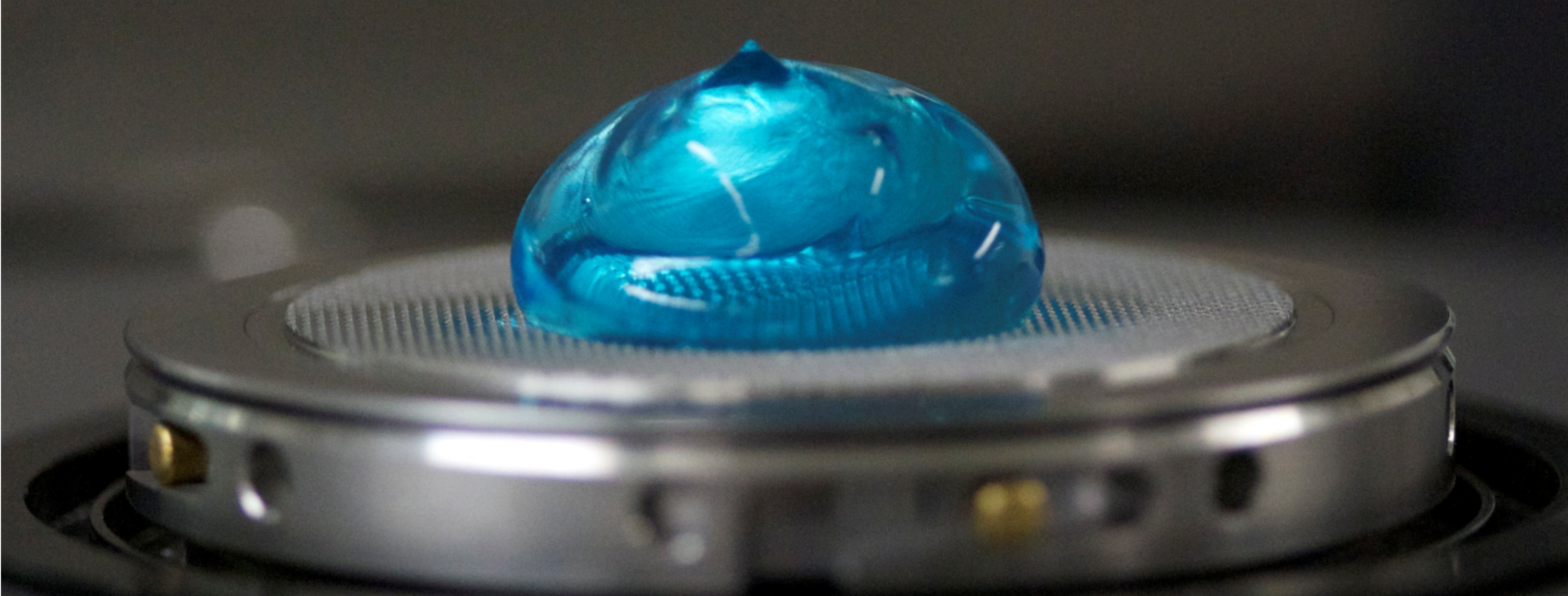
Viscoplastic Fluids

From Theory to Application VI

October 25 - 30, 2015

Banff International Research Station
for Mathematical Innovation and Discovery



PREFACE

BIRS is pleased to be hosting a workshop on Viscoplastic Fluids from Theory to Application. This is the sixth international meeting on this topic, and marks the 10th anniversary of the first workshop, which was held at BIRS in 2005. Viscoplastic materials behave as solids subject to a small applied force, but flow like a fluid when the applied force is large enough. Such materials are very common: in the home, mustard, hair gel, and face cream are all viscoplastic fluids. Heavy oils, slurries of mine tailings, fresh concrete, and wood pulp are examples from industry, while cooling lava and mud are environmental examples. Because of the broad range of applications of these materials, it is important to understand how they behave under a range of conditions, and the mathematics that describes their flow behavior and the transition from solid-like to fluid-like behavior is crucial.

Earlier workshops on Viscoplastic Fluids from Theory to Application have been held biannually since 2005, at BIRS (2005), Monte Verita (2007), Cyprus (2009), Rio de Janeiro (2011), and Rueil-Malmaison (2013). Like the previous meetings, this BIRS workshop will bring together mathematicians, engineers and scientists working on the fundamental aspects of viscoplastic fluids, and to connect them with those working on industrial and environmental applications. The meeting is expected to stimulate a broad and lively discussion of new theoretical developments, analytical and computational methodologies, new and existing applications, and growth in rheological understanding and modelling. In addition, a goal of the workshop is to collectively identify and discuss key open problems and areas for development, setting broad goals for the field over the next 10 years.

The Banff International Research Station for Mathematical Innovation and Discovery (BIRS) is a collaborative Canada-US-Mexico venture that provides an environment for creative interaction as well as the exchange of ideas, knowledge, and methods within the Mathematical Sciences, with related disciplines and with industry. The research station is located at The Banff Centre in Alberta and is supported by Canada's Natural Science and Engineering Research Council (NSERC), the U.S. National Science Foundation (NSF), Alberta's Advanced Education and Technology, and Mexico's Consejo Nacional de Ciencia y Tecnologia (CONACYT).

BIRS Scientific Director, Nassif Ghoussoub
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Message from organizers

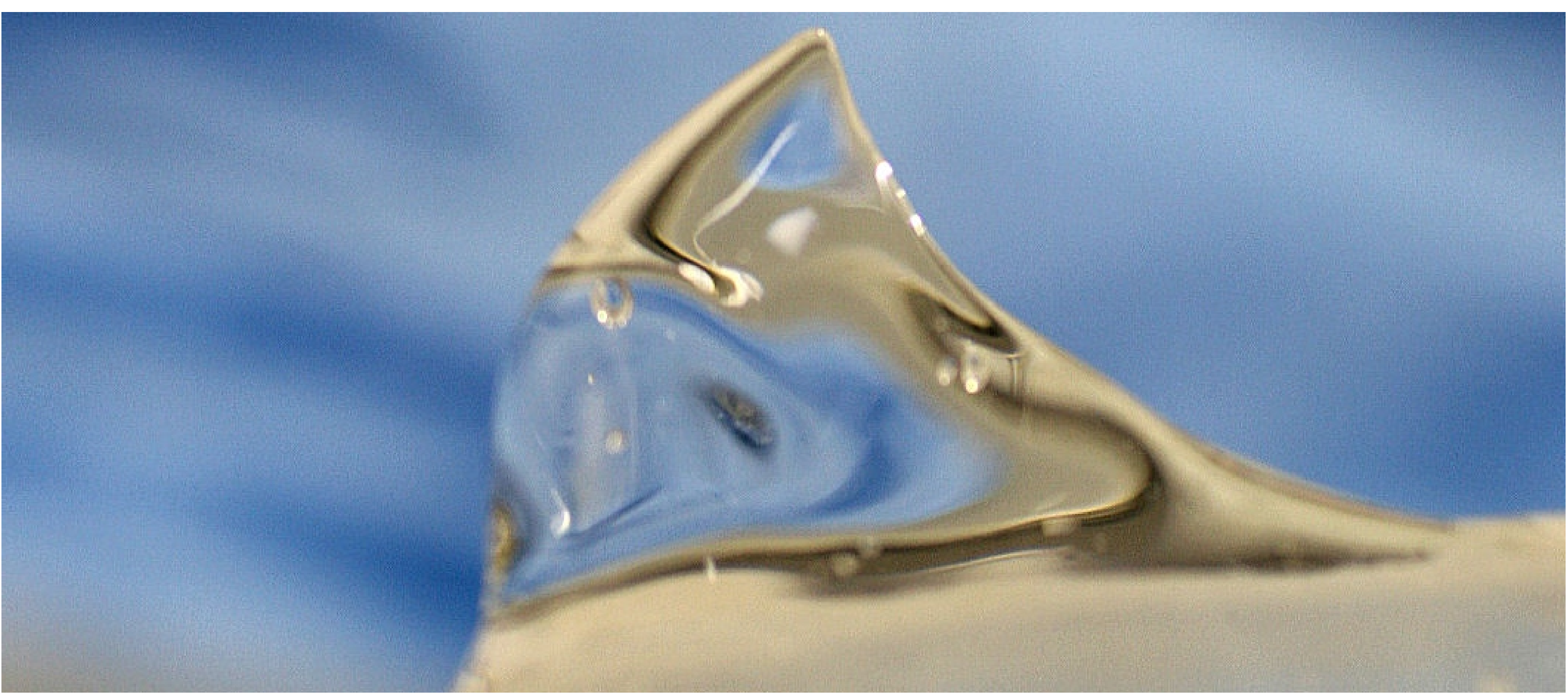
Welcome to Viscoplastic Fluids from Theory to Application. We are delighted to be organizing this 6th edition of this very successful biennial workshop series and in particular to back in Banff at BIRS where the series started. As a 10th anniversary treat, we have reproduced the group photos below from the 5 preceding workshops:

• VPF-1: Banff, Canada, October 22–27 October 2005
• VPF-2: Monte Veritá, Switzerland 14-18 October 2007
• VPF-3: Limassol, Cyprus, 1–5 November, 2009
• VPF-4: Rio de Janeiro, Brazil, November 6–10, 2011
• VPF-5: Rueil Malmaison, France, November 18–21, 2013

How many of these faces do you recognise? Isn't it amazing how some in these photos have not aged a bit, as fresh as plugs in a Bingham fluid. However, those who believe in phase transitions, structure,'panta rei' or elastic creep are showing predictable signs of thixotropic ageing.
The goal of these workshops is to promote interactions between people from the different communities working on viscoplastic fluids. We very much hope that you will join in collegial discussion, mild provocation and in sharing results and insights over the course of the next few days. We are very grateful to the Banff International Research Station for the opportunity to be here and for generous funding of the workshop.

With best wishes for a successful workshop

John de Bruyn (University of Western Ontario)
Ian Frigaard (University of British Columbia)
Sergio Gonzalez Andrade (Escuela Politecnica Nacional)
Ioan Ionescu (Universite Paris 13)
Miguel Moyers Gonzalez (University of Canterbury)



Banff, Canada, 2015

Monday at a Glance

Mon-A

Room: TCPL 201
Chair: Ian Frigaard

8:30-8:45 **BIRS Welcome**
Brent Kearney

8:45-9:00 **Thixotropy and our IKH model**
G.H. McKinley

9:00-9:15 **The yielding behavior of a waxy crude oil**
B.P.P. Forte, E.J. Soares and R.L. Thompson

9:15-9:30 **Modelling thixotropic yield stress fluids as a limit of viscoelasticity (Part I)**
M. Renardy

9:30-9:45 **Modelling thixotropic yield stress fluids as a limit of viscoelasticity (Part II)**
M. Renardy

9:45-10:00 **The mystery of Carbopol**
M. Dinkgreve, M. Fazilati and D. Bonn

10:00-10:15 **Planar squeeze flow of Bingham fluids**
L. Fusi, A. Farina and F. Rosso

Mon-B

Room: TCPL 201
Chair: Jim McElwaine

10:45-11:00 **Vibrating wire rheometry**
J.R. de Bruyn and C.C. Hopkins

11:00–11:15 **On different ways of measuring "the" yield stress**
M. Denn, J. Paredes, M. Dinkgreve, and D. Bonn

11:15-11:30 **Critical Conditions for Flow in Idealized Fractures**
A. Roustaei, T. Chevalier, L. Talon, I.A. Frigaard

11:30–11:45 **About the use of Carbopol gels as model yield stress fluids**
G. Ovarlez and P. Coussot

11:45–12:00 **A fluidity model for the mechanical description of thixotropic elasto-viscoplastic materials**
P.R. de Souza Mendes, R.L. Thompson, B. Abedi and L.U.R. Sica

12:00–12:15 **Yield limit of symmetric-particle motion in viscoplastic fluid**
E. Chaparian, N.J. Balmforth and I.A. Frigaard

12:15-12:30 **Design tools for yield-stress fluids: a rheology-to-structure inverse problem**
R.H. Ewoldt, Arif Z. Nelson

Panel Discussion

Room: TPCL 201 & 202
Chair:

14:00-17:00 **Constitutive behaviour and models around the yield stress**
Moderator: Paulo De Souza Mendes

14:00-17:00 **Hydrodynamic stability & analytical solutions**
Moderator: Raja Huilgol

Tuesday at a Glance

Tues-A

Room: TCPL 201
Chair: Ioan Ionescu

8:30-8:45 **Mesoscopic Model for Bingham Fluids and Mixed Convection Flows in a Lid Driven Cavity (Part I)**
R.R. Huilgol

8:45-9:00 **Mesoscopic Model for Bingham Fluids and Mixed Convection Flows in a Lid Driven Cavity (Part II)**
R.R. Huilgol

9:00-9:15 **Morphology of drop impact onto a viscoplastic gel**
S.Chen, V. Bertola

9:15-9:30 **Boundary Integral simulations of motion and deformation of visco-plastic drops in a non-isothermal viscous fluid**
O.M. Lavrenteva, I. Smagin, A. Nir

9:30-9:45 **Droplet impacts: when yield-stress fluids do and do not stick**
B.C. Blackwell, R.H. Ewoldt

9:45-10:00 **Multigrid Methods for Large-Scale Optimization Problems Arising in Viscoplastic Fluids Simulation I**
S. González-Andrade

10:00-10:15 **Multigrid Methods for Large-Scale Optimization Problems Arising in Viscoplastic Fluids Simulation II**
S. González-Andrade

Tue-B

Room: TCPL 201
Chair: John de Bruyn

10:45-11:00 **The sequencing of dynamic rheological measurements**
S.A. Rogers

11:00–11:15 **The settling of a spherical particle in Carbopol: Elastic effects are as important as yielding**
D. Fraggedakis, Y. Dimakopoulos and J. Tsamopoulos

11:15-11:30 **Particle settling in yield stress fluids: limiting time, distance and applications**
A. Wachs, I. Frigaard

11:30–11:45 **Principal Component Analysis of Particle Motion**
J.R. de Bruyn, H. Chen, R. Liégois and A. Soddu

11:45–12:00 **Fast and Exact: an accelerated dual gradient method for Bingham flow (Part One)**
T. Treskatis, M. Moyers-Gonzalez and C. Price

12:00–12:15 **Fast and Exact: an accelerated dual gradient method for Bingham flow (Part Two)**
T. Treskatis, M. Moyers-Gonzalez and C. Price

12:15-12:30 **Mechanical agitation of yield stress fluids**
J. Derksen

Panel Discussion

Room: TPCL 201 & 202
Chair:

14:00-17:00 **Numerical methods and computational modelling of viscoplastic flows**
Moderator: John Tsamopoulos

14:00-17:00 **Experimental methods: local behaviour, wall slip and visualization of complex flows**
Moderator: Randy Ewoldt

Wednesday at a Glance

Wed-A:

Room: TCPL 201
Chair: Neil Balmforth

8:30-8:45	**The Stokes boundary layer for a thixotropic or antithixotropic fluid** *S.K. Wilson, D. Pritchard, C.R. McArdle*
8:45-9:00	**LAOS for thixotropy and our IKH model** *G.H. McKinley*
9:00-9:15	**Rheopexy and tunable yield stress of carbon blacksuspensions** *G. Ovarlez, L. Tocquer, F. Bertrand and P. Coussot*
9:15-9:30	**Waxy Crude Oil transient behavior : a new modeling approach** *R. Mendes, G. Vinay, G. Ovarlez and P. Coussot*
9:30-9:45	**A Microscopic Gibbs field model for the macroscopic yielding behavior of a viscoplastic fluid** *T. Burghelea, R. Sainudiin, M. Moyers-Gonzalez*
9:45-10:00	**A Microscopic Gibbs Field Model for the Macroscopic Behavior of a Viscoplastic Fluid: a deterministic approximation** *M. Moyers-Gonzalez, R. Sainudiin and T. Burghelea*
10:00-10:15	**Thixotropic fluids: lubrication flow and reduced models** *D. Pritchard, S.K. Wilson, C.R. McArdle, A.I. Croudace*

Wed-B

Room: TCPL 201
Chair: Miguel Moyers-Gonzalez

10:45-11:00	**Inertia effects in viscoplastic flows** *N. Bernabeu and P. Saramito*
11:00–11:15	**Oscillatory flow past a circular cylinder** *A. Alexandrou, N. Kanaris, A. Demou, S. Kassinos*
11:15–11:30	**Investigation of wall slip in contraction flow of stiff viscoplastic materials** *M. Bryan, S. Rough, I. Wilson*
11:30–11:45	**Particle laden flow** *S. Lee*
11:45-12:00	**An issue regarding wall slip measurement in yield-stress (and other) materials** *M. Denn, M. Habibi, M. Dinkgreve, J. Parades and D. Bonn*
12:00-12:15	**Confined viscoplastic flows with heterogeneous wall slip** *P. Panaseti, G.C. Georgiou*
12:15-12:30	**Influence of slip on the flow of a yield stress fluid around a flat plate** *L. Jossic, F. Ahonguio and A. Magnin*

Thursday at a Glance

Thur-A

Room: TCPL 201
Chair: Sergio Gonzalez Andrade

8:30-8:45	**Rheological properties of model flocculated suspensions** *J. Fusiera, J.Goyona, F. Toussaintb, X. Chateaua*
8:45-9:00	**Dynamic settling of particles in a shear thinning fluid** *L. Childs and A. Hogg*
9:00-9:15	**Rheology of dense suspensions of non-colloidal spheres in yield-stress fluids** *S. Dagois-Bohy , S. Hormozi , É. Guazzelli and O. Pouliquen*
9:15-9:30	**Plastic failure of granular material in a drum** *J.N. McElwaine and N.J. Balmforth*
9:30-9:45	**Continuum viscoplastic simulation of a granular column collapse: rheology and lateral wall effects** *I.R. Ionescu, N. Martin and A. Mangeney*
9:45-10:00	**Universal rescaling of flow curves for yield-stress fluids close to jamming** *M. Dinkgreve, J. Paredes, M.A.J. Michels and D. Bonn*
10:00-10:15	**Shear-induced particle migration in a poly-dispersed concentrated suspension of particles in viscoplastic fluid** *O.M. Lavrenteva, A. Nir*

Thur-B

Room: TCPL 201
Chair: David Pritchard

10:45-11:00	**Displacement flows in a non-uniform channel** *S.M. Taghavi and R. Mollaabbasi*
11:00–11:15	**On the Diversity of Convective Regimes in a Silica Colloidal Dispersion: from Laboratory Experiments to Planetary Mantles (Part I)** *A. Davaille, E. Di Giuseppe, E. Mittlestaedt, M-C Renoult, F. Doumenc and L. Pauchard*
11:15–11:30	**On the Diversity of Convective Regimes in a Silica Colloidal Dispersion: from Laboratory Experiments to Planetary Mantles (Part II)** *A. Davaille, E. Di Giuseppe, E. Mittlestaedt, M-C Renoult, F. Doumenc and L. Pauchard*
11:30–11:45	**Thermal plumes in viscoplastic fluids: flow onset and development** *I. Karimfazli, I.A. Frigaard and A. Wachs*
11:45-12:00	**The viscoplastic behaviour of snow** *J.N. McElwaine*
12:00-12:15	**Shallow non-isothermal viscoplastic models for volcanic lava flows** *N. Bernabeu and P. Saramito*
12:15-12:30	**A new nonsmooth model for discontinuous shear thickening fluids** *J.C. De los Reyes and G. Stadler*

Panel Discussion

Room: TPCL 201 & 202
Chair:

14:00-17:00	**Yield stress fluid suspensions** *Moderator: Guillaume Ovarlez*
14:00-17:00	**Geophysical flows** *Moderator: Anne Davaille*

Friday at a Glance

Fri-A

Room: TCPL 201
Chair: Ida Karimfazli

8:30-8:45	**On the transition to turbulence in viscoplastic flows** *A. Alexandrou, N. Kanaris, A. Demou, S. Kassinos*
8:45-9:00	**Micropolar Bingham fluids (Part I)** *V. Shelukhin*
9:00-9:15	**Micropolar Bingham fluids (Part II)** *V. Shelukhin*
9:15-9:30	**Displacement of viscous liquids by a viscoplastic material** *H.M. Caliman, E.J. Soares, R.L. Thompson*
9:30-9:45	**A novel approach for modelling Bingham fluids in lubrication approximation** *L. Fusi, A. Farina, F. Rosso and S. Roscani*
9:45-10:00	**Viscoplastic Dambreaks** *N. Balmforth*
10:00-10:15	**Influence of the initial profile on statistical characteristics of roll waves trains in power-law fluid.** *C. Di Cristo, M. Iervolino, A. Vacca*

Fri-B

Room: TCPL 201
Chair: Xavier Chateau

10:45-11:00	**Obstructed and channelized viscoplastic flow in a Hele-Shaw cell (Part One)** *D.R. Hewitt, N.J. Balmforth, M. Daneshi, D.M. Martinez*
11:00–11:15	**Obstructed and channelized viscoplastic flow in a Hele-Shaw cell (Part Two)** *D.R. Hewitt, N.J. Balmforth, M. Daneshi, D. M. Martinez*
11:15–11:30	**Thermo-responsive polymeric solutions: From rheology to applications** *M. Jalaal, N.J. Balmforth, B. Stoeber*
11:30–11:45	**Thixotropic effects on Laponite start-up flows** *G. Moisés, L. Alencar, M.F. Naccache and I. Frigaard*
11:45-12:00	**Non-Newtonian Rivulet Flow** *S.K. Wilson, F. Al Mukahal and B. Duffy*

Monday Sessions, with Abstracts

Room: TCPL 201

Mon-A

Chair: Ian Frigaard

8:30-8:45 **BIRS Welcome**
Brent Kearney

8:45-9:00 **Thixotropy and our IKH model**
G.H. McKinley

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9:00-9:15 **The yielding behavior of a waxy crude oil**
B.P.P. Forte, E.J. Soares and R.L. Thompson

One of the main challenges of the production of waxy crude oils in basins located in deep water is when there is an interruption of the production. In this case, the oil is exposed to a low temperature environment below the gelation temperature. The set of conditions needed to restore the flow after the oil has achieved the gelled state for a long time is usually called the re-start problem. In order to address the re-start problem one needs to characterize the material. However, under this state, the material exhibits a diversity of complex non-Newtonian features turning the determination of its rheology a challenging task. We performed different tests monitoring the critical stress and strain where a major rupture occurs. Depending on the test, different critical stresses are obtained. We could infer from these experiments a minimum critical stress value that can be associated to the static yield stress of the material. In addition, the material exhibited a remarkably constant critical strain value, turning this last parameter into a representative fingerprint of the material.

9:15-9:30 **Modelling thixotropic yield stress fluids as a limit of viscoelasticity (Part I)**
M. Renardy

Many common fluids, such as shampoo and ketchup, show yield stress behavior which is more complex than that of simple models like the Bingham fluid. Phenomena which are observed include yield stress hysteresis, shear banding, delayed yielding and thixotropy. It will be shown how such phenomena can be obtained from a viscoelastic model, in the limit where the relaxation time is large. The presence of a small parameter naturally makes the model amenable to methods of singular perturbation theory. The dynamics of yielding and unyielding, oscillatory flow, and the temporal development of shear bands will be discussed.

9:30-9:45 **Modelling thixotropic yield stress fluids as a limit of viscoelasticity (Part II)**
M. Renardy

Many common fluids, such as shampoo and ketchup, show yield stress behavior which is more complex than that of simple models like the Bingham fluid. Phenomena which are observed include yield stress hysteresis, shear banding, delayed yielding and thixotropy. It will be shown how such phenomena can be obtained from a viscoelastic model, in the limit where the relaxation time is large. The presence of a small parameter naturally makes the model amenable to methods of singular perturbation theory. The dynamics of yielding and unyielding, oscillatory flow, and the temporal development of shear bands will be discussed.

9:45-10:00 **The mystery of Carbopol**
M. Dinkgreve, M. Fazilati and D. Bonn

There is an ongoing discussion in the literature about the flow behavior of Carbopol. Some authors confirm that it is indeed the model yield stress fluid that many people believe it to be. However, other authors report rheological hysteresis in the flow curve, transient shear banding that persists for a very long time, and the breaking of up-down symmetry in a falling ball experiment. Such behaviors have in the past been associated with thixotropic yield stress fluids, which are very different from simple ones. We will present new experiments that suggest that both types of behavior may be found in the same type of Carbopol, however with different preparations. We will also show some flow visualization experiments with fluorescently labelled Carbopol that elucidate the difference between simple and complicated behavior of the systems.

Monday Sessions, with Abstracts

10:00-10:15 **Planar squeeze flow of Bingham fluids**
L. Fusi, A. Farina and F. Rosso

We study the planar squeeze flow of a Bingham plastic in the lubrication approximation in planar geometry. We consider two cases: (i) planar walls approaching each other in a prescribed way; (ii) parallel walls whose shape depends on both time and longitudinal coordinate. The dynamics of the unyielded region is determined exploiting the integral formulation of the linear momentum balance. We prove that in proximity of the closed end the material is always yielded, so that the rigid part is always detached from it. When dealing with case (ii), we show that the dynamics of the rigid domain is governed by a very complex integral equation. In case (i) we obtain an almost explicit solution.

Monday Sessions, with Abstracts

Room: TCPL 201

Mon-B

Chair: Jim McElwaine

10:45-11:00 **Vibrating wire rheometry**
J.R. de Bruyn and C.C. Hopkins

Vibrating wire devices have been used in the past to determine the viscosity of Newtonian fluids. We are investigating the use of a vibrating wire device to measure the viscous and elastic moduli of non-Newtonian fluids. Our device consists of a small diameter tungsten wire under tension and immersed in a fluid. When a magnetic field is applied and an alternating current is passed through the wire, it vibrates at the driving frequency. The resonance frequency of the wire can be tuned by varying its length and the applied tension. A dual phase lock-in amplifier is used to measure the in-phase and out-of-phase components of the voltage across the wire as a function of frequency. The Navier-Stokes equations can be solved for this system assuming a Newtonian fluid, and an analytic expression can be derived relating the voltage across the wire to the viscosity. For non-Newtonian fluids we modify the Newtonian solution to include a complex viscosity, allowing the viscous and elastic moduli to be determined from the measured voltage. We will discuss the design and operation of our vibrating wire rheometer and demonstrate its ability to accurately measure the viscosity of Newtonian fluids. We will also present preliminary results for Laponite clay suspensions which show that the device is sensitive to changes in the viscoelastic properties of the suspension as it undergoes a gel transition.

11:00–11:15 **On different ways of measuring "the" yield stress**
M. Denn, J. Paredes, M. Dinkgreve, and D. Bonn

Many methods have been proposed for measuring *the* yield stress. We have compared the yield stresses and yield strains measured on emulsions, Carbopol gels, a commercial hair gel, a shaving foam, and a thixotropic emulsion loaded with clay, using a number of common methods that can be easily implemented on conventional rheometers. The intersection between pre-yield and post-yield asymptotes of a stress vs strain curve obtained from oscillatory measurements appears to be the best among the methods examined here; a Herschel-Bulkley fit of a steady-state flow curve gives similar values for the yield stress, but former gives a good value of the yield strain as well. For the thixotropic yield stress materials the stress-strain curve from the oscillatory data gives the dynamic yield stress.

11:15-11:30 **Critical Conditions for Flow in Idealized Fractures**
A. Roustaei

The flow of a yield stress fluid through a fracture is studied computationally and analyticaly. This flow is important for porous media applications, hydraulic fracturing process and squeeze cementing of the oil/gas wells in which cement is pushed into the fractures to strentghen the formation. Due to non-linearity the simple linear darcy law is no more ture and different flowrate-pressure drop is observed. An important question is the minimum pressure required to start the flow in the fracture. For computations, augmented Lagrangian method is used to accurately acount for the Bingham model. We use three different types of 2D geometries for fracture gap: wavy, linear and affine geometry. The first two are characterized by fracture lenght (L), amplitude (H) and a shift (ϕ) between the top/bottom wall. The affine geometry is a random-looking fracture gap model which follows a power law and is common for description of the natural fractures shape [ref]. The Bingham number (B) is ratio of yield stress to viscos stress and is the parameter added by the yield stress fluid. To study critical pressure drop we use the Oldroyd (Od) number which is the ratio of yield stress to the pressure drop. We perform a wide parameter study of (L,H,ϕ,B) space for wavy and linear fractures and a set of computations for affine geometry. Here we focus on the results for the symmetric geometries (ϕ 0) and consider the relevance of darcy-law predictions. Generally for long and thin $(1 \ll L,H \ll 1)$ geometries here the darcy approximation works well and the pressure drop and minimum flowing pressure drop (= critical Oldroyd Od_c) are reasonably predicted. For relatively thicker fracture we expect the darcy prediction to become worse, which is true if we use the geometric gap of fracture. However at large enough (B) fouling layers appear on the walls of the fracture that effectively modify the fracture geometry. We show the darcy estimate can be improved (sometimes significantly) using the new self-selected fracutre geometry. An interesting case is the short fractures of $L \leq L_c(O(1))$ with large amplitude $O(1) \geq H$. In this case all of the uneven part of fracture gets filled with fouling layer close to the flow stop and we recover exactly the uniform channel Od_c 1. For intermediate length a fouling layer forms but fills only part of the fracture.

We study the flow onset Od_c using variational inequalities for the stokes flow of the Bingham fluid. For short fractures a thin symmetric sheard layer is present and using variational formulations we can show the thickness d_0 decays with a power $\sim B^{-k}$ with $-2/5 \leq k \leq -1/3$ and also $(Od_c - Od) \sim B^{-2k}$. For long fractures we show that $(Od_c - Od)\ B{-}1/2$ and for intermediate length fractures we provide a simple model which predicts the start point of fouling X_f in fracture which translates to a value for Od_c. We show that this model gives qualitatively correct results and captures the trends in variation of Od_c in (H,L) plane. Additionally it is able to predict a critical length $L_c\ \ 2\pi$ that for fractures with $L \leq L_c$ we recover $Od_c\ \ 1$ of uniform channel.

11:30–11:45 **About the use of Carbopol gels as model yield stress fluids**
G. Ovarlez and P. Coussot

Carbopol gels are widely used as model yield stress fluids, with a behavior close to the ideal Herschel-Bulkley behavior. In this talk, I will briefly review recent papers dealing with the constitutive behavior of Carbopol gels. Whereas some people report observations basically consistent with the model behavior, other people have recently reported 'exotic' phenomena, such as long-lived transient shear-banding and nonlocal effects. I will present results from systematic macroscopic experiments and propose an explanation for these apparent contradictory observations.

11:45–12:00 **A fluidity model for the mechanical description of thixotropic elasto-viscoplastic materials**
P.R. de Souza Mendes, R.L. Thompson, B. Abedi and L.U.R. Sica

A constitutive model that accounts for thixotropy, viscoelasticity and yielding behavior is presented. It uses the fluidity to specify the microscopic state. The model is composed of two differential equations, one tensorial equation that relates the stress to the rate of strain and one scalar evolution equation for the fluidity. The equation for stress is a modified version of the Oldroyd-B model in which the relaxation and retardation times are functions of the fluidity. In contrast to the existing phenomenological models for thixotropic elasto-viscoplastic materials, the present one relies only on a few material functions that are directly measurable by means of four standard rheological tests. The model predictions were compared with transient shear flow data pertaining to a laponite aqueous suspension, and the agreement turned out to be quite remarkable.

12:00–12:15 **Yield limit of symmetric-particle motion in viscoplastic fluid**
E. Chaparian, N.J. Balmforth and I.A. Frigaard

Yield stress fluids can hold rigid particles statically buoyant if the yield stress is large enough. In addressing sedimentation of rigid particles in viscoplastic fluids, we should know this critical number- yield number-beyond which there is no flow. As we get close to this limit, the role of viscosity becomes negligible in comparison to the plastic contribution (at least at leading order), since we are approaching the zero-shear-rate limit. Employing slipline theory for 2D plastic flows, we are able to determine the yield number for symmetric particles. Moreover, the shape of plugs that attach to the falling particle in this limit can be predicted. Numerical experiments for the sedimentation of symmetric particles in viscoplastic fluid validate the predictions of slipline theory for a wide range of geometries and reveal some surprising effects.

12:15-12:30 **Design tools for yield-stress fluids: a rheology-to-structure inverse problem**
R.H. Ewoldt, Arif Z. Nelson

A yield stress fluid can often be achieved by multiple material structures, transcending the typical organization of the academic discipline into separate material classes. Although our typical conceptual organization leads from structure-to-rheology, property-driven design requires the inverse. The purpose of this work is to discuss design tools for yield stress fluids. Some may say that design and creativity are just "common sense". We will argue against this, and outline design tools that include (i) morphology-based organization, (ii) low-dimensional descriptions of flow curves (iii) scaling laws for predictive design, (iv) consideration of secondary properties, and (v) a strategy for material concept synthesis.

Room: TCPL 201

Tues-A

Chair: Ioan Ionescu

8:30-8:45 **Mesoscopic Model for Bingham Fluids and Mixed Convection Flows in a Lid Driven Cavity (Part I)**

R.R. Huilgol

In order to overcome these inherent problems, the Thermal Difference Discrete Flux Method (TDDFM) proposed by Fu et al (2012) are used to obtain the equations of motion for incompressible fluids in two dimensions, basing the derivation on the D2Q9 lattice. This derivation is extended to compressible fluids as well. Finally, using the D3Q15 lattice, the three dimensional equations of continuum mechanics are derived.

8:45-9:00 **Mesoscopic Model for Bingham Fluids and Mixed Convection Flows in a Lid Driven Cavity (Part II)**

R.R. Huilgol

Replacing the collision integral in the Boltzmann equation by the BGK-W approximation and applying this to the D2Q9 lattice leads to fluid like behaviour. However, there are some drawbacks when these equations are applied to incompressible fluids. The first is that the pressure is proportional to the density and the second is that the viscosity depends on the relaxation time. In addition, there are difficulties in applying the boundary conditions.

9:00-9:15 **Morphology of drop impact onto a viscoplastic gel**

S.Chen, V. Bertola

This work presents an experimental investigation of the impact of Newtonian and viscoplastic drops onto viscoplastic surfaces characterized by different magnitudes of the yield stress; this is relevant, for example, to inkjet manufacturing processes where a layer of fresh material is deposited on a partially dried or cured layer of the same material. To our knowledge, no systematic studies about these systems have been reported in the open literature to date, including their basic phenomenological characterisation. The drop impact morphology was studied using high speed imaging, for impact Weber numbers between 0 and 350, and different fluid/surface combinations, with yield stresses ranging from 0 (Newtonian) to 100 Pa; quantitative data were obtained by digital image processing. Results show there is a strong effect of the fluid yield stress on the drop impact outcome, and in particular the crater depth, on the crown formation and geometry, and on the formation of secondary droplets (splashing). These effects can be interpreted in terms of the Bingham-Capillary number, which compares the yield stress magnitude and the capillary pressure.

9:15-9:30 **Boundary Integral simulations of motion and deformation of visco-plastic drops in a non-isothermal viscous fluid**

O.M. Lavrenteva, I. Smagin, A. Nir

We considered the slow settling motion of deformable visco-plastic drops in a Newtonian fluid. The drops have a temperature-dependent yield stress, and the outer fluid has a temperature gradient. The sedimentation is simulated making use of a variation of Boundary Integral equation method, where the Green function for the Stokes equation is used the integral representation and the non-Newtonian part of the stress is treated as a source term. Integration over the outer unbounded domain occupied by the Newtonian liquid is eliminated by satisfying the boundary condition at using the integral expressions for the adjoined domains. Thus, the problem is reduced to an integral equation in a bounded domain. This reduction is a main advantage when employing this method. The computations are carried for a temperature gradient which is co-linear with gravity and with the drop translation. Piecewise linear temperature dependence of the yield stress is assumed, while all the other physical parameters are assumed constant (a Boussinesq approximation). The study revealed that drops, that are initially spherical, remains almost spherical throughout the translation. However, the shape and size of the un-yielded zone changes considerably as the drop propagates into warmer or cooler regions. A drop that is initially deformed is shown to return regain its spherical shape if the interfacial tension is strong enough (i.e., the capillary number, Ca, is small). If Ca exceeds some critical value, the deformation increases with time and eventually the drop breaks up. While in our previous work, concerning drop migration in VPF with constant yield stress, it was demonstrated that an increase of the constant Bingham number stabilizes the drop shape, it is revealed in this study that, when the drop migrates in the temperature field, the temperature dependence of the yield stress can either stabilize or destabilize the drop in near-critical situations. Examples are discussed.

9:30-9:45 **Droplet impacts: when yield-stress fluids do and do not stick**
B.C. Blackwell, R.H. Ewoldt

In liquid-solid impacts, yield stress fluids can stick and accumulate where they impact, motivating several applications of these rheologically-complex materials. Here we experimentally study yield-stress fluids impacting three types of surfaces where they may (or may not!) stick: coated surfaces, hot surfaces, and permeable surfaces. We describe dimensional analysis that offers physical insight and enables design with yield stress fluids.

9:45-10:00 **Multigrid Methods for Large-Scale Optimization Problems Arising in Viscoplastic Fluids Simulation I**
S. González-Andrade

we show our analytical approach to these problems. This approach is based on a regularization of the Huber type. Further, we analyze the finite element discretization of the problem. Finally, we present a preconditioned descent algorithm combined with an innovative linesearch method based on interpolation techniques, for the numerical solution of the finite-dimensional problems.

10:00-10:15 **Multigrid Methods for Large-Scale Optimization Problems Arising in Viscoplastic Fluids Simulation II**
S. González-Andrade

we motivate the use of multigrid methods for the fast numerical solution of the finite-dimensional and large-scale problems discussed in the first session. Further, we present the main features of the multigrid/optimization algorithm used and show numerical experiments to show the efficiency of the approach. Finally, we discuss some examples arising in hemodynamics.

Tue-B

Room: TCPL 201
Chair: John de Bruyn

10:45-11:00 **The sequencing of dynamic rheological measurements**
S.A. Rogers

Abstract A new quantitative analysis scheme is presented that is commensurate with recent studies [S.A. Rogers et al., J. Rheol. (2011), C.R. Lopez-Barron et al., Phys. Rev. Lett. (2012) and others] suggesting that nonlinear responses to large amplitude oscillatory shear (LAOS) are due to sequences of physical processes. In addition to two *regular* viscoelastic material parameters (moduli, viscosities, compliances, or fluidities), the new scheme includes a new term that accounts for the apparent shifting of the strain equilibrium and the apparent yield stress. This work represents the first material-agnostic analysis in which the strain equilibrium is allowed to shift. Strains in the lab and material frames are therefore distinguished for the first time.
The new technique is shown to accurately describe purely fluid and elastic responses as well as accounting for yielding. It is shown that the position from which strain is meaningfully acquired during LAOS shifts dramatically during a period, spending much of an oscillation near the lab frame strain extremities. By providing temporal resolution to the analysis of viscoelastic responses, this research provides both a rational pathway toward a more complete understanding of results from all time-dependent tests as well as guiding the next generation of model development.

11:00–11:15 **The settling of a spherical particle in Carbopol: Elastic effects are as important as yielding**
D. Fraggedakis, Y. Dimakopoulos and J. Tsamopoulos

For several decades, Carbopol has been assumed to be the ideal viscoplastic material, exhibiting only yield phenomena without viscoelastic effects in yielded regions. Recently, it has been shown that when stresses do not overcome the yield criterion, it behaves as an ideal Hookean solid, Piau (2007). Also, experiments (Putz et al. (2006); Holenberg et al. (2012)) reveal phenomena which can be attributed only to elastic properties of the fluidized region, such as the appearance of the so-called "negative wake", Harlen (2002), downstream a falling sphere and the loss of fore-aft symmetry of the yield surface around a sedimenting particle. We use the constitutive model for elasto-visco-plastic fluids proposed by Saramito (2007) and Cheddadi et al. (2012) and extract the property values from the rheological characterization of Carbopol by Holenberg et al. (2012) and Putz et al. (2007) via the LAOS method of Ewoldt et al. (2010). We also show that in almost every elasto-visco-plastic materials, the Kinematic Hardening (KH) concept introduced by Dimitriou et al. (2013) is necessary for the their correct rheological characterization via LAOS. Our study is based on the axisymmetric sedimentation of a particle in materials which exhibit elastoviscoplastic behavior and indicates that Carbopol cannot be considered as the ideal plastic material anymore. To limit the computation requirements, we examine the settling in a cylinder, but this does not affect our results in any way, because, most often, the yield surface arises at a distance smaller than the radius of the cylinder. Moreover, when elasticity comes into play, the derived stoppage criterion for a sedimenting sphere by Beris et al. (1985) and experimentally confirmed by Tabuteau et al. (2007) is not satisfied, as a complex stress field is developed around the particle and fluidization near the rigid surface is favored. The existence of the yield surface near the sphere enhances the formation of shear layers, which are responsible for the formation of the negative wake, irrespective of the position of the confinement in relation to the sphere.

Acknowledgement: This work has been partially supported by GSRT through the Greece-Israel bilateral project entitled PHARMAMUDS, grant # 3163 and through the program "Excellence", project "FILCOMICRA", Grant # 1918.

11:15-11:30 **Particle settling in yield stress fluids: limiting time, distance and applications**
A. Wachs, I. Frigaard

We investigate the settling of a single solid particle in a domain filled with a yield stress fluid. We derive an analytical expression of the critical Bingham number above which the particle does not settle any more using the kinetic energy decay equation. In $2D$, we are able to supply an estimate of the finite stopping time t_{stop} while in $3D$, although it is very likely that t_{stop} exists, it cannot be proven analytically. We compare the analytical estimates to numerical predictions in the case of a $2D$ cylinder settling in a 4:1 channel. Numerical simulations are performed using a specifically designed Lagrange multiplier based algorithm that properly computes finite time decay. We discuss the extension to other particle shapes and also address the computational issues related to the slow convergence of our algorithm.

11:30–11:45 **Principal Component Analysis of Particle Motion**
J.R. de Bruyn, H. Chen, R. Liégois and A. Soddu

We demonstrate the application of Principal Component Analysis (PCA) to the analysis of particle motion data in the form of a time series of images. PCA has the ability to resolve and isolate spatiotemporal patterns in the data. We show that this translates into the ability to separate individual frequency components of the particle motion. We also show that PCA can be used to extract the fluid viscosity from images of particles undergoing Brownian motion. PCA thus provides an efficient alternative to more traditional particle tracking methods for the analysis of microrheological data.

11:45–12:00 **Fast and Exact: an accelerated dual gradient method for Bingham flow (Part I)**
T. Treskatis, M. Moyers-Gonzalez and C. Price

For the numerical solution of viscoplastic flow problems, a large community relies on various regularisation techniques, another group prefers the augmented Lagrangian approach. While the latter method has a number of very advantageous features, its applicability has always been limited by its significantly slower convergence.

Over the past few years, "fast" or "accelerated" gradient methods have become very popular in non-smooth convex optimisation. Based on one such algorithm, FISTA, we derive an accelerated dual gradient method (ADG) which is directly applicable to the problem of Bingham flow. The resulting method introduces no spurious regularisation, it relies on no heuristic parameters and it is ideally suited for identifying yielded and unyielded regions with high accuracy. Furthermore, the algorithm turns out to be virtually identical to the augmented Lagrangian method (ALG2 / ADMM), but includes two additional steps to achieve a higher order of convergence. The computational cost of this acceleration is absolutely negligible.

In this talk, we present some analytical highlights and numerical examples. The results demonstrate how ADG outperforms ALG2 / ADMM by orders of magnitude. Therefore, we recommend to upgrade implementations of the augmented Lagrangian method with the accelerated algorithm.

12:00–12:15 **Fast and Exact: an accelerated dual gradient method for Bingham flow (Part II)**
T. Treskatis, M. Moyers-Gonzalez and C. Price

The same as above.

12:15-12:30 **Mechanical agitation of yield stress fluids**
J. Derksen

We numerically study mobilization of liquid mixtures that include Bingham liquids in agitated tanks under laminar and transitional conditions. The simulation procedure is based on the lattice-Boltzmann method for flow dynamics, and a finite volume scheme to solve for the local and time dependent composition of the liquid mixtures. Flow dynamics and liquid composition are intimately coupled. The moderate Reynolds numbers tentatively allow us to directly simulate the transitional flow, without a need for a turbulence closure model. The results quantify the increase of mixing time with increasing yield stress and also density differences between the liquids.

Wednesday Sessions, with Abstracts

Room: TCPL 201

Wed-A:

Chair: Neil Balmforth

8:30-8:45 **The Stokes boundary layer for a thixotropic or antithixotropic fluid**
S.K. Wilson, D. Pritchard, C.R. McArdle

We describe the oscillatory boundary layer in a semi-infinite fluid bounded by an oscillating wall (the so-called "Stokes problem") for a thixotropic or antithixotropic fluid. We obtain asymptotic solutions in the limit of small-amplitude oscillations, and use numerical methods to explore the behaviour of the system for larger-amplitude oscillations. The solutions obtained differ significantly from the classical solution for a Newtonian fluid. In particular, for antithixotropic fluids the velocity reaches zero at a finite distance from the wall (in contrast to the exponential decay for a thixotropic or a Newtonian fluid).

Reference:

C. R. McArdle, D. Pritchard and S. K. Wilson, J. Non-Newt. Fluid Mech. 185-186 (2012) 18-38

8:45-9:00 **LAOS for thixotropy and our IKH model**
G.H. McKinley

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9:00-9:15 **Rheopexy and tunable yield stress of carbon blacksuspensions**
G. Ovarlez, L. Tocquer, F. Bertrand and P. Coussot

We show that besides simple or thixotropic yield stress fluids there exists a third class of yield stress fluids. This is illustrated through the rheological behavior of a carbon black suspension, which is shown to exhibit a viscosity bifurcation effect around a critical stress along with rheopectic trends, i.e., after a preshear at a given stress the fluid tends to accelerate when it is submitted to a lower stress. Viscosity bifurcation displays here original features: the yield stress and the critical shear rate depend on the previous flow history. The most spectacular property due to these specificities is that the material structure can be adjusted at will through an appropriate flow history. In particular it is possible to tune the material yield stress to arbitrary low values. A simple model assuming that the stress is the sum of one component due to structure deformation and one component due to hydrodynamic interactions predicts all rheological trends observed and appears to well represent quantitatively the data.

9:15-9:30 **Waxy Crude Oil transient behavior : a new modeling approach**
R. Mendes, G. Vinay, G. Ovarlez and P. Coussot

Waxy crude oils transportation in pipelines may exhibit specific issues. The solidification of waxy components during the cool down process provides complex viscoplastic and time-dependent characteristic fluid behavior which has a critical impact for predicting flow restart after pipeline shut-in. The rheological behavior of waxy crude oils as observed through specific tests (Magnetic Resonance Imaging velocimetry and rheometry tests) clearly does not correspond to the usual thixotropic behavior. From these observations, we give a general picture of the rheological behavior of waxy crude oils based on four main characteristics expressed as follows; a) Once the oil-gel structure is broken from rest, by achieving a critical shear stress or a critical deformation, a strong destructuring flow takes place, irreversibly changing the fluid structure state; b) In a first stage, this destructuring essentially depends on the deformation undergone by the fluid from its solid-liquid transition and in a second stage, it also depends on the flow characteristics, i.e. shear rate history; c) After being sufficiently sheared, an equilibrium state is achieved for a given shear rate. This equilibrium state depends on the maximum shear rate experienced by the fluid; c) From that equilibrium state the behavior can be essentially considered as that of a simple liquid if the fluid is not sheared beyond that maximum "historical" shear rate. We propose a new model able to represent those trends experimentally observed. This model is then used to predict the transient flow characteristics of such a material under complex flow.

9:30-9:45 **A Microscopic Gibbs field model for the macroscopic yielding behavior of a viscoplastic fluid**
T. Burghelea, R. Sainudiin, M. Moyers-Gonzalez

We present a Gibbs random field model for the microscopic interactions in a viscoplastic fluid. The model has only two parameters which are sufficient to describe the internal energy of the material in the absence of external stress and a third parameter for a constant externally applied stress. The energy function is derived from the Gibbs potential in terms of the external stress and internal energy. The resulting Gibbs distribution, over a configuration space of microscopic inter- actions, can mimic experimentally observed macroscopic behavioral phenomena that depend on the externally applied stress. A simulation algorithm that can be used to approximate samples from the Gibbs distribution is given and it is used to gain several insights about the model. Corresponding to weak interactions between the microscopic solid units, our model reveals a smooth solid-fluid transition which is fully reversible upon increasing/decreasing external stresses. If the interaction between neighboring microscopic constituents exceeds a critical threshold the solid- fluid transition becomes abrupt and a hysteresis of the deformation states is observed even at the asymptotic limit of steady forcing. Quite remarkably, in spite of the limited number of parameters involved, the predictions of our model are in a good qualitative agreement with macro rheological experimental results on the solid-fluid transition in various yield stress materials subjected to an external stress.

9:45-10:00 **A Microscopic Gibbs Field Model for the Macroscopic Behavior of a Viscoplastic Fluid: a deterministic approximation**
M. Moyers-Gonzalez, R. Sainudiin and T. Burghelea

We present a Gibbs random field model for the microscopic interactions in a viscoplastic fluid. The energy function is derived from the Gibbs potential in terms of the external stress and internal energy. An approximating differential equation for the expected proportion of the material in the solid phase is derived by a spatio-temporal rescaling of the toroidal square lattice upon which the Gibbs random field model is defined. The asymptotic dynamics of this differential equation matches with those of the rescaled simulations from the Gibbs field model and can account for the macroscopic behaviors, including solid-fluid phase transitions in the presence of constant as well as varying external stress and the associated hysteresis.

10:00-10:15 **Thixotropic fluids: lubrication flow and reduced models**
D. Pritchard, S.K. Wilson, C.R. McArdle, A.I. Croudace

In lubrication or thin-film geometries it is possible to develop significantly reduced descriptions of non-Newtonian flow. Lubrication theory is well developed for generalised Newtonian and viscoplastic fluids. For thixotropic fluids, additional challenges – and perhaps opportunities – arise when the aspect ratio of the flow becomes comparable with either the advective or the temporal Deborah number associated with the thixotropic response. I will briefly describe some recent work in which we systematically construct lubrication descriptions of two-dimensional and pipe flow, presenting results from some (relatively) accessible regimes and discussing the difficulties in other regimes.

Wed-B

Room: TCPL 201
Chair: Miguel Moyers-Gonzalez

10:45-11:00 **Inertia effects in viscoplastic flows**
N. Bernabeu and P. Saramito

In this talk, we investigate the flow of a Bingham fluid in a driven cavity flow with both inertia and viscoplastic effects. The time-dependent algorithm bases on the method of characteristic and an augmented Lagrangian algorithm together with mesh auto-adaptive techniques. Both high Reynolds and Bingham numbers are investigated and accurate detection of rigid zones in inertia vortices are presented, thanks to the adaptive mesh algorithm.

11:00–11:15 **Oscillatory flow past a circular cylinder**
A. Alexandrou, N. Kanaris, A. Demou, S. Kassinos

In this presentation we propose to discuss recent results from numerical experiments of oscillatory flow of viscoplastic fluid past a 2D cylinder. The work is motivated by an interest in the production of thermoelectric materials using solid spheres as a way to mix and grind the material. Critical parameters for this problem are the Reynolds and Bingham numbers as well as the Struhal number associated with vortex shedding and the relative ratio of the various frequencies associated with phenomena observed in the wake.

11:15–11:30 **Investigation of wall slip in contraction flow of stiff viscoplastic materials**
M. Bryan, S. Rough, I. Wilson

We present flow visualisation data for cylindrical contraction flow of several stiff viscoplastic materials: a concentrated Carbopol gel, a micro-crystalline cellulose/water paste and a dry solid soap. The visualisation was carried out through a glass window onto a hemicylindrical flow channel, with image analysis of seed particles used to calculate the flow field. Of particular focus are the static areas adjacent to the contraction zone which have been observed to change shape and extent with time. Some attempts have been made to model a representative Bingham plastic flow with wall slip using the augmented Lagrangian method, with limited success owing to the complex wall behaviour required to model such flows. The wall slip behaviour of the solid soap material has also been investigated, which has been found to exhibit a velocity and local pressure dependent wall shear stress.

11:30–11:45 **Particle laden flow**
S. Lee

11:45-12:00 **An issue regarding wall slip measurement in yield-stress (and other) materials**
M. Denn, M. Habibi, M. Dinkgreve, J. Parades and D. Bonn

It is readily shown that the conventional method of measuring wall slip velocities in a rotational parallel-plate rheometer, in which the shear rate is plotted versus the reciprocal of the gap spacing at constant stress, is valid only for a specific relation between the viscosity function and the dependence of the slip velocity on wall stress, and this relation is not satisfied for a foam and two emulsions investigated in this work. Yet, the slip-corrected flow curves are in good agreement with flow curves obtained in a roughened cone-and plate rheometer, indicating that the method is robust despite the lack of rigor. “Why?” is an open question.

12:00-12:15 **Confined viscoplastic flows with heterogeneous wall slip**
P. Panaseti, G.C. Georgiou

The steady, pressure-driven flow of a Bingham plastic in a channel is considered assuming that different Navier slip laws apply along the two parallel walls due to slip heterogeneities. Hence, the velocity profile is allowed to be asymmetric. The different flow regimes are identified and the results are discussed and compared with available experimental data.

12:15-12:30 **Influence of slip on the flow of a yield stress fluid around a flat plate**
L. Jossic, F. Ahonguio and A. Magnin

This experimental study deals with the influence of slip on the non-inertial flow of a viscoplastic fluid around a flat plate moving at a constant velocity. The bulk and interfacial properties of the viscoplastic fluid have been finely characterized. The drag force has been analyzed with regards to the flow velocity and for two tribological conditions: adherence and slip. The drag force decreases with the velocity and is reduced in the presence of slip. Kinematic fields have been measured by PIV, to determine the influence of both the velocity and the tribological conditions on the liquid and solid regions of the flow. The results highlight no significant influence of the flow velocity on the thickness of the boundary layer and rigid zones. The wall shear stresses along the plate obtained from force measurements and slip velocities are then compared to rheometrical measurements. The present experimental results have been compared with theoretical and numerical data from the literature.

Thursday Sessions, with Abstracts

Room: TCPL 201

Thur-A — Chair: Sergio Gonzalez-Andrade

8:30-8:45 **Rheological properties of model flocculated suspensions**
J. Fusiera, J.Goyona, F. Toussaintb, X. Chateaua

Suspensions of colloidal particles suspended in a Newtonian fluid are encountered in many fields of daily life or industrial sectors. Complex behavior of colloidal suspensions comes from the interplay between hydrodynamical and several physico-chemical interactions between the particles. Even if a lot of works have been devoted to these topics, the complex relationships between the inter particulate forces and the suspension's overall macroscopic behavior are far from being fully understood. In this work we are interested in measuring rheological properties of modern fresh cement pastes in which particles flocculation controls flow behavior in the aim of developing a micromechanical model of this material. As in real systems diversity in sizes and shapes combined with changes of constituents in time due to chemical reactions make the system hard not to say impossible to control and then to understand we choose to work with model systems to avoid this complexity. We used two different particles: micrometric monodisperse spherical silica particles synthesized via Stöber process and crushed quartz particles, both of them suspended in aqueous solution. In these systems, particles interact through hydrodynamical forces, van der Waals attractive forces and electrostatic repulsive forces. According to the double layer theory, the magnitude of the last forces can be easily controlled by changing salt concentration of the aqueous solution: when salt is added the range of the repulsive electrostatic potential is reduced. When this range is low enough, attractive van der Waals forces are not screened anymore and particles tend to attract each other, coagulate and form flocs. Besides these flocs can be destroyed by hydrodynamic forces when the suspension is sheared. Consequently the suspension is thixotropic. Macroscopic characterization is performed through rheometric measurements of both the yield stress and the elastic modulus after several resting times. By changing one parameters at a time, we observed increase of the yield stress and the elastic modulus with rest time, volume fraction and ionic force. When plotting elastic modulus against yield stress a single curve is obtained for each kind of material, whatever the solid volume fraction, the rest time, and the ionic strength. Moreover we obtain a master curve for silica suspensions by rescaling the yield stress by the particle size squared and the elastic modulus by the particle size. Micromechanical interpretation of this result will be discussed to conclude the presentation.

8:45-9:00 **Dynamic settling of particles in a shear thinning fluid**
L. Childs and A. Hogg

We investigate theoretically the settling of particles through a non-Newtonian fluid that is undergoing shear flow. The suspending fluid is assumed to have power-law rheology; this means that the effective local viscosity depends upon the local rate of strain. Thus the settling velocity of an individual, relatively dense particle is not constant throughout the fluid domain, but varies spatially with the local settling velocity. We present three-dimensional computations of the flow field around a single particle to determine the effective settling velocity as a function of the rate of strain and then apply this model to dilute of suspensions of particles distributed throughout a fluid undergoing a non-uniform shear flow. We show that the shear profile exercises a strong control on the settling of the suspension and the distribution of the accumulating deposit underneath it.

9:00-9:15 **Rheology of dense suspensions of non-colloidal spheres in yield-stress fluids**
S. Dagois-Bohy , S. Hormozi , É. Guazzelli and O. Pouliquen

We have studied the rheology of dense suspensions of rigid particles in a visco-plastic fluid (Dagois-Bohy et al., JFM 2015). An original setup is used, consisting in an annular shear cell with the top plate being replaced by a grid with mesh size smaller than the particle size. This grid moves vertically in the suspension and imposes a pressure on the particles, which is measured and controlled throughout the experiments, while the suspending fluid is free to flow through it. Unlike in conventional suspension rheology measurements, here the solid volume fraction varies so that the particle pressure balances the imposed pressure. This setup has already been proven useful in the case of Newtonian suspensions (Boyer et al., PRL 2011), allowing first to study higher packing fractions than in classical volume imposed rheology, and second providing unique measurements of the normal stress in the solid phase. In the case of a yield stress suspending fluid, an additional stress scale (i.e. the yield stress) enters the problem and the rheology can no longer be described using a single dimensionless number. By carrying out systematic experiments with different yield stress fluids at different imposed pressures and different shear rates, the project team could propose empirical constitutive laws rationalized in the framework of previously proposed homogenization theories

(Chateau et al., JOR 2008).

References: Boyer, F., Guazzelli, E. & Pouliquen, O. Unifying suspension and granular rheology Phys. Rev. lett 107, 188301, (2011).

Chateau, X., Ovarlez, G. & Luu Trung, K. Homogenization approach to the behavior of suspensions of noncolloidal particles in yield stress fluids. J. Rheol. 52, pp. 489âĂŞ506, (2008).

Dagois-Bohy, S., Hormozi, S., Guazzelli, E. & Pouliquen, O. Rheology of dense suspensions of non-colloidal spheres in yield-stress fluids. J. Fluid Mech. 776, R2 1âĂŞ11 (2015).

9:15-9:30 **Plastic failure of granular material in a drum**
J.N. McElwaine and N.J. Balmforth

Grains in a horizontally rotating drum is one of the simplest experiments to perform, yet is exemplifies the great complexity of granular matter. Depending on the regime there can be solid-like, liquid-like and gas-like regions simultaneously, stopping and starting and entertainment and deposition. Despite the decades of study most aspects of drum flow cannot be explained by any theory, and the literature contains many overly simplistic and simply wrong papers on this subject. We describe experiments designed to study the transition from episodic avalanching to continuous flow (slumping to rolling) in drums half full of granular material. Experiments are conducted in drums with different radii and widths, and with different granular materials, ranging from glass spheres with different radii to irregularly shaped sand. Image processing is performed in real time to extract relatively long time series of the surface slope derived from a linear fit to the granular surface. For the drums and materials used, the transition mostly takes the form of a blend of the characteristics of episodic avalanching and continuous flow, that gradually switches from slumping to rolling as the rotation rate increases. For sand, a hysteretic transition can be observed in which one observes prolonged episodic avalanching or continuous flow at the same rotation rate, over a window of rotation speeds. For the smallest ballotini (1 mm diameter) and the sand in both the largest and smallest drums, the transition takes the form of noise-driven intermittent switching between clearly identifiable phases of episodic avalanching or continuous flow. We formulate dimensionless groupings of the experimental parameters to locate the transition and characterise the mean surface slope and its fluctuations. We extract statistics for episodic avalanching, including angle distributions for avalanche initiation and cessation, the correlations between successive collapses, mean avalanche profiles and durations, and characteristic frequencies and spectra.

9:30-9:45 **Continuum viscoplastic simulation of a granular column collapse: rheology and lateral wall effects**
I.R. Ionescu, N. Martin and A. Mangeney

The present work focuses on the modeling of dry granular flows in the context of the granular column collapse in an inclined channel and detailed comparison with experimental thickness profiles and front velocities. A nonlinear Coulomb friction term, representing the friction on the lateral walls of the channel is added in the model, providing the ability to accurately simulate this column collapse on large slopes. We show that accouting for lateral friction effect in the simulations is crucial at large slopes In other respect, we show that a Drucker-Prager constant viscosity model with a well-chosen value for the viscosity is able to predict the slow propagation phase at large slopes, experimentally observed, whereas the viscosity provided by the $\mu(I)$ rheology, evaluated from physical quantities, does not behave as well. Finally, we show that the present model predicts the appearance of shear bands in the bulk when refining the mesh. This behaviour appears to be unstable (as it induces shear bands as narrow as 4 grain diameter, to the best of our refining capacities) but is not affecting the simulations in terms of velocity range and free-surface movements. We also show that this effect is triggered by the coupling of the plasticity criterion with the pressure field.

9:45-10:00 **Universal rescaling of flow curves for yield-stress fluids close to jamming**
M. Dinkgreve, J. Paredes, M.A.J. Michels and D. Bonn

The experimental flow curves of four different yield-stress fluids with different interparticle interactions are studied near the jamming concentration. By appropriate scaling with the distance to jamming all rheology data can be collapsed onto master curves below and above jamming that meet in the shear-thinning regime and satisfy the Herschel-Bulkley and Cross equations, respectively. In spite of differing interactions in the different systems, master curves characterized by universal scaling exponents are found for the four systems.A two-state microscopic theory of heterogeneous dynamics is presented to rationalize the observed transition from Herschel-Bulkley to Cross behavior and to connect the rheological exponents to microscopic exponents for the divergence of the length and time scales of the heterogeneous dynamics. The experimental data and the microscopic theory are compared with much of the available literature data for yield-stress systems.

10:00-10:15 **Shear-induced particle migration in a poly-dispersed concentrated suspension of particles in viscoplastic fluid**

O.M. Lavrenteva, A. Nir

We studied the shear-induced diffusion of spherical particles suspended in a Bingham fluid. Such phenomena were studied before for migration in Newtonian fluids, and results were obtained for cases involving various viscometric flows of the suspensions. The migration in VPF is a new study, and is complicated by the existence of a yield stress in the domain, in which case the particles suspended in unyielded regions, that are not sheared, are not free to migrate. A phenomenological model for the shear-induced migration was adopted and employed, and results were obtained for suspensions of Stokesian particles having initially homogeneous mono-dispersed and bi-dispersed particle size distributions.

For the case in which the suspension is forced to flow in a tube, the evolution of particle concentration distributions and bulk velocity distribution are calculated. For a constant flow rate, the change in the local pressure drop is recorded as well. When a VPF flows in a tube, there exists a core of unyielded material at the center of the tube, the radial extent of which depends on the Bingham number. In a mono-dispersed suspension particles migrate from the high shear region near the tube wall and tend to accumulate near the un-yielded zone boundary, where they eventually reach the maximum concentration, The dynamics in Newtonian suspensions in which accumulation is at the center of the tube, is the limiting case of $Bn = 0$. For the bi-dispersed suspension cases a separation of sizes occurs. The bigger particles migrate from the wall region inward while the smaller particles are being displaced in the opposite direction. The dynamics depends on the particle size ratio and on the partial concentrations of the two sizes in the suspension. The evolution of concentrations and velocity distributions, and the change in pressure drop are not monotonous and the dynamics appears to be more complex.

Thur-B

Room: TCPL 201
Chair: David Pritchard

10:45-11:00 **Displacement flows in a non-uniform channel**
S.M. Taghavi and R. Mollaabbasi

We consider displacement flows in non-uniform plane 2D geometry, i.e., a diverging or a converging channel. The two fluids are miscible and buoyancy is significant. We assume that the channel is oriented close to horizontal. We demonstrate how the nonuniformity of the displacement flow geometry can affect the propagation of the interface between the heavy and the light fluids in time for various parameters studied, e.g., the viscosity ratio, a buoyancy number, and the rheological features. By setting the diffusive effects to zero, at longer times the solution behaviour can be predicted from the associated hyperbolic problem, using which it is possible to directly compute the interfacial features, e.g., front heights and speeds.

11:00–11:15 **On the Diversity of Convective Regimes in a Silica Colloidal Dispersion: from Laboratory Experiments to Planetary Mantles (Part I)**
A. Davaille, E. Di Giuseppe, E. Mittlestaedt, M-C Renoult, F. Doumenc and L. Pauchard

Planets long-term cooling, as well as surface phenomena such as plate tectonics, volcanoes and earthquakes, are mainly controlled by the existence and patterns of convective motions in their solid-state mantle. The latter strongly depend on rocks' rheology and their ability to strongly localize deformation. Two main regimes are usually considered: "Stagnant Lid" where convective motions develop below a "lithosphere" (=skin) which remains stagnant, and "Plate Tectonics" with the continuous rejuvenation of the planet surface by "subduction" (=sinking) of its cold gravitationally unstable lithosphere. However the necessary conditions for the latter regime are still debated. We run new laboratory experiments with silica colloidal dispersions to explore the problem, and a diversity of regimes was observed besides the two end members already mentioned. The rheology of silica colloidal dispersions varies from viscous to elasto-visco-plastic to brittle when their water content decreases (Di Giuseppe et al, 2012). So as an analogy to cooling from above, the fluid is dried from above. It can also be heated from below in order to produce active upwellings. Humidity, temperature, fluid thickness and solution concentration were systematically varied, which results in changing the intensity of convection and the magnitude of the rheological parameters of the fluid. As the fluid surface dries, a denser chemical boundary layer (CBL) develops, constituted of a thin brittle film on top of a more ductile layer; and convection develops under this stagnant lid. When the bottom of the tank was insulated, so that there was no hot upwellings formation, convection was driven by cold instabilities only. Two main mechanisms were observed to break the skin. In some cases, solutal small-scale convection was sufficient to trigger subduction. But the most common case was drying-induced stresses which cause the skin to buckle, and then induce plastic failure, thereby initiating subduction of the gravitationally unstable skin. Subduction is always one-sided and proceeds quickly by trench roll-back. Then the whole process starts again. Shear banding and a lubrication layer on the top of the subducting slab seem to be key ingredients to break the surface plate and initiate subduction episodes. When the fluid was also heated from below, hot plumes were observed to trigger one-sided subduction along part of their rim. Depending on the strength and the buoyancy of the lithosphere, this could trigger episodic gravitationally sustained subduction, or continuous plate tectonics, or on the contrary, subduction could stop after slab break off. Subduction therefore appears as a necessary condition for Plate Tectonics, but is not a sufficient one. Moreover, in the laboratory, we never observed continuous Plate Tectonics without the existence of hot plumes. Last but not least, an experiment always passed through a succession of different regimes, and this should also be the case for a planet.

11:15–11:30 **On the Diversity of Convective Regimes in a Silica Colloidal Dispersion: from Laboratory Experiments to Planetary Mantles (Part II)**
A. Davaille, E. Di Giuseppe, E. Mittlestaedt, M-C Renoult, F. Doumenc and L. Pauchard

The same as above.

11:30–11:45 **Thermal plumes in viscoplastic fluids: flow onset and development**
I. Karimfazli, I.A. Frigaard and A. Wachs

When a fluid has a yield stress, it has been shown that the equilibrium motionless state is linearly stable; e.g. in the Rayleigh-

Bénard configuration. However, on changing to localised heater configurations the static background state exists only if the yield stress is sufficiently large. When the yield stress is less than a critical value, buoyancy stresses result in the onset of motion in a stationary visco-plastic fluid layer. This was observed in the recent experimental study of Davaille et al. (2013) where multiple distinct plumes developed in strongly convecting flows.

We have studied an analogous two dimensional problem from the perspective of an ideal yield stress fluid (Bingham fluid) that is initially stationary in a locally heated rectangular tank. We investigate the effect of the yield stress on the onset mechanism. We show that when yield stress is less than the critical value motion onset is delayed by a finite time. We illustrate that the ratio of advective and conductive heat transfer plays a key role in determining the dynamics of flow development. When advection is weak, the passage to a steady state is relatively smooth and monotone. With strongly advecting flows, we observe an increasing number of distinct plume heads and a tendency for plumes to develop as short-lived pulses.

11:45-12:00 **The viscoplastic behaviour of snow**
J.N. McElwaine

Avalanches and other geophysical flows kill hundreds of people a year and have a significant economic impact. Snow has a complex viscoplastic rheology that is poorly understood we report on snow chute experiments in which velocity profiles and basal shear force were measured for snow flowing down a chute 34 m long and 2.5 m wide. The flows were approximately steady by the end of the chute where measurements were taken and the angle was 32 degrees. Measurements of the basal shear stress confirm approximate dynamic balance. The velocity profile was measured using opto-electronic sensors and showed a large slip velocity at the base, a shear layer of around 50 mm and an overlying plug-like flow of about 350 mm. The velocity profile is compatible with both a Herschel-Bulkley rheological model, which combines a constant critical stress with a power law dependence on the mean shear rate, and a Cross model where the effective viscosity varies between two limits. Estimates of the Reynolds number suggest that the flow is not turbulent. The measurements are used to estimate the distribution of energy dissipation and to show that its concentration near the base may locally melt the snow, and thus serve as an explanation for icy melt surfaces observed at the base of flowing avalanche tracks.

12:00-12:15 **Shallow non-isothermal viscoplastic models for volcanic lava flows**
N. Bernabeu and P.Saramito

A new shallow reduced model of lava flow advance and cooling on a general topography is presented in this paper. The lava rheology is modelled by a non-isothermal tridimensional viscoplastic fluid where the rheological properties are supposed temperature-dependent. An asymptotic analysis leads to reduce the 3D problem to a 2D surface one with depth-averaged equations. These equations are numerical approximated by an auto-adaptive finite element method, based on the Rheolef C++ library, allowing to saves computational time. The proposed approach is first evaluated by comparing numerical prediction with non-isothermal experimental measurements for a silicone oil flow. Next, the December 2010 eruption of Piton de la Fournaise (La Réunion island) is numerically reproduced and compared with available data.

12:15-12:30 **A new nonsmooth model for discontinuous shear thickening fluids**
J.C. De los Reyes and G. Stadler

A novel nonsmooth continuum mechanical model for discontinuous shear thickening flow is presented. The model obeys a formulation as energy minimization problem and its solution satisfies a Stokes type system with a nonsmooth constitute relation. Solutions have a free boundary at which the behavior of the fluid changes. We present regularity results and study the limit of the model as the viscosity in the shear thickened volume tends to infinity. A mixed problem formulation is discretized using finite elements and a semismooth Newton method is proposed for the solution of the resulting discrete system. Numerical problems for steady and unsteady shear thickening flows are presented and used to study the solution algorithm, properties of the flow and the free boundary. These numerical problems are motivated by recently reported experimental studies of dispersions with high particle-to-fluid volume fractions, which often show a sudden increase of viscosity at certain strain rates. Extensions to the full viscoplastic case are also addressed.

Room: TCPL 201
Fri-A
Chair: Ida Karimfazli

8:30-8:45 **On the transition to turbulence in viscoplastic flows**
A. Alexandrou, N. Kanaris, A. Demou, S. Kassinos

This presentation will focus on our latest results for three-dimensional flow of Bingham fluids when the flow transitions from laminar to turbulent flow. These flows are obtained by using direct numerical simulations and they are (a) flow past a 3D cylinder and (b) flow through a circular pipe.

The confined case of a cylinder in a plane channel with a fixed blockage ratio (ratio of the cylinder diameter to the channel height) of 0.2 has been studied for values of the Bingham number (*Bn*) and Reynolds number (*Re*) based on the cylinder diameter and bulk flow velocity in the range $0<Bn<5$ and $150<Re<600$, respectively. The onset of three-dimensional flows for different Bingham numbers has been determined. Mode A and B instabilities have been identified in the flow, and the influence of viscoplastic effects on the evolution of these instabilities has been described. For the flow in a circular pipe the work focused on understanding the flow and the conditions under which the flow becomes asymmetric. Again the results are obtained for various *Re* and *Bn* numbers.

8:45-9:00 **Micropolar Bingham fluids (Part I)**
V. Shelukhin

Starting from the notion of the Cosserat continuum, we develop further the theory of the Bingham fluid to take into account micro-rotations and microinertia of the fluid particles. Besides the Cauchy stress tensor, one should take into account the couple stress tensor as well. This is why such a fluid may have two yield stresses; the classical yield stress controls the small shear stress whereas the second yield stress controls the small couple stress. The theory allows for explanation of some effects which occur in drilling fluids, animal blood, hydro-fracture fluids and etc. For the flows between two parallel planes Calculations reveal that the apparent viscosity increases as the canal thickness decreases in agreement with the inverse Fahraeus-Lindquist effect for the blood seepage through a narrow capillary tubes at high values of hematocrit.

As for applications in transport of drilling cuttings, the model predicts that even small increase of the drilling mud discharge may result in a significant pressure growth within the borehole if the cutting concentration and the mud composition are such that the rotation viscosities, corresponding to the mud-cutting mixture, are not negligible. An asymptotic analysis is performed for the case of flows within a Hele-Shaw cell under the pressure gradient. A generalization of the Darcy law is derived for the averaged velocity (with respect to the transversal variable), being a function of the pressure gradient. In contrast to the Newtonian fluids, the apparent viscosity increases due to micro-rotations. Such a viscosity is a decreasing function of the pressure gradient. Moreover, the apparent viscosity goes to infinity when the pressure gradient attains the limit critical value. As for plasticity, the limit critical value becomes greater due to micro-rotations.

The theory is developed further for the case of non homogeneous fluid when concentration of polar particles depends on the spaces variables. A generalized Fick law for the diffusive flux is formulated which agrees both with the thermodynamics and with the constitutive law for the couple stress tensor. Due to the fact that the diffusive flux depend on both the rate of strain tensors, we explain the Serge-Silberberg effect stating that concentration attains its maximum between the center and wall for steady flows through the circular tube. Besides, we prove that the plug zone depends on the concentration value.

By studying the joint flow of a viscous and a micropolar fluid, we obtained a new boundary condition for the equations of the viscous fluid for the case where a thin layer of a granular fluid is present on the interface with the solid. Examples of using this condition in problems of drilling mud flow in the presence of a mud cake on the borehole wall are given. Finally, we discuss mathematical problems concerning solvability of the equations governing micropolar Bingham fluid flows.

9:00-9:15 **Micropolar Bingham fluids (Part II)**
V. Shelukhin

The same as above.

9:15-9:30 **Displacement of viscous liquids by a viscoplastic material**
H.M. Caliman, E.J. Soares, R.L. Thompson

The liquid-liquid displacement has been analysed since the pioneering work of Goldsmith & Mason (1963). This kind of problem has a number of practical applications as oil recovery in porous media and cementing of oil wells, in which the control of the liquid film attached to the wall is quite important. Considering two immiscible liquids, the physical mechanism is governed by the viscosity and density ratios, capillary number, Reynolds number, besides the non-Newtonian rheological properties of each material. This work is a contribution on the understanding of the role played by viscoplastic materials in such phenomenon. In a simple experimental apparatus, a Carbopol solution is used to displace a Newtonian liquid in a capillary tube. The images of the interface are recorded during the test. From these images, we have the interface shape and the thickness of the displaced liquid attached to the wall as a function of a dimensionless yield-stress. In addition, by a simple volume balance, we also have a measure of the displacement efficiency. It is shown that the displacement efficiency and the liquid film attached to the wall are not directly related.

9:30-9:45 **A novel approach for modelling Bingham fluids in lubrication approximation**
L. Fusi, A. Farina, F. Rosso and S. Roscani

We present a novel approach for modelling the lubrication flow of a Bingham fluid in a channel of non uniform width. The novelty consists in deriving the rigid plug equation using an integral approach where the unyielded part is treated as an evolving non material volume. We prove the existence of a true unyielded plug exists even when the maximum width variation is not "small".

9:45-10:00 **Viscoplastic Dambreaks**
N. Balmforth

I report the results of computations for two-dimensional dambreaks of viscoplastic fluid, focussing on the final shape of the slump and the manner in which the fluid reaches this resting state. Also of interest is the style in which the fluid block first yields and the dependence of both that failure mechanism and the final shape on the initial aspect ratio.

10:00-10:15 **Influence of the initial profile on statistical characteristics of roll waves trains in power-law fluid.**
C. Di Cristo,M. Iervolino ,A. Vacca

Thin layer of both Newtonian and non-Netwonian fluids flowing in an inclined plane may exhibit free-surface long-wave instabilities, which may degenerate into a series of progressing bores, known as roll-waves. The prediction of this instability is a concern in many processes related to both environmental and industrial applications. For analyzing fine sediment-water mixtures, magmas and mining residuals when the yield stress is negligible, the power-law fluid model remains one of the most widely adopted models, with either shear-thinning ($n<1$, n being the rheological index) or shear-thickening ($n>1$) behavior. Moreover, the flow model based on depth-averaged continuity and momentum conservation equations accordingly to the von Kármán's integral method (Ng and Mei, 1984) represents a reasonable trade-off between the physical description and the mathematical complexity. The present study investigates the influence of non-uniform flow profiles on the evolution of natural roll wave trains in non-Newtonian power-law fluids. Indeed, almost all previous studies on the evolution of instabilities in power-law fluids consider uniform unperturbed conditions, whereas in any real physical system hypocritical or hypercritical flow profiles are encountered, depending on the prescribed boundary conditions. Conversely, different works have demonstrated the important effect of gradually varying unperturbed profiles on the instability development in Newtonian (Dracos and Glenne, 1967; Kranenburg, 1990; Bohorquez, 2010) and Herschel & Bulkley (Di Cristo et al. 2015) fluids. Moreover, Campomaggiore et al. (2015) analyzed the spatial evolution of a single perturbation in a power-law fluid in presence of different accelerated and decelerated unperturbed profiles. In this study, a further investigation is carried out through fully non-linear simulation of the development of a roll-wave train in presence of different unperturbed gradually-varying profiles. Either hypocritical or hypercritical initial conditions are considered. The numerical simulations, performed using a second order Runge-Kutta Total Variation Diminishing Finite Volume Method, analyze the influence of the initial profile on the roll-waves evolution in all the different development phases, in terms of the main statistical characteristics, e.g. the mean water depths either at the crest or at the trough and the mean wave period. The effect of non-uniform conditions can be important in the estimation of the spatial growth rate value used in the criteria for predicting instabilities occurrence.

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Room: TCPL 201

Fri-B

Chair: Xavier Chateau

10:45-11:00 **Obstructed and channelized viscoplastic flow in a Hele-Shaw cell (Part I)**
D.R. Hewitt, N.J. Balmforth, M. Daneshi, D.M. Martinez

The flow of viscoplastic fluid down slender conduits or through porous media has application in a range of industrial and geophysical settings, from the plumbing of mud volcanoes to the transport of proppant slurries in hydraulic fracturing. The problem is significantly complicated by the yield stress, which can cause the fluid to clog up the conduit or medium and interfere with flow. This work comprises a theoretical and numerical study of viscoplastic flow in a Hele-Shaw cell in the presence of various kinds of obstructions. The work has two main directions. First, flow around isolated blockages in the cell is investigated, by analogy with classical visualizations of Newtonian potential flow in a Hele-Shaw cell. This work is extended to consider flow past step-wise contractions or expansions in the width of the cell, all within the simplifying Hele-Shaw approximation of a narrow gap. It is shown that the yield stress of the fluid leads to stagnant regions in the vicinity of the obstruction, while the length scale over which the flow is affected by the obstruction increases as the yield stress is increased.

Secondly, more complex arrays of obstacles are considered. In particular, flow in a cell with randomly "roughened" walls is investigated, and it is shown that constructive interference of local contractions and expansions in this case leads to a pronounced channellization of the flow if the yield stress is large. This limit of large yield stress is equivalent to the limit of weak flow, which corresponds to the situation at the initiation of motion when the applied pressure drop just exceeds the critical value required to drive any flow. An optimization algorithm based on minimization of the pressure drop is derived to construct the paths of the flow channels in this limit.

11:00–11:15 **Obstructed and channelized viscoplastic flow in a Hele-Shaw cell (Part II)**
D.R. Hewitt, N.J. Balmforth, M. Daneshi, D.M. Martinez

The same as above.

11:15–11:30 **Thermo-responsive polymeric solutions: From rheology to applications**
M. Jalaal, N.J. Balmforth, B. Stoeber

Thermo-responsive polymers are one the most widely utilized type of the stimuli-responsive materials. The aqueous solutions of these polymers undergo a sol-gel transition at a particular temperature. They have been used in clinical applications such as drug and gene delivery for decades. However, more recently they have also been used in several fluidics applications such as micro-mixers, micro-pumps, 3D bio-printers etc. Here, we present the rheology of a commonly used type of thermo-responsive fluids, aqueous solutions of Pluronic F127. We show that in the sol phase, the fluid is Newtonian and in the gel phase it becomes a shear-thinning yield-stress fluid. Moreover, at very high temperatures, the solutions indicates time-dependant behaviour. Finally we demonstrate how one can use the solution to control the impact of a droplet on a solid surface.

11:30–11:45 **Thixotropic effects on Laponite start-up flows**
G. Moisés, L. Alencar, M.F. Naccache and I. Frigaard

Numerical and experimental analyses of start-up flows of thixotropic materials are shown. Experiments were performed in a horizontal tube loop using Laponite solutions. Laponite (hydrous sodium lithium magnesium silicate) is a synthetic crystalline-layered silicate colloid with crystal structure and composition closely resembling the natural smectite clay hectorite. The particles are colloidal disks of 25 nm diameter and 1 nm thickness. Their faces are charged negatively when the particles are suspended in an aqueous solution and, depending on the pH solution, their sides can be charged positively. The synthetic colloid Laponite exhibits an array of different phases and behaviors due to both attractive and repulsive interactions, anisotropy and net charge, as well as an anisotropic charge distribution. The salt (NaCl) controls the inter-particle interactions. Upon increasing of the ionic strength, electrostatic potential is screened more strongly; eventually van der Waals attractions may prevail over electrostatic repulsion, leading to gel formation, due to colloids agglomeration. Rheological tests were carried out to show the influence of Laponite and salt concentrations in the yield stress and thixotropic characteristics of aqueous solutions of Laponite. Start-up flows of Laponite were performed in a horizontal tube loop, and the velocity profiles are obtained for different values of pressure drop. The results show the effects of pressure drop and salt concentration on fluid displacement. Numerical solutions were also obtained, using an Oldroyd-B type phenomenological constitutive equation to model the fluid thixotropic behavior. The results obtained show the effect of pressure on fluid displacement for different levels of thixotropy, with good qualitative agreement with the experiments.

11:45-12:00 **Non-Newtonian Rivulet Flow**

S.K. Wilson, F. Al Mukahal and B. Duffy

Gravity-driven flow of a thin rivulet of a generalised Newtonian fluid down a locally planar substrate is considered. In the special case of a power-law fluid the behaviour of the rivulet is shown to depend strongly on the value of the power-law index of the fluid. For example, a rivulet of strongly shear-thinning fluid "self-channels" its flow down a narrow central channel between two “levees” of slowly moving fluid that form at its sides, and in the central channel there is a “plug-like” flow except in a boundary layer near the substrate. The behaviour of rivulets with constant contact angle and constant width is locally the same but globally very different. If time permits, current work on rivulet flow of Carreau and generalised Ellis fluids will also be described.

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