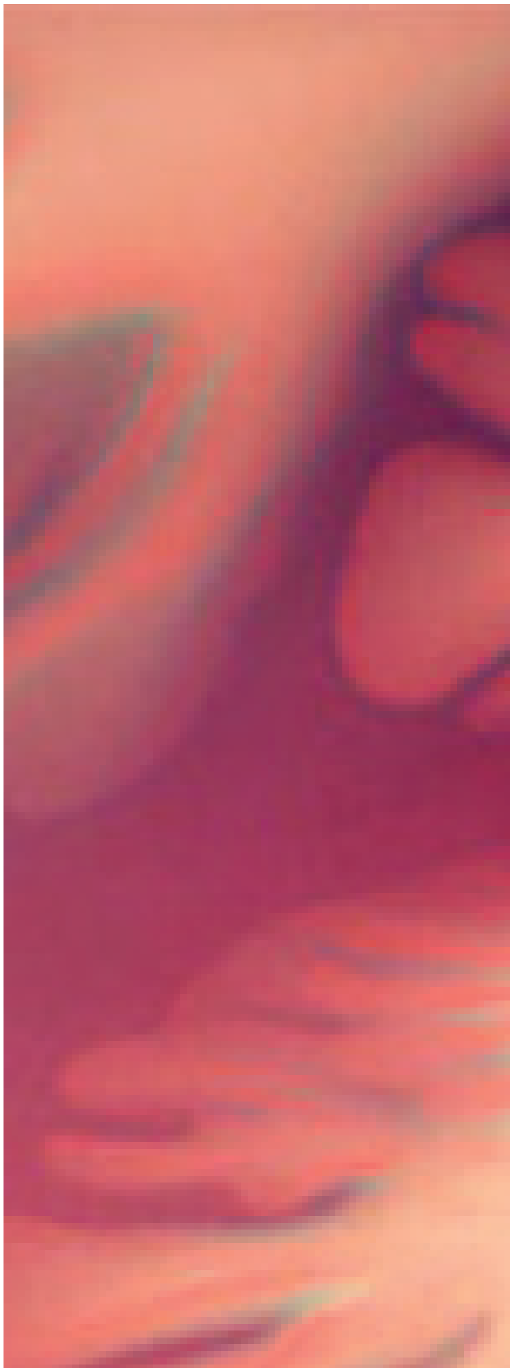
Pacific Institute *for the* Mathematical Sciences



COMPLEX FLUIDS & FLOWS IN INDUSTRY & NATURE II

Conference program

July 24-26, 2013

Pacific Institute for the Mathematical Sciences

Rm 100 Geography Bldg

1984 West Mall, Vancouver

Complex Fluids and Flows in Industry and Nature II

Fluids that exhibit physical behaviours which are not Newtonian are extremely common in nature and in industrial contexts. Equally prevalent are interfacial flows, multi-phase mixtures and suspensions. Examples include: mud, lava, polymer melts, cosmetic creams, ketchup, mayonnaise, chocolate, heavy oils, pulp suspensions, cement slurries, granular flows, pastes, etc.. Due to the complexity of studying such systems, applied mathematics plays a key role in research and in practical application of solutions to the many unsolved flow problems. This workshop brings together a select group of researchers in this area, with a strong mathematical focus, drawn from many disciplines, to advance research.

We are also happy to use the occasion of this workshop to celebrate the 70^{th} Birthday and many scientific contributions of G.M. Homsy.

Best wishes and enjoy the workshop!

Neil Balmforth, UBC, Canada

Ian Frigaard, UBC, Canada

Elisabeth Guazzelli, Aix-Marseille University, CNRS, France

Satish Kumar, University of Minnesota, USA

Getting Started

Get Connected: Select the "ubcvisitor" wireless network on your wireless device. Open up a web browser, and you will be directed to the login page.

- **All talks are in GEOG 100 and of 25 minutes duration. Coffee/Tea & lunch are in MATH 125/126**
- **Speaker abstracts begin on page 5**

Workshop at a glance

Tuesday July 23rd July, 2013

6: 00PM	Registration & welcoming reception/buffet: **Mahony & Sons,** 5990 University Blvd. An informal welcome: food/beverages will be served all evening. Come and relax when you have settled in.

Wednesday July 24th July, 2013

8:30 AM	Registration & opening
9:00 AM	**Jacques Magnaudet** (IMFT, France), The hard life of air bubbles crossing a fluid/fluid interface
9.25 AM	**Sarah Hormozi** (UBC), Frozen-in patterns in yield stress fluids
9.50 AM	**Amy Shen** (Univ. Washington), Microstructure and Rheology of a Flow-Induced Structured Phase in Wormlike Micellar Solutions
10.15 AM	**Hossein Hejazi** (Univ. Calgary), Chemically Driven Hydrodynamic Instabilities in Porous Media
10.40 AM	Coffee/tea Break (Math 125/126)
11.10 AM	**Kenny Breuer** (Brown), Swimming in Silly Putty
11.35 AM	**Paul Grassia** (Manchester), Three Films Good, Four Films Bad! (A Introduction to Foam Rheology)
12.00 AM	**Roberto Zenit** (UNAM, Mexico), Locomotion of microorganisms in complex fluids
12.25 PM	**Eliot Fried** (McGill), A dissipative particle dynamics model for suspensions of self-propelled bacteria
12.50 PM	Lunch (Math 125/126)
2.00 PM	**Satish Kumar** (Univ. Minnesota), Dynamic Wetting Failure and Air Entrainment: What can Thin-Film Models Teach Us?
2.25 PM	**Gwynn Elfring** (UBC), Interfacial dilatational rheology
2.50 PM	**Shelley Anna** (Carnegie Mellon), Probing Dilational Interfacial Stresses of Complex Interfaces Using a Microscale Spherical Bubble
3.15 PM	**Jalel Azaiez** (Univ. Calgary), Viscous Fingering Instability for Time-Dependent Injection Velocities
3.40 PM	Coffee/tea Break (Math 125/126)
4.00 PM	**Bamin Khomami** (Univ. Tennessee), Polymer Induced Breakdown of Large-Scale Taylor Vortex Structures and the Resulting Drag Enhancement in Turbulent Taylor-Couette Flows: Direct Numerical Simulations and Mechanistic Insight
4.25 PM	**Eckart Meiburg** (UCSB), Gravity-driven Interfacial Flows: Vorticity-based Models
4.50 PM	**Eric Shaqfeh** (Stanford), Vesicles and Vesicle Suspensions in Flow
6.30 PM	**Dinner cruise from Granville Island**. We will sail on the M.V. Carousel II, (Accent Cruises Ltd, #100-1676 Duranleau St. Vancouver), sailing around the Vancouver shoreline from 7.00-10.00 PM. Boarding from 6.00 PM at the dock (see map and directions). Take bus from UBC and board the boat before departure!

Thursday July 25th July, 2013

9:00 AM	**François Charru** (IMFT, France), Sand ripples and dunes
9.25 AM	**Morris Flynn** (Univ. Alberta), Buckling of a thin, viscous film in an axisymmetric geometry
9.50 AM	**Anthony Wachs** (IFP, Lyon, France), The use of Zick & Homsy's analytical solution in the DNS of particulate flows
10.15 AM	**Paul Steen** (Cornell), Vibrating Sessile Rayleigh Drops

10.40 AM	Coffee/tea Break (Math 125/126)
11.10 AM	**Joe Goddard** (UCSD), Dissipation Potentials for the Rheology of Particulate Media
11.35 AM	**Kamran Alba** (UBC), Miscible density-unstable displacement flows in inclined tube
12.00 AM	**Thomas Ward** (Iowa State), Pulsatile gas injection in a radial Hele-Shaw cell
12.25 PM	Lunch (Math 125/126)
2.10 PM	**Neil Balmforth** (UBC), Some Contact Line Problems
2.35 PM	**Rouslan Krechetnikov** (UCSB), Chemically-driven interfacial singularities
3.00 PM	**Hadi Mohammadigoushki** (UBC), Size segregation in sheared two-dimensional foams.
3.25 PM	**Juan Gomba** (UNCP, Buenos Aires, Argentina), Closed-analytical solutions for the shape of two dimensional droplets under partially-wetting conditions.
3.50 PM	Coffee/tea Break (Math 125/126)
4.20 PM	Special Session Highlighting the Research Contributions of G. M. Homsy
	☯ **Paul Grassia** (Manchester): Thermal convection
	☯ **Serafim Kalliadasis** (Imperial College): Thin film flows
	☯ **Eckart Meiburg** (UCSB): Porous media flows
	☯ **Eric Shaqfeh** (Stanford): Complex fluids
	☯ **Thomas Ward** (Iowa State)Drops and bubbles
6.30 PM	Cocktails followed by Banquet Dinner in honour of G.M. Homsy at **Cecil Green Park House**

Friday July 26th July, 2013

9:00 AM	**Hadi Mehrabian** (UBC), Capillary-inertial jet production and disintegration
9.25 AM	**Parviz Moin** (Stanford), On the congruity of transitional and fully developed turbulent boundary layers
9.50 AM	**Harish Dixit** (UBC), The elastocapillary Landau-Levich problem
10.15 AM	**Xiu Mei Xu** (IMEC, Belgium), Wetting transitions on patterned substrates
10.40 AM	Coffee/tea Break (Math 125/126)
11.10 AM	**Serafim Kalliadasis** (Imperial College), The contact line problem and related menaces
11.35 AM	**Pirouz Kavehpour** (UCLA), Spreading and Arrest of Molten Liquid on a Cold Solid Substrate
12.00 PM	**Ian Frigaard** (UBC) A weighted residual method for multilayer non-Newtonian fluid flows
12.25 PM	Close

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Abstracts: Wednesday July 24th July, 2013

9:00 AM **Jacques Magnaudet** (IMFT, France): The hard life of air bubbles crossing a fluid/fluid interface.

We investigate the dynamics of isolated air bubbles crossing the horizontal interface separating two Newtonian immiscible liquids initially at rest by means of experiments and DNS. High-speed video imaging is used to obtain a detailed evolution of the various interfaces involved in the system. The size of the bubbles and the viscosity contrast between the two liquids are varied by more than one and four orders of magnitude, respectively, making it possible to obtain bubble shapes ranging from spherical to toroidal. A variety of flow regimes is observed, including that of small bubbles remaining trapped at the fluid–fluid interface in a film-drainage configuration. In most cases, the bubble succeeds in crossing the interface without being stopped near its undisturbed position and, during a certain period of time, tows a significant column of lower fluid which sometimes exhibits a complex dynamics as it lengthens in the upper fluid. Direct numerical simulations of several selected experimental situations are performed with a code employing a volume-of-fluid type formulation of the incompressible Navier–Stokes equations. Comparisons between experimental and numerical results confirm the reliability of the computational approach in most situations but also points out the need for improvements to capture some subtle but important physical processes, most notably those related to film drainage. Influence of the physical parameters highlighted by experiments and computations, especially that of the density and viscosity contrasts between the two fluids and of the various interfacial tensions, is discussed and analysed in the light of simple models.

9.25 AM **Sarah Hormozi** (UBC): Frozen-in patterns in yield stress fluids

Stable multi-layer flows can be achieved at high Reynolds numbers by using a yield stress fluids in a lubricating outer layer. These flows have been demonstrated to be linearly and nonlinearly stable as well as observable experimentally and computationally; see Frigaard (2001), Moyers-Gonzalez et al. (2004), Huen et al. (2007), Hormozi et al. (2011a) and Hormozi et al. (2011b).
We present results of experimental, computational and theoretical studies targeted at extending the visco-plastic lubrication concept to patterned extrusion products and to the transport of encapsulated fluid droplets. In the experimental and computational parts, we show that by controlling the flow rates and rheology of different fluid streams it appears possible to engineer wavy walled tubes/channels, inserts and to produce droplets of varying shapes and sizes. In all cases the yield stress of the fluids "freezes in" the interface shape between simultaneously pumped streams of two fluids. A distinction between this method and other droplet forming techniques is that length-scales are governed by the inlet conditions and the fluid rheological properties, rather than by capillary phenomena. This opens up possibilities for application in industries that do not operate on the micro-scale, as in most large scale industrial processing, (e.g., oil, food, personal care and drug industries). We also present the result of an asymptotic solution that gives the relation between the size of encapsulated droplet and the state of stress in the flow. Joint work with G. Dunbrack, A. Maleki-Zamenjani and I. Frigaard.

References:

I.A. Frigaard, J. Non-Newt. Fluid Mech., 100, (2001) 4976.

M. Moyers-Gonzalez, I.A. Frigaard & C. Nouar, J. Fluid Mech.,506, (2004) 117-146.

C.K. Huen, I.A. Frigaard & D.M. Martinez, J. Non-Newt. Fluid Mech., 142, (2007) 150-161.

S. Hormozi, K. Wielage-Burchard & I.A. Frigaard, J. Fluid Mech.,673, (2011) 432-467.

S. Hormozi, K. Wielage-Burchard & I.A. Frigaard, J. Non-Newt. Fluid .Mech.,166, (2011) 262-278.

9.50 AM **Amy Shen** (Univ. Washington): Microstructure and Rheology of a Flow-Induced Structured Phase in Wormlike Micellar Solutions

The surfactant molecules found in soaps and detergents can self-assemble into a variety of phases or morphologies, including spherical, cylindrical, and lamellar aggregates. The morphologies that arise are highly sensitive to changes in ionic strength, temperature, and flow conditions, and can be expressed by phase maps for each variable. In particular, cylindrical micelles in the presence of inorganic or organic salts can self-assemble into large, flexible, and elongated wormlike micelles. In equilibrium, these wormlike micelles transition, with increasing salt concentration, from slightly entangled to branched and, finally, to multi-connected structures. By introducing controlled flow conditions via microfluidics, we find that these micellar structures can follow very different trajectories on the phase map and, moreover, that previously unobserved nanoporous structures can be created. Here, we describe the flow of two different solutions of wormlike micelles through an array of narrowly spaced micropillars, illustrating the structures' microstructural and rheological evolution. Each aqueous solution contains different amounts of the surfactant cetyltrimethyl amonioum bromide (CTAB) and sodium salicylate salt (NaSal) that results in a weakly viscoelastic/shear thickening and strongly viscoelastic/shear thinning solution. Previous studies have described the formation of shear-induced structures from wormlike micellar solutions under pure shear flow with a Couette cell geometry; however, when the flow was stopped, the shear-induced structures would disintegrate. Using our microdevice, we subjected the solutions to high strain rates (~104 1/s) and total strain (~103), and observed the formation of a gel-like, stable, flow-induced structured phase (FISP). We highlight three key results: (1) FISPs are stable and can form from both shear-thickening and shear-thinning micellar solutions; (2) FISPs contain highly entangled, branched and multi-connected micellar bundles, formed at low salt concentrations, enabled by the spatial confinement and flow conditions. Micropost arrays allow for high extension and shear rates, which promote flow alignment and high stretching of the wormlike micelles, decreasing their bending rigidity. The free energy of surfactant molecules in end-caps therefore increases relative to the curvature energy in the cylindrical micellar body, leading to a decrease in the work required to form junctions. As flexible adjacent micelles flow through the confined microposts, it becomes energetically favorable to minimize the number of end caps while concurrently promoting the formation of cross-links, yielding highly entangled, branched, and multi-connected bundles; (3) transitions of the rheological properties relating to the form and flow of matter (e.g., zero-shear viscosity, stress-relaxation time, and plateau modulus) are associated with structural evolution from the precursor to the FISP, which can be correlated with the mesh size and the degree of entanglement in each system.

10.15 AM **Hossein Hejazi** (Univ. Calgary): Chemically Driven Hydrodynamic Instabilities in Porous Media

Reactive flows in porous media have important applications in numerous engineering processes, natural phenomena and environmental issues; e.g., geological flow displacements and chemical fixed bed processing, to name just a few. Reactive systems are able to trigger motion of fluids or develop interfacial instabilities as soon as chemical reactions lead to heterogeneity in the physical properties of the solution such as its density, surface tension or viscosity. This interfacial instability, known as the Saffman-Taylor instability, manifests itself in the form of finger-shaped intrusions of one fluid into another one. Whether in the energy, environmental or other sectors, the efficiency and success of a displacement process that involves chemical reactions is strongly dependent on the flow instability. The instability in turn is closely linked to the subtle interactions between chemistry and hydrodynamics.

In this presentation, the evolution of miscible interfaces in the presence of a chemical reaction in porous media will be presented and discussed. A general bimolecular chemical reaction, A+B -->C, is adopted for the reactive process. The problem is analyzed through mathematical techniques including linear stability analysis and full nonlinear simulation. The linear stability analysis is a powerful mathematical tool that reduces the complex and nonlinear equations to simple ones which can be handled easily and sometimes analytically. Furthermore, full nonlinear simulations are conducted by using a highly accurate Hartley-based pseudo-spectral method combined with a stable finite difference time-stepping algorithm. Physical mechanisms of flow instabilities in reactive interfaces are discussed. Conditions for enhancing the efficiency of some geological reactive flow applications such as in-situ upgrading of heavy oil reservoirs and in-situ soil and water pollutant removal are presented.

11.10 AM **Kenny Breuer** (Brown): Swimming in Silly Putty

Flagellated bacteria swim at low Reynolds number using one or more rotating helical flagella. We present some theory and experiments that explore the the mechanics that govern flagellar propulsion in both Newtonian and viscoelastic media, as well as some observations about the different ways in which viscous and elastic stresses can be used to control swimming behavior.

11.35 AM **Paul Grassia** (Manchester): Three Films Good, Four Films Bad! (An Introduction to Foam Rheology)

Since the work of Plateau (1873) and Kelvin (1887) it has been well known that films in a static foam meet threefold (and never fourfold) along junctions, now known as Plateau borders. The fourfold state is energetically unstable -- and will lead to bubble rearrangements producing new films, such that the threefold film meeting rule is recovered. Foam rheology concerns the application of strain to a foam, a process which causes certain films to grow but others to shrink. A detailed description of foam rheology requires tracking the evolving geometry of the strained films, which can induce the `forbidden' fourfold film meeting states, from which the foam must subsequently relax. The foam's inherent relaxation rate following the fourfold state can differ substantially from the externally imposed rate of strain driving foam flow and deformation: moreover the relaxation rate can be set either by viscous dissipation effects or by departures from physicochemical equilibrium. The effects of deforming foam at different rates will be considered here. Strong viscous dissipation can delay the onset of the fourfold film state, postponing the foam's relaxation, which leads to highly elongated bubbles and possibly even produces film bursting. Slow physicochemical equilibrium might suppress the fourfold film state - and the subsequent relaxation - altogether. Even weak departures from physicochemical equilibrium are shown to lead to non-trivial, non-linear rheological behaviour.

12.00 AM **Roberto Zenit** (UNAM, Mexico): Locomotion of microorganisms in complex fluids

The fundamental mechanisms of microorganism motility have been extensively studied in the past. Most previous work focused on cell locomotion in simple (Newtonian) fluids. However, in many cases of biological importance (including mammalian reproduction and bacterial infections), the fluids that surround the organisms are strongly non-Newtonian (so-called complex fluids), either because they have shear-dependent viscosities, or because they display an elastic response. These non-Newtonian effects challenge the most fundamental intuition in fluid mechanics, resulting in our incapacity to predict its implications in biological cell locomotion. In this talk, our on-going experimental investigation to quantify the effect of non-Newtonian behavior on the locomotion and fluid transport of microorganisms will be described. Several types of magnetic micro-robots were designed and built. These devices were actuated to swim or move in a variety of fluids: Newtonian, elastic with constant viscosity (Boger fluids) or inelastic with shear-thinning viscosity. We have found that, depending on the details of locomotion, the swimming performance can either be increased, decreased or remain unaffected by the non-Newtonian nature of the liquid. Some key elements to understand the general effect of viscoelasticity and shear-thinning viscosity of the motility of microorganisms will be discussed.

12.25 PM **Eliot Fried** (McGill): A dissipative particle dynamics model for suspensions of self-propelled bacteria

We present a model for the simulation of self-propelled bacteria solutions based on the dissipative particle dynamics (DPD) framework. To mimic the rod-like geometry of an individual bacterium, two DPD particles are connected by a stiff harmonic spring to form a single DPD molecule. The bacterial motility is modeled through a constant self-propulsion force applied along the rod axis of each DPD molecule. We perform numerical simulations of this system using a customized version of the open-source LAMMPS (Large-scale Atomic/Molecular Massively Parallel Simulator) software package. To investigate the influence of the particle density and particle aspect ratio on the statistics of the system, we study various statistical objects, including probability-density functions of the velocity field, equal-time velocity correlation functions, velocity energy spectra, and structure functions of longitudinal velocity increments.

2.00 PM **Satish Kumar** (Univ. Minnesota): Dynamic Wetting Failure and Air Entrainment: What can Thin-Film Models Teach Us?

Dynamic wetting is crucial to processes where liquid displaces another fluid along a solid surface, such as the deposition of a coating liquid onto a moving substrate. Numerous studies report the occurrence of dynamic wetting failure and air entrainment past some critical process speed. However, the factors that influence this transition remain poorly understood from an empirical and theoretical perspective. In this talk, I will discuss the results from experiments and hydrodynamic modeling aimed at addressing this issue. The experiments involve two novel devices that allow for systematic determination of the influence of meniscus confinement. The hydrodynamic model is analyzed with (i) lubrication theory and (ii) a two-dimensional finite-element method (FEM). Wetting failure is found to coincide with turning points in steady-state solution paths. While both approaches (i) and (ii) do a remarkable job of qualitatively matching experimental observations, only the two-dimensional model yields quantitatively accurate predictions due to the highly two-dimensional nature of the stress field in the displacing liquid. The implications of these observations for the utility of thin-film modeling and the physical mechanisms of air entrainment will be discussed.

2.25 PM **Gwynn Elfring** (UBC): Interfacial dilatational rheology

Many methods for measuring the mechanical properties of fluid interfaces involve generating a flow at the interface with both dilatation and shear such as by translating a probe through a fluid interface. We examine here the force on a translating probe at an interface laden with a surfactant, that exhibits Newtonian interfacial rheology. If the surfactant is insoluble a common assumption is that the interface is incompressible, thus the motion of the interface is decoupled from surfactant concentration, and hence Marangoni and diffusive flows are longer a factor. Conversely if the surfactant is soluble, it may be assumed instantly equilibrated, again decoupling the motion of the interface from surfactant conservation. In this study we assume that the interface is neither incompressible nor equilibrated. In particular we look at the effects on the force measured by a probe due to small deviations in the concentration field which result from the dilatational flows induced by the probe.

2.50 PM **Shelley Anna** (Carnegie Mellon): Probing Dilational Interfacial Stresses of Complex Interfaces Using a Microscale Spherical Bubble

Adsorbed species such as surfactants, macromolecules, and particles impart unique mechanical properties to the interface, which in turn influence flows near these complex interfaces and the three-dimensional rheology of emulsions and foams in which they are embedded. Assessing two-dimensional mechanical properties is challenging, in part because controlling the deformation of an interface is strongly coupled to the three-dimensional flow field and geometry. While shear deformation of an interface has been examined in detail, other modes of deformation such as dilation, extension, and bending are much more difficult to isolate from one another. In this talk, we present analysis and experiments in which we probe the purely dilational response of an interface using a spherical bubble interface. The bubble is pinned at the tip of a capillary tube tens of micrometers in diameter, and the pressure jump across the interface is oscillated at small amplitude while the time-dependent radius of the spherical interface is measured optically. We show that the resulting deformation is neither stress nor strain rate controlled, and that the response of the interface contains both isotropic and dynamic components that can each depend on the radius of curvature and the rate of deformation of the interface. We show through a careful analysis of the force balance on the interface that the radius of curvature and frequency can be used together to help separate various microstructural responses, therefore enabling validation of interfacial constitutive models. The microscale bubble size is advantageous in minimizing the influence of the three dimensional flow on the measured response. We demonstrate the influence of geometry on dilational modulus using three model experimental systems at air-water interfaces: reversibly adsorbed nonionic polyoxyethylene surfactants that undergo diffusion-limited transport to the interface; partially irreversibly adsorbed Tween-80 surfactants that exhibit a viscoelastic Kelvin-Voigt like response to dilation; and mixtures of ionic CTAB and nanoparticle silica that irreversibly adsorb and exhibit a more complex dynamical response. Finally, we comment on the impact of the dilational interfacial response on emulsion stability via preliminary experiments in which we examine the coalescence of two identical microscale bubbles with known dilational modulus.

3.15 PM **Jalel Azaiez** (Univ. Calgary): Viscous Fingering Instability for Time-Dependent Injection Velocities

Flow instabilities resulting from the displacement of a high-viscosity fluid by a low-viscosity one in porous media are encountered in a variety of processes, such as enhanced oil recovery, CO2 sequestration, groundwater flows, fixed bed regeneration, soil remediation and filtration. Most existing studies have focused on displacements where the injection velocity is constant. However, in a number of systems such as cyclic steam stimulation (CSS) and CO2 huff-n-puff processes, the fluids are injected at time dependent rates where the velocity can be positive (injection process), zero(soak period) or negative(production process).

In this study, the stability and development of time-dependent injection flow displacements in homogeneous porous media are examined. Different time-dependent velocity profiles that may result in a positive or zero net injection flow rate are considered. The effects of different flow parameters such as the distribution of the velocity, its amplitude, the period of the injection cycle and the strength of diffusion, are analyzed. It is found that for velocities that lead to the same net injection flow rate, different instability characteristics as well as different finger structures can be obtained. The dynamics of such flows are analyzed both qualitatively and quantitatively.

4.00 PM **Bamin Khomami** (Univ. Tennessee): Polymer Induced Breakdown of Large-Scale Taylor Vortex Structures and the Resulting Drag Enhancement in Turbulent Taylor-Couette Flows: Direct Numerical Simulations and Mechanistic Insight

In this presentation, we report for the first time polymer-induced breakdown of large-scale Taylor vortex (TV) structures leading to drag enhancement in viscoelastic turbulent Taylor-Couette flows (TCF). Specifically, upon addition of trace amount (dilute solutions) of soluble high molecular weight polymer the Newtonian large-scale TVs are replaced by small-scale Taylor and Görtler vortices in the inner and outer cylinder wall regions, respectively. This flow transition is facilitated by the presence of large polymeric hoop stresses in a narrow region near the outer wall. The polymeric body force in this region changes the direction of the radial fluid motion from an outflow-dominated to an inflow-dominated regime, giving rise to strong and highly localized velocity streaks and a commensurate dramatic drag increase (DI) of up to 62%. Finally, a simple mechanism for this striking flow transition based on a self-sustaining process composed of viscoelastic Taylor-Couette (TC) and an "elastic Görtler" instability is proposed.

4.25 PM **Eckart Meiburg** (UCSB), Gravity-driven Interfacial Flows: Vorticity-based Models

Efforts to develop analytical models that predict the front velocity of gravity currents date back over seven decades to the work by von Karman (1940). The most commonly employed model today is due to Benjamin (1968), even though the issue of how to correctly model such currents remains far from settled, e.g. Shin et al. (2004). All of the above models impose the conservation of mass and streamwise momentum in order to describe the current. However, they require an additional equation to obtain a closed system. Towards this end, they invoke an empirical energy argument, thus introducing a certain degree of arbitrariness.

Interestingly, high-resolution Navier-Stokes simulations show that the dynamics of gravity currents are determined by the conservation of mass and momentum alone, so that one should not be free to impose an additional energy constraint. Hence, a physically correct analytical gravity current model also should be based on the conservation of mass and momentum alone. We show that it is indeed possible to develop such a model, based on the vorticity formulation of the momentum conservation equation. Predictions by the new model are shown to be in excellent agreement with numerical simulation results, much closer than the earlier models. These comparisons furthermore demonstrate that the earlier models do not conserve vertical momentum.

We then extend the concept of circulation-based modeling to a wider range of gravity-driven flows with interfaces and free surfaces, such as internal bores and intrusions.

4.50 PM **Eric Shaqfeh** (Stanford): Vesicles and Vesicle Suspensions in Flow

It is well known that individual vesicles or liposomes (i.e. fluid enclosed by a lipid bilayer membrane suspended in a second fluid) are characterized by a remarkable dynamics in flow. For vesicles that are "near spheres" this dynamics includes at least 5 different types of orbits in shear flow that are functions of the viscosity ratio between the inner and outer fluid as well as the Capillary number based on the bending modulus. However, this dynamics becomes even more rich as the reduced volume falls below about 0.65 where now there are atleast three equilibrium shapes (prolates, discocytes, and stomatocytes) which are linearly stable. It is therefore not surprising that a suspension of vesicles is characterized by fascinating collective behavior as well. I will discuss our recent development of a numerical code (based on Loop subdivision) which allows the Stokes flow simulation of non-dilute suspensions of vesicles and capsules at essentially any value of the reduced volume. We will then use these numerical simulations to examine a number of interesting phenomena including: 1) The lift of a vesicle away from a wall and the resulting "Fahraeus-Lindqvist" layer for the flow of a wall-bound suspension of vesicles, 2) The effective rheology and dynamics of a non-dilute vesicle suspension under shear, and 3) The stability of vesicle shapes in extensional flows.

Notes:

9:00 AM **François Charru** (IMFT, France): Sand ripples and dunes

Sand or granular patterns emerge from erodible flat beds in a wide variety of physical environments: in water channels, rivers and coastal areas, in deserts on Earth and under methane or CO2 atmospheres on other planets, in hydraulic engineering and industrial pipe flows. These bedforms exhibit different shapes depending on the symmetries of the fluid forcing, or the boundary conditions. Their size ranges from the centimeter scale for ripples up to hundreds of meters for dunes. The dynamics of these patterns results from the interaction between the fluid flow and the bed topography through particle transport, which may take place in a thin bedload layer, or in a larger saltation layer, or as a suspension.

The understanding of the formation of sand patterns has stimulated a huge number of studies, notably since the pioneering work of Bagnold in the middle of the last century. Some important issues, still debated, are the following. What are the relevant dynamical mechanisms controlling the emergence of bedforms? Do they form by linear instability or non-linear processes like pattern-coarsening? What determines their time and length scales, so different in air and water? What are the similarities and differences between aeolian and subaqueous patterns? What is the influence of the mode of transport: bedload, saltation or suspension? Can bedforms emerge under any hydrodynamical regime, laminar and turbulent? The presentation will discuss the above issues and propose, from the recent literature, a unified description of bedform growth and evolution.

9.25 AM **Morris Flynn** (Univ. Alberta), Buckling of a thin, viscous film in an axisymmetric geometry

By adapting the Foppl-von Karman equation, which describes the deformation of a thin elastic membrane, we present an analysis of the buckling pattern of a thin, very viscous fluid layer subject to shear in an axisymmetric geometry. A linear stability analysis yields a differential eigenvalue problem, whose solution, obtained using spectral techniques, yields the most unstable azimuthal wave-number, m^*. Contrary to the discussion of Slim et al. (J. Fluid Mech., vol. 694, pp. 5-28, 2012), it is argued that the axisymmetric problem shares the same degeneracy as its rectilinear counterpart, i.e. at the onset of instability, m^* is indefinitely large. Away from this point, however, a comparison with analogue experimental results is both possible and generally favorable. In this vein, we describe the laboratory apparatus used to make new measurements of m^*, the phase speed and the wave amplitude; note that no prediction concerning the latter two quantities can be made using the present theory. Experiments reveal a limited range of angular velocities wherein waves of either small or large amplitude may be excited. Transition from one to the other regime does not appear to be associated with a notable change in m^*.

9.50 AM **Anthony Wachs** (IFP, Lyon, France): The use of Zick & Homsy's analytical solution in the DNS of particulate flows

We employ a Finite Volume/Fictitious Domain Method to investigate the dynamics of particulate flows. This Direct Numerical Simulation (DNS) method, implemented in our code PeliGRIFF, works well from creeping ($Re \approx 0$) to inertia dominated flows up to

Re < 1000, and more generally is designed to examine a wide range of flows: dilute or concentrated regimes, isothermal or non-isothermal flows, mono- or polydisperse suspensions, with spherical and angular particles. The fully parallel features of PeliGRIFF shows promising computing capabilities up to 1 billion cells in DNS, thus offering actual opportunities largescale computations. However, DNS solutions at the micro-scale are generally expected to act as reference solutions. It is then crucial to assess their accuracy. We present assorted validation cases with mesh refinement convergence tests. Among them, the classical creeping flow through an infinite ordered array of mono-disperse spheres is a good candidate: (i) it possesses an analytical solution derived by Zick & Homsy in 1982 and (ii) allows to examine the effect of the solid volume fraction on the solution accuracy. We evidence that the dense regime is tougher to simulate than the dilute regime, even at Re≈0. Finally, we present various results on particulate flows to illustrate what can be achieved with such a DNS tool and describe the features of the multi-scale framework in which DNS is one elementary brick.

10.15 AM **Paul Steen** (Cornell): Vibrating Sessile Rayleigh Drops

More than a century ago, Rayleigh reported the natural frequencies and mode shapes for an inviscid free drop, vibrating due to surface tension. In many applications, however, drops are constrained by solid substrates and this constraint influences both the frequencies and shapes of the Rayleigh spectrum. In this talk, we report observations of mechanically-excited sessile drops, guided by a solution of the linear stability problem for a drop sitting on a planar plate and subject to the Hocking contact-line condition. Spectrum splitting and mode-mixing are highlighted.

11.10 AM **Joe Goddard** (UCSD): Dissipation Potentials for the Rheology of Particulate Media

This presentation is concerned with the usage of generalized dissipation functions or "dissipation 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 and Hill, and have been generalized to Cosserat continua. Physical justifications for the existence of dissipation potentials are often based on the assumption of extremal dissipation (or entropy generation). While plausible for Stokesian fluid-particle suspensions, this is less than evident for granular media and other viscoplastic materials.

By contrast, in remarkable work that seems to have been largely ignored, Edelen (1972-73) has proposed a purely mathematical construct giving general force-dependent velocity (or thermodynamic "flux") as the gradient of a dissipation potential plus a non-dissipative term that represents a "gyroscopic" flux or flux that is usually ruled out of Onsager-type theories. When gyroscopic terms are absent, one obtains the "hyperdissipative" analog of the well-known "hyperelastic" body of solid mechanics. This formalism applies to all strictly dissipative physicochemical phonomena.

The present work casts Edelen's formulae in a more transparent form, provides the extension to Legendre-Fenchel dual potentials and considers the special role of homogeneous potentials. Among other things, this leads to a comparatively easy demonstration that plastic limit surfaces are a natural consequence of rate-independence and convex duality. It is further shown that dissipation potentials allow for compact representation of constitutive equations for the viscoplasticity of fluid-particle suspension and granular media with evolutionary microstructure. This supplants earlier treatments of gradient effects and particle migration in dense suspensions and holds promise for the treatment of related segregation effects in granular media. Finally, it is shown that the above purely dissipative models may be extended to include elastic effects based on additive decomposition of strain rates and the existence of both elastic and dissipative potentials.

11.35 AM **Kamran Alba** (UBC): Miscible density-unstable displacement flows in inclined tubes

The displacement flow of two Newtonian fluids in an inclined pipe is studied experimentally. The fluids have the same viscosity but different densities. The configuration is density-unstable i.e. the displacing fluid is denser than the displaced fluid and is placed above it. It is found that three dimensionless groups describe these flows: a densimetric Froude number Fr, a Reynolds number Re and the pipe inclination, Beta . Our experiments cover fairly broad ranges of these parameters: $0 \leq Fr \leq 9$; $0 \leq Re \leq 2400$; $0 \leq Beta \leq 85$ degree. Phenomenologically, our experimental flow observations vary from well mixed fully diffusive regimes, through buoyancy-dominated inertial exchange regimes, to laminar viscous flows. The degree of stability varies in each flow regime. We characterize the different flow regimes observed in terms of the three dimensionless groups. The leading order approximations to the velocity of the displacement front and the macroscopic diffusion in each regime are then provided.

12.00 AM **Thomas Ward** (Iowa State): Pulsatile gas injection in a radial Hele-Shaw cell

The pulsatile flow of a gas used to displace a finite volume of viscoelastic liquid will be presented. Experiments are performed using a radial Hele-Shaw cell at gap spacings ranging from 50-200 microns. The viscoelastic liquids are a mineral oil mixed with various concentrations of high molecular weight poly-isobutylene (M.W. 4.7 million at concentrations 100-500 ppm). Air injection pressures range from 0.1-0.5 psi and pulsating frequencies range from 0.1-10 Hz. Analysis of the finite liquid volume allows for measurement of the residual liquid film. Also the gas expansion rate as a function of the pulsation frequencies will be presented. The experiments reveal a clear correlation between the pulse frequency, film formation and stability (finger formation) for a wide range of experiments.

2.10 PM **Neil Balmforth** (UBC): Some Contact Line Problems

The dynamics of a fluid film advancing over a plane is often sensitively controlled by surface tension. This leads to the fingering of a falling film and dictates the spreading rate of a drop. In this talk I will describe some related situations in which surface tension competes with a non-Newtonian fluid rheology or is replaced by the stresses of an elastic surface layer.

2.35 PM **Rouslan Krechetnikov** (UCSB): Chemically-driven interfacial singularities

In this talk I will discuss the physical origin of chemically-driven singularities at fluid interfaces and the development of a systematic mathematical theory aimed at the resolution of the singular behavior. In the first part of the talk, I will present an analytical study of the structure of steady Marangoni-driven singularities in the context of chemical-reaction driven tip-streaming, which identifies the conditions when such singularities are observable. In the second part of the talk, I will focus on establishing a connection to Arnold's singularity and the mean curvature flow theories as analytical tools for understanding the chemically-driven singularities in general.

3.00 PM **Hadi Mohammadigoushki** (UBC), Size segregation in sheared two-dimensional foams.

We report experiments on simple shear of a monolayer of bidisperse and polydisperse bubbles in a Couette device. The bubbles segregate according to their sizes, with larger ones in the middle of the gap and smaller ones closer to the walls, when the shear rate and the bubble size ratio are each above a threshold. The spatial distribution of the larger bubbles becomes flatter across the gap as its area fraction increases. To explain these observations, we adapt a model for monodisperse emulsions that predicts the spatial distribution of droplets as an outcome of the competition between migration away from the walls and shear-induced diffusion. The dense packing of bubbles in our foam intensifies bubble–bubble interaction, which manifests itself both in lateral migration due to wall repulsion and in collision-induced diffusion. After accounting for this difference via an effective capillary number based on the deformation of the bubbles, the model predicts the observed bubble distributions accurately.

3.25 PM **Gary Leal** (UCSB): Theoretical Studies of Shear Banding in Polymer Solutions

Theoretical solutions for the motion of polymeric liquids almost all assume that the fluid remains homogeneous; i.e. that there are no spatial gradients of concentration in the case of solutions. In this work, we use an updated version of the two-fluid model, that allows for the possibility of spatial gradients, to study flow of a polymer solution in a simple shear device. We show that there is a range of shear rates where the flow is linearly unstable, and that this instability leads to shear banding, even though the constitutive equation for the polymer is monotonic in shear stress versus shear rate (i.e. there is no "constitutive instability" as in the case of worm-like micelles). Our solutions exhibit various features that resemble recent experimental data of Wang and coworkers, but also show some new behavior that has not yet been seen experimentally.

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9:00 AM **Cherif Nouar** (LEMTA, France): Instability of streaks in pipe flow of shear-thinning fluids.

This study is motivated by the experimental results published by Escudier *et al.* (2005 and 2009), Esmael and Nouar (2008), Guzel *et al.* 2010} dealing with the transition to turbulence in a pipe flow of shear-thinning fluids, where a streaky flow with an azimuthal wavenumber n = 1 is observed in the transitional regime. Here, a linear stability analysis of pipe flow of shear-thinning fluids modulated azimuthally by finite amplitude streaks is performed. The shear-thinning behavior of the fluid is described by the Carreau model. The streaky base flows considered are obtained from two-dimensional direct numerical simulation using finite amplitude longitudinal rolls as initial condition and by extracting the velocity field at time tmax where the amplitude of the streaks reaches its maximum, denoted Amax. It is found that the amplitude Amax increases with increasing Reynolds number as well as with increasing amplitude E0 of the initial longitudinal rolls. For sufficiently large streaks amplitude, streamwise velocity profiles develop inflection points leading to instabilities. Depending on the threshold amplitude Ac, two different modes may trigger the instability of the streaks. If Ac exceeds approximately 41.5% of the centerline velocity, the instability mode is located near the axis of the pipe, i.e. it is a *center mode*. For weaker amplitude Ac, the instability mode is located near the pipe wall, in the region of highest wall normal shear, i.e, it is a *wall mode*. The threshold amplitude Ac decreases with increasing shear-thinning effects. The energy equation analysis indicates that : (i) Wall modes are driven mainly by the work of the Reynolds stress against the wall normal shear. (ii) For center modes, the contribution of the normal wall shear remains dominant. However, it is noticed that the contribution of the Reynolds stress against the azimuthal shear increases with increasing shear-thinning effects.

9.25 AM **Parviz Moin** (Stanford): On the congruity of transitional and fully developed turbulent boundary layers

Transition from laminar to turbulent flow is very sensitive to the details of the inflow disturbance. In low disturbance environments such as flight, boundary layers transition via the growth and non-linear breakdown of initially small amplitude waves. When forced by noisy free-stream perturbations as in turbine passages, the flow may instead bypass these modal instability mechanisms.
Despite considerable effort devoted to such details of transition, little is known about how the basic structure of near-wall turbulence is first established in boundary layer flows. The asymptotic allure of high Reynolds number research often obscures the origins of turbulence, but, if elementary structures found at moderate Reynolds number carry some essential transport properties of developed turbulence, they may provide a clear and more manageable window through which to study the salient physics of wall turbulence, even at high Reynolds number. We obtain and analyze these elementary structures in the late transition zone and compare their mean dynamics with developed turbulence. It is shown that coherent hairpin-packet solutions are the dominant stress-bearing structure in the late stages of controlled transition and, more importantly, the flow statistics and mean dynamics are the same as higher-Reynolds number wall turbulence. Similar hairpin-packet solutions are also observed in bypass transition (Wu & Moin 2009; Park et al. 2012). We suggest the solution of the Navier-Stokes equations in the late stages of transition manifested in hairpin-packets constitute a basic building block of wall turbulence and model of near-wall boundary layer dynamics under quite general conditions.

9.50 AM **Harish Dixit** (UBC): The elastocapillary Landau-Levich problem

We consider the dip-coating flow problem when the interface possesses both elasticity and surface tension. We define two parameters, El -- the ratio of surface elasticity to viscous forces and Ca -- the ratio of surface tension to viscous forces. We consider the problem when both these parameters are small. The relevant expansion then depends on the relative size of elasticity to surface tension. We develop the solution for the free boundary as a matched asymptotic expansion, thus determining the film thickness as a function of the small parameter. A remarkable aspect of the problem is the occurrence of multiple solutions, and five of these are found numerically. In any event the film thickness varies as $U^{4/7}$, where U is the plate speed, in agreement with the experiments of Ouriemi and Homsy.

10.15 AM **Xiu Mei Xu** (IMEC, Belgium): Wetting transitions on patterned substrates

The wettability of a substrate is often characterized by water contact angles. On an ideal smooth surface, the static water contact angle depends on the surface chemistry. On the other hand, the wetting behavior on a patterned substrate depends on the surface chemistry of the material as well as some geometry factors. For structures made of hydrophilic materials, the classical models predict that the stable wetting state is either a hemi-wicking or Wenzel state. When the intrinsic contact angle exceeds a critical value, there's a transition from the Wenzel state to the superhydrophobic Cassie-Baxter state. The superhydrophobic properties are desired for applications such as self-cleaning or drag reduction. While for applications that require a good wetting, mixing or transport property in-between the structures, the superhydrophobicity should be avoided. Therefore it is important to know the transition criterion from the Wenzel to Cassie-Baxter state. By comparing the total surface free energy at different wetting states, the critical contact angle for the transition can be derived as a function of the geometry factors, and it should be always in the hydrophobic regime. However, many literatures reported some discrepancies between the experimental measurements and the theoretical predictions, and Cassie-Baxter state is often observed even when the classic models predict a stable Wenzel state. The possible reasons for this discrepancy include the lack of control on the structure profile during the fabrications, the surface roughness on the main structures and the lack of inspection methods besides the contact angle measurements etc. To date, the investigation of the wetting transition is still an active research area. In this work, we study the static wetting on nanopillar structures with well-defined geometry factors. Ordered arrays of silicon nanopillars of 30-40 nm in diameter with varying heights are fabricated, and the surface roughness on the nanopillars is below 1 nm. To achieve a wide coverage in the contact angle regime, the surface chemistry of the nanopillars is modified by different surface treatments including self-assembled monolayer depositions. The measured contact angles are found to be consistently higher than the Wenzel predictions. We develop a novel inspection method that allows us to quantitatively measure the nano-scale wetting depths and to accurately determine the critical contact angle for wetting transition. It is found there's a consistent shifting of the Wenzel curves toward the hydrophilic regime. For tall pillars the Wenzel to Cassie-Baxter transition happens even when the intrinsic contact angle is below 90 degrees, where we also observe the coexistence of Wenzel and Cassie-Baxter states. Molecular dynamics simulations are carried out to uncover the underlying mechanism for this earlier than expected wetting transitions. If time allows, I may also address some dynamic capillary instability features during the imbibition on micrometer pillars of very high aspect ratios.

11.10 AM **Serafim Kalliadasis** (Imperial College): The contact line problem and related menaces

The moving contact line problem is a long-standing and fundamental challenge in the field of fluid dynamics, occurring when one fluid replaces another as it moves along a solid surface - such as when a droplet spreads, fluid rises in a capillary, or as a substrate is immersed in a solution during dip coating. In the frame of reference of the moving contact line an apparent paradox arises: static fluid- fluid interface, yet fluid velocity at the solid satisfying the no-slip boundary condition. As a consequence of the multivaluedness for the velocity, the shear stress has a non-integrable singularity. In this talk we will review recent progress on the problem made by our group, including related ``menaces'' such as contact line hysteresis effects, random substrate heterogeneities and thin adsorbed films in front of the contact line.

The motion of a contact line is examined, and comparisons drawn, for a variety of proposed models in the literature. We first scrutinise a number of models in the classic test-bed system, that of spreading of a thin two-dimensional droplet on a planar substrate, showing that slip, precursor film and interface formation models effectively reduce to the same spreading behaviour. Extensions to consider substrate heterogeneities in this prototype system for slip models and diffusion dominated phase field models are considered, such as for surface roughness and fluctuations in wetting properties through chemical variability.

Analysis of a solid-liquid-gas diffuse-interface model is then presented, with no-slip at the solid and where the fluid phase is specified by a continuous density field, the principal aim to show that the diffuse-interface alone can remove the singularities associated with the moving contact line problem. We first obtain a wetting boundary condition on the solid that allows us to consider the motion without any additional physics at the microscale, e.g. without density gradients at the wall away from the contact line associated with precursor films. Careful examination of the asymptotic behaviour as the contact line is approached is then shown, where finite stress and pressure are found alongside a well defined velocity -- as opposed to the non-integrable singularities and multivaluedness found in the classical model.
Joint work with David Sibley, Andreas Nold & Nikos Savva

11.35 AM **Hadi Mehrabian** (UBC): Capillary-inertial jet production and disintegration

Capillary suction through a combination of tube and nozzle can be used to eject droplets. Such capillary-inertial ejection process is studied using Cahn-Hilliard diffuse interface method. A criterion for ejection is proposed and it is shown that the presence of nozzle is essential to have droplet ejection. Finally, the size of produced droplets are estimated and numerical results are compared with experiments.

12.00 AM **Pirouz Kavehpour** (UCLA): Spreading and Arrest of Molten Liquid on a Cold Solid Substrate

The physics of non-isothermal liquid spreading followed by phase change, unlike universal equations established for isothermal spreading, is still a mystery. The motivation for the study stems from industrial applications such as thermal spray coating, rapid prototyping, 3D printing, plastic electronics and solder jetting in microelectronics. This presentation will focus on the dynamic and thermal characteristics of liquid spreading and subsequent arrest on a cold solid substrate. Spreading of liquid was recorded and the evolution of liquid spread diameter and liquid-solid contact angle were measured from the recordings of a high-speed digital camera. After solidification initiation at the basal plane, a liquid drop is pinned to a solid substrate showing fixed footprint (D^*) and contact angle (θ^*). For theorization of our data, we present a new hypothesis for spreading drop solidification. We assume that drop stops because a finite volume of ice (nuclei) forms at the contact point vicinity. Stable nuclei forms when enough energy from thermal activation is provided. This region emerges under an arbitrary isotherm adjacent to solid-liquid-gas contact point. A physical theory using scaling law analysis was provided to explain the relationship between arrested base diameter and Stefan number. Our proposed hypothesis was further corroborated by free fall impact and inclined wedge experiments.

12.25 PM **Juan Gomba** (UNCP, Buenos Aires, Argentina): Closed-analytical solutions for the shape of two dimensional droplets under partially-wetting conditions

The talk is about a work I started few years ago in collaboration with 'Bud' Homsy and continued with Carlos Perazzo and Jonatan Mac Intyre. We have found closed-analytical solutions for the shape of a two-dimensional droplets in equilibrium with a surrounding nanometric film. The modeling includes the effects of gravity, surface tension and molecular forces arising between the liquid and the substrate. We have found novel expressions that relate microscopic and nanoscopic aspects, such as the strength of the molecular forces and the thickness of the nanometric precursor film, with macroscopic quantities, e. g., the cross sectional area, the height and the width of the droplet. We also compare the results of using different models for the disjoining-conjoining pressure term.

12.50 PM **Ian Frigaard** (UBC): A weighted residual method for multilayer non-Newtonian fluid flows

We study buoyant displacement flows in a plane channel with two fluids in the long wavelength limit in a stratified configuration. Weak inertial effects are accounted for by developing a weighted residual method. This gives a first order approximation to the interface height and flux functions in each layer. As the fluids are shear-thinning and have a yield stress, to retain a formulation that can be resolved analytically requires the development of a system of special functions for the weight functions and various integrals. For displacement flows the addition of inertia can either slightly increase or decrease the speed of the leading displacement front, which governs the displacement efficiency. A more subtle effect is that a wider range of interface heights are stretched between advancing fronts than without inertia.

We study stability of these systems via both a linear temporal analysis and a numerical spatio-temporal method. To start with the Orr-Sommerfeld equations are first derived for two generalized non-Newtonian fluids following Herschel-Bulkley model and the analytical expressions for growth rate and wave speed are obtained for the long wavelength limit. The predictions of linear analysis based on weighted residual method shows excellent agreement with the Orr-Sommerfeld approach. For displacement flows in unstable parameter ranges we do observe growth of interfacial waves that saturate nonlinearly and disperse. The observed waves have similar characteristics to those observed experimentally in pipe flow displacements. Although the focus in this study is on displacement flows, the formulation laid out can be easily used for similar two-layer flows e.g. co-extrusion flows.

Notes:

Participants:

Last Name	First Name	Email
Alba	Kamran	kamran.alba@yahoo.com
Anna	Shelley	sanna@cmu.edu
Azaiez	Jalel	azaiez@ucalgary.ca
Babaie	Ashkan	ashkan.babaie@alumni.ubc.ca
Balmforth	Neil	njb@math.ubc.ca
Behzadfar	Ehsan	ebehzadfar@chbe.ubc.ca
Breuer	Kenny	kbreuer@brown.edu
Charru	François	francois.charru@imft.fr
Dixit	Harish	hdixit@gmail.com
El Kaissy	Mohamed	drkaissy@hotmail.com
Elfring	Gwynn	gelfring@mech.ubc.ca
Flynn	Morris	mrflynn@ualberta.ca
Fried	Eliot	mechanicist@gmail.com
Frigaard	Ian	frigaard@math.ubc.ca
Goddard	Joe	jgoddard@ucsd.edu
Gomba	Juan	jgomba@engineering.ucsb.edu
Grassia	Paul	paul.grassia@manchester.ac.uk
Grecov	Dana	dgrecov@mech.ubc.ca
Hejazi	Hossein	shhejazi@ucalgary.ca
Hewitt	Duncan	drh39@cam.ac.uk
Homsy	George -"Bud'	bud@pims.math.ca
Hormozi	Sarah	s_hormozi@yahoo.com
Jalaal	Maziyar	m_jalaal@yahoo.com
Kalliadasis	Serafim	s.kalliadasis@imperial.ac.uk
Karimfazli	Ida	idakf@interchange.ubc.ca
Kavehpour	Pirouz	pirouz@seas.ucla.edu
Khomami	Bamin	bkhomami@utk.edu
Ko	William	wka11@sfu.ca
Konaganti	Vinod	vkonaganti@chbe.ubc.ca
Krechetnikov	Rouslan	rkrechet@engineering.ucsb.edu
Kumar	Satish	kumar030@umn.edu

Lawrence	Greg	lawrence@civil.ubc.ca
Leal	Gary	lgl20@engineering.ucsb.edu
Magnaudet	Jacques	magnau@imft.fr
Maleki	Amir	amir.maleki.zamenjani@gmail.com
Mehrabian	Hadi	hadi.mehrabian@gmail.com
Meiburg	Eckart	meiburg@engineering.ucsb.edu
Mohammadigoushki	Reza	h.mohammadi@chbe.ubc.ca
Moin	Parviz	moin@stanford.edu
Moises	Gustavo	gustavomoises@yahoo.com
Noroozi	Nader	Noroozi@mech.ubc.ca
Nouar	Cherif	cherif.nouar@univ-lorraine.fr
Ouriemi	Malika	malika_ouriemi@brown.edu
Ponetti	Giordano	giordanoponetti@gmail.com
Roustaei	Ali	ali.rostai@gmail.com
Shaqfeh	Eric	akjensen@stanford.edu
Shen	Amy	amyshen@uw.edu
Steen	Paul	phs7@cornell.edu
Stockie	John	stockie@math.sfu.ca
Stoeber	Boris	boris.stoeber@ubc.ca
wachs	anthony	anthony.wachs@ifpen.fr
Ward	Thomas	thomasw@iastate.edu
Wetton	Brian	wetton@math.ubc.ca
Wu	Tenghu	tenghuwu@chbe.ubc.ca
Xu	XiuMei	xmxu@ymail.com
Yang	Li	yangli@corning.com
Zare	Marjan	marjan.zr64@gmail.com
Zenit	Roberto	zenit@unam.mx
Zick	Aaron	zick@zicktech.com

Directions:

General Travel Directions:

Feel free to search and plan your public transport rides by visiting http://www.translink.ca/, where directions, ticket costs and bus schedules are indicated.

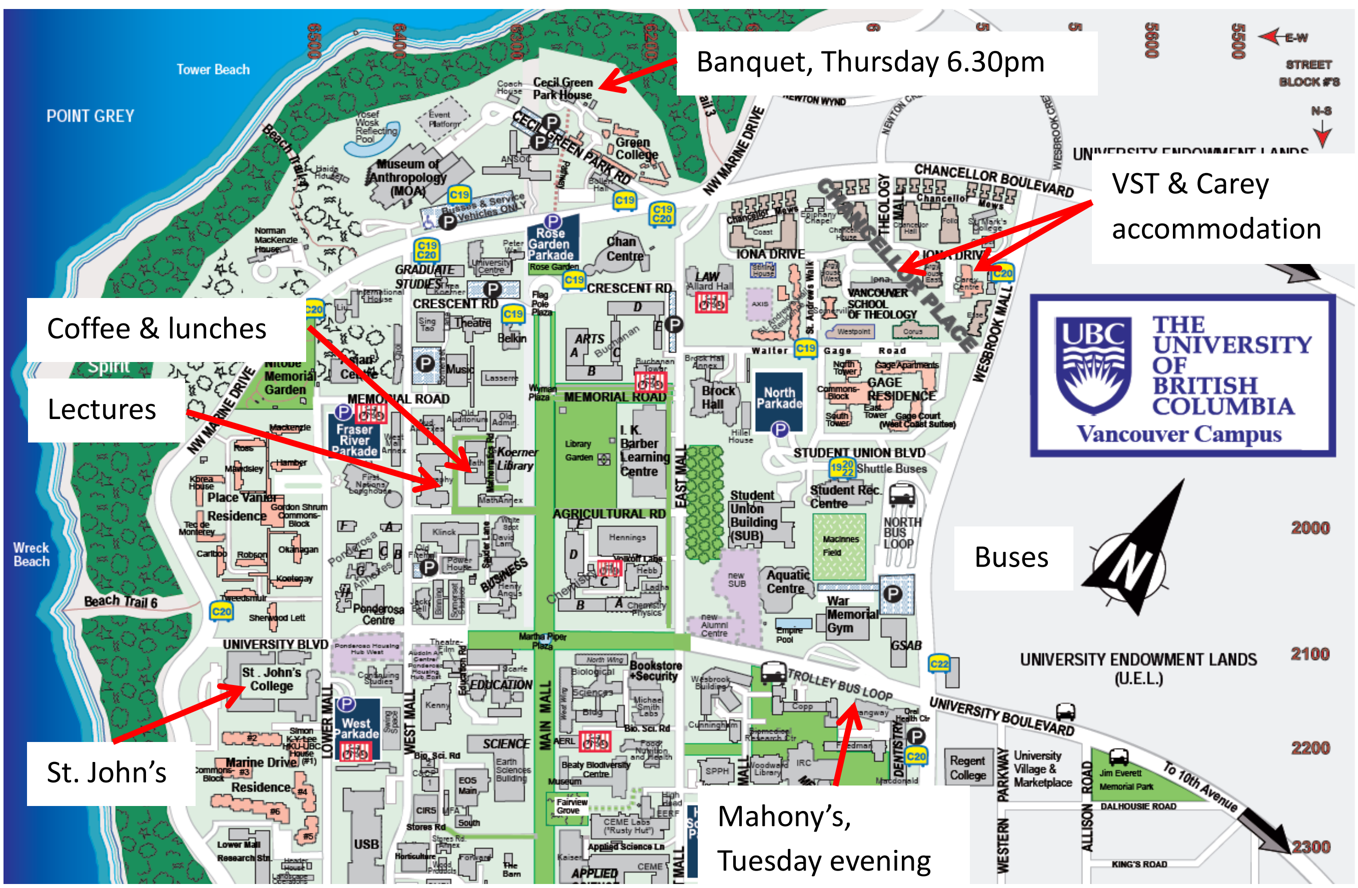
Airport to UBC:

Easiest by taxi (25min, around $30). By public transport, take the Canada Line (rail) to Broadway-City Hall station. From Broadway-City Hall station, cross Broadway and Cambie streets to get to the #99 UBC bus stop in front of London Drugs. Tickets (valid for the whole journey to UBC) can be purchased from the machine in the airport station. Cost: approximately $6. Journey time: Circa more than 1 hour.

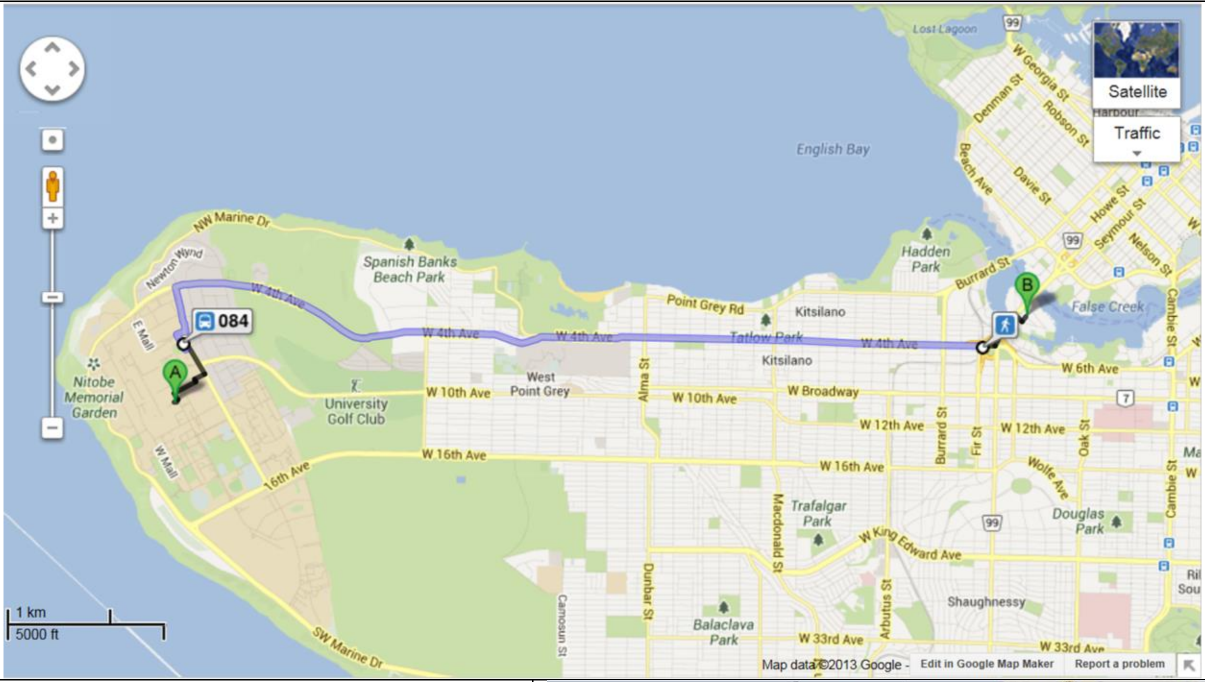
UBC Map link:

http://www.maps.ubc.ca/PROD/images/pdf/ubcmap.pdf

Locations on UBC campus:



Directions for dinner cruise: 24th July: 6.30pm onwards



We will sail on the M.V. Carousel II, (Accent Cruises Ltd, #100 1676 Duranleau St. Vancouver), sailing from Granville Island around the Vancouver shoreline from 7.00-10.00 PM. Boarding starts from 6.00 PM at the dock (see map to right).

Take bus 84 from the main UBC loop (bus times: 17.47, 18.02, 18.17…) and descend at 4th Avenue & Fir St., (ask the driver for the Granville Island stop). Walk down to Granville Island from 4th avenue.