from Direct Numerical Simulations (DNS). The particle velocity distribution in the gravity driven flow in a vertical channel is analysed using a Langevin formulation for the force due to turbulent fluctuations, and the results are compared with DNS simulations incorporating one-way coupling (the force due to turbulent velocity fluctuations on the particle is incorporated, but not the reverse force due to the particle on the fluid turbulence). For monodisperse particles, there is quantitative agreement between the fluctuating force simulations (FFS) and DNS simulations, provided the time correlation of the fluid velocity fluctuations is calculated in a 'moving Eulerian reference frame moving with the fluid mean velocity. Comparisons are also made with experimental measurements of the particle velocity distributions using PIV and Particle Tracking Velocimetry. Good agreement is obtained only if the polydispersity in the particle size distribution is incorporated in the FFS. At lower mass loading (0.19), there is no significant modification of the fluid phase turbulent intensity, and the particle velocity distribution is well predicted by the FFS with one way coupling. At a higher particle mass loading of 1.7, there is a significant increase in the turbulent velocity fluctuations due to the particles. It is then necessary to incorporate the modified fluid turbulence intensity in the fluctuating force simulation.

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Dynamic flow structure in multiphase systems using single radio-labelled particle tracking

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Mobile particulate systems are of general interest in the multiphase reactor engineering community, owing to their wide applicability as reactors and separators in the petroleum refining and downstream process industry. The flow pattern in these ”real-world” systems is considerably more complex than what may be achieved in sanitized laboratory environments; consequently rigorous theoretical treatment of the flow in such systems is as yet elusive. This limitation poses a cap on predictive scale-up of such industrial vessels, whose design is primarily based on average flow rates, or more recently, on profiles of velocity and volume fraction of the phases [1]. The fluctuations in the flow, generally multi-scale is nature, are not characterized well and thus that information is not incorporated into design and scale-up protocols today.

Radioactive Particle Tracking (RPT) ([2], [3]) has become popular in recent decades as a method for probing the velocity fields in opaque, multiphase systems non-invasively. The basic idea in this method is to track the motion of a single tracer particle (made radioactive by incorporation of a suitable isotope) over many realizations of the flow, and then deriving ergodic means of the velocity profiles, RMS velocities, etc. In the past (e.g. [2]), most of the data treatment of RPT was done by projecting the data onto an Eulerian grid, since that was thought to be most useful from a reactor engineering perspective and also as validation data for CFD and other models.

In this presentation, the focus will be on RPT data treatment using the theory of non-linear dynamical systems. The time-series of the tracer location, which is of Lagrangian nature, serves as a ”signature” of the flow pattern and indeed, the flow regime that exists in the multiphase system. Using the theory of non-linear dynamics ([4], [5]), distinct parameters that characterize the flow (such as Kolomogorov entropy) are evaluated, and their physical interpretation vis-a-vis the flow pattern and the underlying forces, is discussed. As examples, a gas-liquid system (air- water bubble column) and a gas-solid system (unary and binary fluidized bed) are taken.

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Living suspensions

Chemotactic catalytic colloids

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Phoretic motion uses stresses generated e.g. by electric fields to generate force-free propulsion [1]. Artificial phoretic swimmers create this field themselves [24] to propel themselves in a direction determined by the orientation of their surface patterns of reactivity and mobility, if the ambient reactant concentration is uniform. Can a polar active particle of this type discover and reorient itself with respect to an imposed gradient of reactant concentration? We show that it can, thus offering a theoretical construction of chemotaxis in reactive colloids. We calculate the dependence of the taxis on particle shape and patterning. We also examine the case when reaction product distribution evolves on timescales comparable to the particle reorientation time. Finally, we consider the effect of interparticle interaction between two such chemotactic particles.

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Hydrodynamic coordination of bacterial motions: from bundles to biomixing

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The fluid dynamics of a suspension of swimming organisms are interesting and important both at the scale of the suspension and at the scale of individual organisms. This presentation will address the dynamics at each of these scales.

Experiments with suspensions of swimming cells have revealed characteristic swirls and jets much larger than a single cell, as well as increased effective diffusivity of tracer particles. In this presentation we describe theory and simulations of hydrodynamically interacting microorganisms that may shed some light on the observations [1, 3, 2, 5]. In the dilute limit, simple arguments reveal the dependence of swimmer and tracer velocities and diffusivities on concentration. As concentration increases, we show that cases exist in which the swimming motion generates dramatically enhanced transport in the fluid. A physical argument supported by a mean field theory sheds light on the origin of these effects.

It is well known that many microorganisms propel themselves through their fluid environment by means of multiple rotating flagella that self-organize to form bundles. We examine the dynamics and parameter dependence of this process [4]. The initial stage of bundling is driven purely by hydrodynamics, while the final state of the bundle is determined by a nontrivial and delicate balance between hydrodynamics and elasticity. As the flexibility of the flagella increases a regime is found where, depending on initial conditions, one finds bundles that are either tight, with the flagella in mechanical contact, or loose, with the flagella intertwined but not touching. That is, multiple coexisting states of bundling are found. The parameter regime at which this multiplicity occurs is comparable to the parameters for a number of bacteria.

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Active suspensions under flow

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The measurement of a quantitative and macroscopic parameter to estimate the global motility of a large population of swimming biological cells is a challenge. Experiments on the rheology of active suspensions have been performed. Effective viscosity of sheared suspensions of live unicellular motile microalgae (Chlamydomonas Reinhardtii) is far greater than for suspensions containing the same volume fraction of dead cells [1]. We relate these macroscopic measurements to the orientation of individual swimming cells under flow. Moreover results concerning the coupling between flow and biased swimming of cells will be presented.

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Pair-correlations in a bacterial suspension

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I will present a calculation of the pair-correlations induced by hydrodynamic interactions in an isotropic homogeneous suspension of swimming bacteria. The bacteria are assumed to execute a run-and-tumble motion, as is typical of many species including E.Coli; wherein periods of smooth swimming (runs) are punctuated by abrupt and large changes in swimming direction (tumbles). The calculation of the pair probability is for a suspension of random tumblers, the statistics of the tumbling process in this case being entirely specified by τ, the mean-free-time between successive tumbles. The results will be presented for two limiting regimes. The first pertains to the region where the pair-separation (r) is much smaller than the mean-free-path, $U\tau$ (U being the swimming speed) of the run-and-tumble motion, so the orientation de-correlation due to tumbles may be neglected during a pair-interaction. The second regime corresponds to distances much larger than $U\tau$, in which case the pair-interaction occurs along diffusive trajectories. One may then use a multiple-scales analysis to obtain an averaged equation, governing the pair-distribution function in physical space, in terms of an effective drift velocity and a diffusion coefficient. If time permits, I will discuss details of the solution procedure when the dimensionless parameter ($r/U\tau$) is comparable to unity.

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Rheology of active suspensions: active rotors

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In this work, we conduct a numerical investigation on sheared suspensions of active particles on which a torque is applied: rotors. Particles are spherical, non-colloidal, mono-dispersed and neutrally buoyant. Sice the torque modifies particles rotation, we show that it can indeed strongly change the effective viscosity of semi-dilute or even more concentrated suspensions. We perform our calculations up to a volume fraction of 28%. And we compare our results to data obtained at 40% by Yeo and Maxey[1] with a totally different numerical method. Depending on the torque orientation, one can increase (decrease) the rotation of the particles. This results in a strong enhancement (reduction) of the effective shear-viscosity of the suspension. We construct a dimensionless number Θ which represents the average relative angular velocuty of the particles divided by the vorticity of the fluid generated by the shear flow. We show that the contribution of the particles to the effective viscosity can be suppressed for a given and unique value of Θ independently of the volume fraction. In addition, we obtain a universal behavior (*i.e.* independent of the volume fraction) when we plot the relative effective viscosity divided by the relative effective viscosity without torque as a function of Θ. Finally, we show that a modified Faxén law can be equivalently established for large concentrations

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The dynamics of active suspensions: effects of confinement and of concentration

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We use a kinetic theory and continuum simulations to study the emergence of coherent structures, large-scale flows, and collective dynamics in suspensions of motile particles such as swimming microorganisms or artificial microswimmers, focusing specifically on the effects of oxytaxis in confinement and of concentration.

First, we extend the previous kinetic model of Saintillan & Shelley [1] to account for oxytaxis using a run-and-tumble model, in which the swimmers change their tumbling frequency based on the temporal changes in the oxygen field they sample. Using three-dimensional numerical simulations, we study the behavior of such suspensions in thin liquid films surrounded by oxygen baths on both sides. As the microorganisms consume the dissolved oxygen, gradients form causing them to swim towards the free surfaces where the oxygen concentration is higher. We demonstrate the existence of a transition from one-dimensional dynamics (in the direction normal to the interfaces) in thin films to chaotic three-dimensional dynamics and pattern formation as film thickness increases. This transition, which is consistent with experimental observations, is shown to be associated with an enhancement of oxygen mixing and transport into the liquid.

Next, we investigate the effects of increasing concentration by including in the model a steric alignment potential in the spirit of the classic Doi & Edwards theory [2] for passive rod suspensions. We first present results from linear stability analyses, for both a uniform isotropic suspension and a uniform aligned suspension, and show that steric interactions lead to new modes of instability, including in suspensions of pullers (head-actuated swimmers), which are stable in the dilute limit. The linear predictions are then compared to fully non-linear three-dimensional simulations, and we characterize the long-time dynamics in suspensions of both pushers and pullers.

This work was done in collaboration with Amir Alizadeh Pahlavan (UIUC), Barath Ezhilan (UIUC), and Michael Shelley (NYU).

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Reaction-induced motion: chemical swimming, sailing and surfing

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The design of nanoengines that can convert stored chemical energy into motion is a key challenge of nanotechnology, especially for engines that can operate autonomously. Recent experiments have demonstrated that it is possible to power the motion of nanoscale and microscale objects by using surface catalytic reactions – so-called catalytic nanomotors [1]. The precise mechanism(s) responsible for this motion is(are) still debated, although a number of ideas have been put forth [2]. Here, a very simple mechanism is discussed: A surface chemical reaction creates local concentration gradients of the reactant (the fuel) and product species. As these species diffuse in an attempt to re-establish equilibrium, they entrain the motor causing it to move. This process can be viewed either as osmotic propulsion or as self-diffusiophoresis – or more figuratively as 'chemical swimming.' The concentration distributions are governed by the ratio of the surface reaction velocity to the diffusion velocity of the reactants and/or products. For slow reactions the reaction velocity determines the self-propulsion. When surface reaction dominates over diffusion the motor velocity cannot exceed the diffusive speed of the reactants. The implications of these features for different reactant concentrations and motor sizes are discussed and the theoretical predictions are compared with Brownian Dynamics simulations. We also show that it is possible to obtain directed reaction-induced motion by controlling the *shape* of the motor – 'chemical sailing' – which may lead to easier fabrication of nanomotors. Finally, when motors are confined to an interface they can 'surf' the reaction-induced concentration gradient. Through these mechanisms the motor is able to harness the ever present random thermal motion via a chemical reaction to achieve directed autonomous motion.

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Evaluation of proposed mechanisms for ciliary beating of eukaryotic cells

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The present study aims at understanding the beating mechanism of a cilium — a slender cylindrical appendage that propels eukaryotic cells. The core structure of the cilium, known as the axoneme, consists of nine microtubules doublet surrounding a central pair of microtubules. The dynein motors on the doublets generate active shear forces that are responsible for relative sliding and bending of doublets. Several theories have been put forward over the last several decades to explain the self-organizing beating nature of axoneme, i.e., how the axoneme can spontaneously generate a steady beat without any biochemical control. These theories differ in their predictions of the relation between the forces generated by the motors and the relative sliding of the microtubules. To test these theories we have determined both the forces generated by the motors and the rate of sliding of doublets. A slender body theory together with the experimental data on beating was used to first determine the distribution of the hydrodynamic force acting along the length of a cilium. This force distribution was then combined with the moments balance equation for active filaments to determine the forces generated by the motors. The shape of the beats also allowed us to determine the relative sliding of the doublets. Several different beat patterns were analyzed and the findings were compared with various theories. None of the existing theories appear to be satisfactory. A need for additional measurements will be discussed.

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Measurements of extensional viscosities of suspensions of motile microbes

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The effective viscosity of an active suspension of rod-like self-propelled particles in either shear or extensional flows is predicted to depend on whether particles push fluid away from their ends, or draw it inward. We study extensional flows of low-viscosity aqueous microbial suspensions with a novel capillary-breakup device that uses surface acoustic waves to create observable liquid bridges rapidly from microliter-sized sessile droplets. The dynamics of mid-filament necking of the liq- uid bridges of both live- and dead-cell suspensions are qualitatively similar to those observed for (Newtonian) standard glycerol-water mixtures. This permits extraction of effective extensional viscosities of cell suspensions by comparison with theoretical predictions of capillary breakup for Newtonian liquid bridges at arbitrary Ohnesorge number. In line with recent predictions for ac- tive suspensions, we observe that *Escherichia coli* "pusher" suspensions have a lower extensional viscosity than the corresponding dead-cell suspensions, while in *Dunaliella tertiolecta* "puller" sus- pensions, the behaviour is reversed. The observed concentration-dependence of active suspension viscosities is correlated with swimming motility characterized in terms of mean swimming speeds and diffusivities obtained through cell-tracking image-analysis of static suspension samples.

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Poster presentation

Segregation of circular disks in a horizontally vibrated tapered channel

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Segregation in a granular mixture under externally forcing conditions is a well-known phenomenon in nature as well as in industry. It is seen that when shaken along the x-direction in an inclined zig-zag channel, a mixture of rice and paddy segregates axially along the y-direction, with rice moving down and paddy upwards against gravity; see Fig. 1. The experiments show that the mixture first separates vertically along the z-direction, before segregating axially. It is observed, both experimentally and numerically, that upwardflow of the disks dominates its downward flow beyond a critical vibration frequency. The parameters that affect the critical frequency include base friction, the channel's inclination, its shape, particles' size and density ratios, and their material properties. We hypothesize that the segregation occurs because of the difference in the critical frequency corresponding to two different species. To this end, here we investigate on the effects of disks' size, their density, and the channel's inclination on the critical frequency.

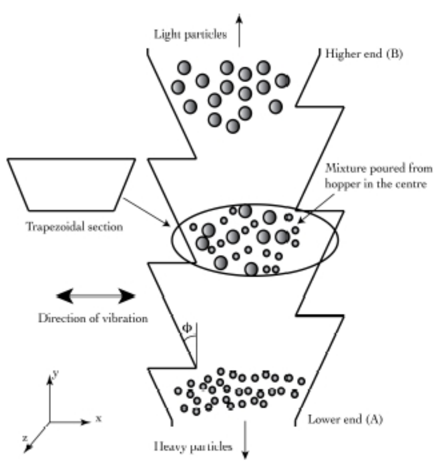

Figure 1: A schematic diagram showing the top view of zigzag channel. Reproduced from [1].

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Influence of particle shape on plastic granular flows

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How particle shape affects the complex rheology of granular materials is a vast topic which is now being increasingly addressed both experimentally and numerically. However, a systematic and quantitative investigation of shape-dependence is still largely elusive since particle shape character- istics such as elongation, angularity, slenderness and nonconvexity are described by distinct groups of parameters, and the effect of each parameter is not easy to isolate experimentally.

In this work, we introduce a low-order parameter η which describes the degree of distortion from a perfectly circular/spherical shape in 2D/3D. We shows that, for several simulated packings composed of different particle shapes (Fig. 1), the shear strength is an increasing function of η whereas the solid fraction increases first to a maximum value but declines as η increases. Another interesting finding is that the effect of specific shape parameters (angularity, nonconvexity, elonga- tion,...) is of second order. Performing an additive decomposition of the stress tensor based on a harmonic approximation of the angular dependence of contact normals and forces, we show that the increasing mobilization of friction force and the associated anisotropy are key effects of particle shape.

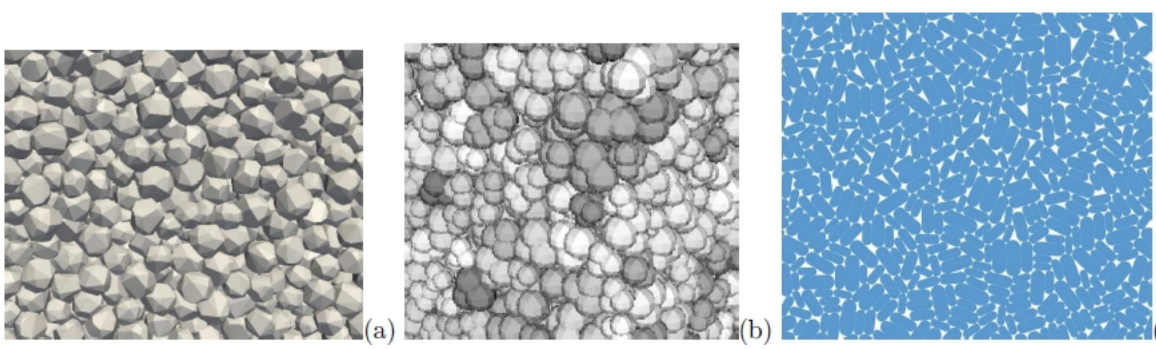
(a) (b) (c)

Figure 1: Snapshots of simulated systems: (a) polyhedral 3D, (b) non-convex 3D and (c) elongated 2D particles.

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Active viscosity of bacterial suspensions

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Active suspensions are fluids laden with self-swimming entities such as bacteria, algae or artificial swimmers. The self-propelled particles inject energy into the suspending fluid, leading to very different properties of active compared to passive suspensions. In particular, it has been predicted theoretically that the viscosity of suspensions of so called pushers can be reduced compared to the viscosity of the suspending fluid [1,2].

Pioneering experimental measurements have confirmed that finding [1], but no bulk rheological experiments at controlled shear rates exist up to date. Here we present experiments measuring the viscosity of a wild type E-Coli suspension. To this purpose, we use a Y shaped micro-fluidic channel as a rheometer [3] allowing us to resolve small differences between the viscosity of the suspending fluid and the active suspension at low shear rates and with a high resolution. We systematically vary the shear rate and the bacterial density. In this way we show that in a specific range of parameters the viscosity of the active suspension is lower than the viscosity of the suspending fluid. We discuss our results in the perspective of recent theoretical and experimental works [1, 2].

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Gradient Monte Carlo: a high throughput method for computing thermodynamic properties

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There are many physical situations involving external fields or a nonisothermal environment. Monte Carlo (MC) simulations can be useful to understand such experimental systems at steady state. In this context, we formulate a general framework to study these systems via inhomogeneous MC simulations[1] incorporating spatially varying temperature and gravitational fields. Using this approach, we study hard spheres in an external field with either uniform or nonuniform temperature. We present comprehensive results from our MC simula- tions, and compare these with theoretical results based on the CarnahanStarling equation of state.

We consider next the case of mixtures of hard spheres and propose a new method for calculating the chemical potential of each species. The results are compared to chemical potentials computed using the classical Widom particle insertion method for a spatially uniform system.

The Gradient Monte Carlo method proposed enables us to access a wide range of pressuredensity values (states) in a single simulation and is a useful approach for high throughput computations of thermodynamic properties.

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Validation of constitutive models for C-Φ materials at multiple length scales

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Mechanical behavior of granular materials is predominantly governed by the inter-grain inter- action and friction. Cementation or cohesion(C), which often exists between the grains, also has a significant effect on their mechanical behavior. Geomaterials, such as cemented sands or soft rocks are a classic example of such C-Φ materials, where geological processes (deposition and subsequent aging) aid in building the cohesion between the grains. Cohesion can also be imparted in materials like powders due to environmental effects.

The strength of cemented granular materials is due to cementation bond strength between the grains and the frictional resistance of the grains. One of the simplest constitutive model for a C-Φ material is akin to a visco-plastic solid model (such as Kelvin model), where the cohesive component(C) is represented by a spring and the friction(Φ) between particles is represented by a dash-pot. An experimental study has been made to examine validity of this constitutive model for these C-Φ materials at multiple length scales(Figure 1). The model granular material used for this study is a cemented sand reconstituted from naturally found Cauvery delta sand of mean grain size 0.45mm and ordinary Portland cement. A series of uniaxial compression and extension tests are performed on cylindrical specimens of various diameters, at the same aspect ratio. The strength of the cohesive component in both compression and extension is determined from the peak of the true stress-strain plot. A few tests are performed using a micro indenter to quantify the magnitude of this cohesion at the inter-granular scale, and to validate the constitutive model at multiple length scales.

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Prediction of saltation velocity in pneumatic conveying system

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Saltation of particles during pneumatic transport is investigated using numerical simulations. Coupled CFD-DEM (Computational Fluid Dynamics and Discrete Element Method) technique is employed to simulate the dynamics of the gas-solid mixture. In this method, the equation of motion for individual particle is coupled with the continuum description of the momentum conservation of the fluid phase. The well known spring dashpot model is used to describe the inter-particle as well as the wall-particle collisions. The spring constants are determined following the Hertzian contact theory. Simulations are performed using the open source software MFIX (Multiphase Flow with Interphase Exchanges). Influence of the physical properties such as the size and the elastic modulus of the particle and the ratio of the solid to the fluid density on the saltation condition, is studied. A plausible reason behind the existence of a critical particle diameter beyond which the saltation velocity decreases with the increase in the particle size, will be presented.

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Size segregation of granular particles in a 2d system under vertical vibration

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An extremely intriguing phenomenon in granular matter research is size segregation under vertical vibrations [1, 2]. Contrary to intuition, a disordered mixture when subject to vertical vibrations, tends to order where large particles in a bed of small particles, typically rise to the top [15], giving rise to the so-called Brazil nut effect (BNE). We experimentally study the dynamics of a large particle in a quasi-two-dimensional rectangular cell packed with small grains. The large particle, which is initially kept at the bottom, rises upward when the column is vibrated. We track the motion of the large particle using high speed video imaging and analyze our data to estimate the rise time. We see that the peak-to-peak velocity of shaking, rather than the peak-to-peak acceleration, is the relevant parameter for describing the results.

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Caging dynamics in colloidal glasses of laponite

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The glassy state refers to an out-of-equilibrium, disordered state of matter which originates due to the jamming or freezing of the constituents comprising the system. In this jammed or frozen state, the motion of the constituents appears to be arrested and the dynamics of the system continues to slow down with time in a phenomenon known as "aging". Colloidal glasses are soft glasses (i.e. they have a very low shear modulus when compared to hard glasses) and exhibit all the properties typically expected in hard glassy materials, for example, jamming, disorder and non-equilibrium aging behavior. We study glass formation in the context of aging colloidal suspensions prepared by dissolving a glass former (Laponite- a synthetic hectorite clay) in deionized water. In colloidal glasses, the constituent particles or clusters are trapped in cages formed by their neighbors, which restricts their motion and slows down their dynamics. Such caging dynamics, whose time scales are typically expected to be 1-100 μs, was studied by Dynamic Light Scattering (DLS) experiments. The intensity autocorrelation function (ACF) exhibited by a glassy Laponite suspension has a stretched exponential form due to the presence of competing relaxation rates in the system. The origin of this non-exponential decay in aging colloidal glasses is investigated further by performing rheology, mobility and conductivity experiments. A simple toy model is developed to understand the results.

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Inertial particles in leap-frogging vortex-pair flow

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Volumetrically heated jets and plumes have been found [1] to have greatly reduced entrainment and more mixing in the core. This cut-off of entrainment is thought to lead to the greater heights achieved by clouds in comparison with unheated jets or plumes. A toy-model for these flows can be constructed using leap- frogging point-vortex pairs (LFVP), where the effect of heating (i.e. addition of buoyancy) is modelled as an increase in the velocity of the point-vortices. The stable and unstable manifolds of these systems are found to intersect (infinitely many times) which, since the manifolds are impenetrable, means that fluid is entrained and detrained from the active region. The entrainment has been found to weaken with the addition of buoyancy [2,3].

The aforementioned studies used tracers to study the flow of the fluid medium. Here, we use inertial particles to study what happens to water droplets in clouds. Particle inertia is simulated using a non-zero response time, which is equivalent to postulating a Stokes-drag on the particle [4]. The effects of the particles on the flow are neglected. The resulting ordinary differential equations governing the kinematics are integrated numerically using fourth order Runge-Kutta time-stepping.

We do not know whether manifolds in dissipative systems such as this one are impenetrable. However, we find that the stable and unstable manifolds enclose smaller areas between intersections with increasing inertia, indicating that the entrainment is reduced. Beyond a certain inertia, there are no intersections (Figure 1). This indicates that inertial particles that start out inside the region bounded by the manifolds remain inside for long periods of time. In addition, our simulations also show that there are large regions with few or no inertial particles, with the inertial particles collecting into an annular region. (Figure 2).

Our ultimate aim is to understand how water droplets and turbulence interact in a cloud, and whether this interaction can affect the lifetime of a cloud significantly. Droplets of water in clouds are known to have sizes in the 10-200 m range [5], which puts them in the Stokesian regime. Volumetric heating in clouds is provided by the release of latent heat upon condensation of water vapour. Since water droplets act as nuclei for further condensation, the kinematics of water droplets modelled as inertial particles may tell us how much condensation to expect. A more complete study will be presented at the meeting.

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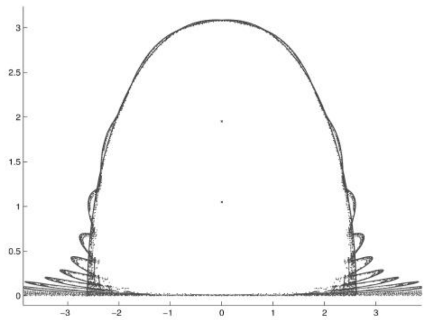

Figure 1: Intersections of the stable and unstable manifolds

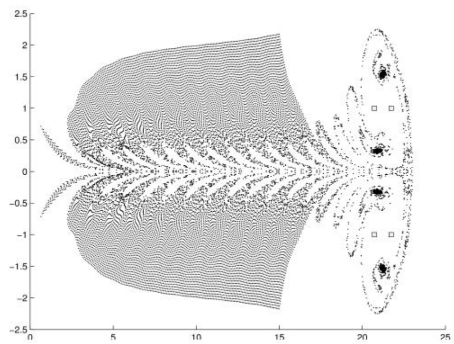

Figure 2: Particles entrained by the LFVP

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Drop deformation and dielectrophoresis in quadrupole fields for perfect dielectric systems

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We conduct a detailed non-linear analysis of the deformation and breakup of a perfect dielectric (PD) drop, suspended in another perfect dielectric fluid, in the presence of a quadrupole electric field is presented using analytical (asymptotic) and numerical (Boundary Integral) methods. The quadrupole field is the simplest kind of an axisymmetric non-uniform electric field. Several novel features are observed as compared to that of a drop under a uniform electric field. The first order analysis predicts oblate deformation for a PD-PD system when the dielectric constant of the suspending medium is larger than that of the drop ($Q = \epsilon_i/\epsilon_e < 1$). This is in contrast to uniform electric fields where oblate shapes are observed only in leaky dielectric (LD-LD) systems. Prolate shapes are observed for $Q > 1$, and the deformation is larger than that for uniform fields for similar electric capillary numbers. The steady state shapes are defined by several higher harmonics as compared to the uniform field. At large capillary numbers, prolate deformations ($Q > 1$) show breakup whereas oblate deformations ($Q < 1$) do not. Positive and negative dielectrophoresis is observed when the drop is placed off center, and its translation and simultaneous deformation under quadrupole fields is also investigated. The electro-hydrostatics is unaffected by the viscosity ratio. However, the break-up of the drop and the dielectrophoretic motion and deformation strongly depend upon the viscosity ratio.

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Fingering-like instability in suspension of vesicles

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Finger like pattern occurs in an interface when a liquid of lower viscosity or higher density is pushed through another immiscible or miscible liquid of higher viscosity or lower density. Viscous fingering phenomena is well understood by the Saffman-Taylor instability mechanism. Here we report an observation of a fingering like phenomena that occurrs when an aqueous suspension of vesicles is in contact with water. Unlike in the regular viscous fingering case, the vesicle suspension is of a lower bulk density and higher viscosity compared to water. Understanding this phenomenon has important consequences in the synthesis of vesicles by a coacervation technique and possibly to enhancement of mass transfer seen in nano-particle suspensions.

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