Small scale hydrodynamics: theory and application in microfluidics and thin films (10w5035)

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1 Context and Objectives

The meeting was organized from the point of view that a revolution is currently occurring in the miniaturization of fluid mechanical devices. Many developments are driven by medical, biochemical, bioanalytical, nanoliter scale chemical reaction engineering, and microfluidic "lab-on-a-chip" devices. Still others find their motivation in the development of advanced materials, such as superhydrophobic and patterned surfaces with unique wetting, electrical and material properties, self-assembled materials that acquire their structure as a result of non-hydrodynamic forces, and so-called 'complex fluids': colloids, polymer solutions, and particulate suspensions, that involve what is often counter-intuitive fluid mechanical behavior. Electromagnetic forces, surface tension and surface tension variations due to coupling with other fields, substrate variations, and complex rheology all become more efficient at the small scales involved and represent additional forces and degrees of freedom that can be used to manipulate flows in new ways. Theories and approaches appropriate for larger scale fluid mechanics are either not valid or need to be re-interpreted or extended. For instance, the devices feature fluid layers so thin that often gravity is irrelevant while other forces created by, say, minute temperature, chemical or wettability gradients become dominant. Microfluidic devices often feature small scale mechanical pumps, sensors, and strong coupling between thermal, chemical, electromagnetic and fluid velocity fields. The further advancement of such devices would greatly benefit from mathematical modelling and predictive analysis.

Scientists working on microfluidics, and thin films, often operate in disparate and disconnected communities. The lead journals and scientific meetings are often quite different and often have different foci. The sheer pace of progress means that many ideas and avenues are possibly being pursued in parallel. Additionally, there is the lost opportunity for interdisciplinary approaches that enable quantum leaps forward in understanding and development of both new devices and new mathematical approaches. There is no obvious venue where experimentalists, modellers, and applied mathematicians from the two communities are brought into contact with the specific aim of identifying areas ripe for synergistic advances. This workshop provided exactly this venue.

Hence, the main objective of this workshop was to bring together the leading researchers in microfluidics and thin films from across several disciplines in order to foster awareness and the cross-disciplinary transfer of ideas. The broad and interdisciplinary nature of the participants led to a lively workshop characterised by interaction and discussion.

2 Scientific Progress and Outcomes

Participants were all allocated 25 minute talks with time for questions and discussion built into the format. The talks were grouped into sessions that followed broad themes, there was deliberately no attempt to separate theory and experiment talks. The workshop allowed younger researchers and postdocs to present their recent results, while more experienced researchers tended to present more of an overview of their research and of their area. All presentations were of very high quality and stimulated discussion, some leading to new collaborations. The speakers, talk titles and abstracts are listed in alphabetical order in the following section, with the programme itself given at the end of the report. Notably the programme was organised around themes rather than methods allowing for maximal interaction and, as can be seen from the absracts, was strongly inter-disciplinary in nature.

By all measures, the workshop was a success. We were fully subscribed at 43 participants, the vast majority of whom stayed for the entire week. In terms of demographics, the speakers included 8 women ranging from very senior full professors to assistant professors, postdoctoral researchers and PhD students, all from major universities and highly-ranked departments. There was also an excellent mix of junior and senior participants. There were 16 junior level researchers, including 2-3 postdoctoral fellows, representing a full 40 percent of the total number of attendees.

The workshop was very broad in scope, and encompassed the leading experts in experimental, computational, and theoretical aspects of a wide range of phenomena. This was one of its strengths, but makes a concise summary of outcomes difficult. We include here the following testimonials received, which give a good representation of the success of the workshop.

“I really enjoyed the workshop, and I would like to thank you for giving me the opportunity to come and present my work. The organization was splendid, and it was a very nice group of people. Also, I find that 25 minutes is sort [of] the ideal talk length... Regarding suggestions for a future workshop, I think you should definitely do it (or whoever else takes over, let me know if you need some help by the way). The setup is ideal, both for talks and informal discussions. I would suggest maybe having a few more students come and give talks (possibly shorter), as I think they would benefit from mixing with the faculty. And, at least in my mind, the more experimental talks, the better!”

“Thank you very much for organizing this outstanding workshop in such a nice environment! I think it was useful for people working actively in the field and it would be a good idea to organize something similar in 2-3 years. I would suggest to enforce speakers to be on schedule and to leave a bit more freedom when to have dinner since some of us come from different time zones.”

“The meeting covered a wide variety of topics... with all papers at the forefront of the area. I enjoyed the single session with all talks in the same lecture theatre, meeting new people and catching up with old friends. The facilities, such as computing/printing etc including the hall of residence were great. Nice informal atmosphere with plenty of opportunity for discussions. On the plus side also the fact that all attendees stayed at the same hall. Overall a great experience, hope there is a follow-up meeting.”

“[The meeting] was one of the best if not the best meeting I have attended. The scientific program was excellent and the workshop provided a very good opportunity to hear what people are thinking about in microfluidics etc. Without a doubt, it will influence the things I work on next... The organization, facilities etc. were all first class. Clearly, it would be very good to hold a similar meeting again.”

“Thanks again for organizing such a wonderful meeting in Banff, and for inviting me to be a part of it. It was a rare joy to spend four days in such a beautiful and stimulating environment.”

“Great environment for a workshop – small, high quality participants, meals together, lounge, all contributed to a very interactive environment. I met many people I had not previously known, furthered one collaboration and potentially started at least one other. The range of topics was great – a bit of eclecticism is good in meetings like this but you don’t want too much. I think this workshop struck the balance really well. I would be excited to attend another in a couple years.”

“I particularly enjoyed the conference at BIRS. The format... allows for much greater interaction between participants. As everyone stays in the dorm and eats in the cafeteria, it is difficult not to form contacts. As a new worker, these sorts of contacts are invaluable to me. Work I had done impinged on two of the topics... making several directly relevant to my research. In two of these cases, the work discussed had not been published and came from fields that I wouldn’t normally read the literature from... The mix of disciplines meant that there were people I would not normally see talk. The mix of theory and experiment made the conference particularly fruitful.... The organization of the conference around the topic of microfluidics rather than a technique made this sort of interaction more likely, but credit is due to the organizers for building a program that was so well integrated.”

“I had an excellent time and learned a great deal. The number of participants was just right—I had the chance to talk with everyone there. I also liked the length of the talks and the way there was usually a break after every 2 or 3 talks. Of course, the setting and facilities were superb. I would support having a similar workshop in the future, perhaps in 3 or 4 years... It would be good to bring in some new people so that there are fresh viewpoints. I think it worked very well the way you had a mix of junior and senior people, and people from a variety of disciplines and backgrounds."

"The workshop was very good: impeccably organized, top-notch scientific level, a spectacular location, and wonderful food! I was very impressed by the standard of the presentations: all speakers seemed genuinely concerned to put over their work in a clear and interesting way. I made several new contacts, and got ideas for problems to work on."

"It was really one of the best workshops that I have attended in a long time and did provide new collaborations and ideas, even in my own dept. It would be great to have another workshop."

"I am very honored to be invited to talk to such as distinguished audience at this point in my career. I learned a great deal in every talk and it was great to see what a wide range of problems and approaches people are studying in the small scale fluids world. A number of people had suggestions for future directions or directed me to relevant literature. I had an in depth discussion with one of the participants that will greatly help with some of the problems that have cropped up in the course of my experiments. The format was much better than a national meeting-type conference (my only other point of comparison). It really allowed for some in depth conversations to happen. A particular highlight for me was having meals with everyone else at the workshop. Not only was the food great, but it gave me a chance to meet people I probably would have never met at a national meeting in an informal environment."

3 Summary of Presentations

Shelley Anna: The Impact of Surfactant Sorption Kinetics on Microscale Tipstreaming In this talk, we examine the role of surfactant adsorption and desorption at the oil-water interface in the tipstreaming process, in which submicron sized droplets are synthesized via formation of a thin thread emitted from a larger parent drop.

Neil Balmforth: First contact in a viscous fluid A lubrication theory is presented for the effect of fluid compressibility and solid elasticity on the descent of a two-dimensional smooth object falling under gravity towards a plane wall through a viscous fluid. The final approach to contact, which takes infinite time in the absence of both effects, is determined by numerical and asymptotic methods. Compressibility can lead to contact in finite time either during inertially generated oscillations or if the viscosity decreases sufficiently quickly with increasing pressure. The approach to contact is invariably slowed by allowing the solids to deform elastically; specific results are presented for an underlying elastic wall modelled as a foundation, half-space, membrane or beam.

Michael Booty: Surfactant solubility effects We investigate the influence of surfactant, and in particular the influence of solubility of surfactant in the bulk flow, on the evolution of a prestretched inviscid bubble surrounded by a viscous fluid. Direct numerical simulations at low Reynolds number show that insoluble surfactant can cause the bubble to contract to form a quasisteady slender thread connecting parent bubbles, whereas in the absence of surfactant the bubble proceeds directly to pinch-off near a local minimum radius of the initial profile. Surfactant solubility effects in the diffusion-controlled regime are expressed by three parameters, and we present results on the influence of these on thread formation. The simulations are complemented by a long wave analysis for a capillary jet in the Stokes flow limit, which bears out the mechanisms described in the simulations. With soluble surfactant, a slender thread forms but can pinch-off later due to exchange of surfactant between the interface and exterior bulk flow. (Joint work with Yuan-Nan Young, Michael Siegel, and Jie Li.)

Richard Braun: Models for the Dynamics of the Human Tear Film Lubrication theory is used to describe the dynamics of models for the human tear film in one-dimensional moving domains and two-dimensional eye-shaped domains. In the latter, the boundary conditions and flow in the sub-millimeter menisci around the edge of the domain appear to be very important. Results for the two cases will be compared and contrasted. (This work is in collaboration with K.L. Maki, W.D. Henshaw, P.E King-Smith, L. P. Cook, T.A. Driscoll, and A. Heryudono)

Kenny Breuer: Droplet formation and contact line flows We look at a variety of problems motived by contact drop deposition - the generation of small drops on a hydrophobic substrate generated using a retracting needle. The resulting droplet size depends strongly on the complex interactions between the liquid bridge surface tension, governing droplet pinchoff, and the contact line motion which limits the liquid bridge retreat as a depositing needle is withdrawn from the substrate. We present theoretical results on the liquid bridge stability with a moving contact line, and explore the sensitivity of these results to the dynamic contact angle behavior. These predictions are compared with detailed experiments on the droplet size, free-surface shape and evolution and finally measurements, with sub-micrometer scale resolution, of the flow near the retreating contact line.

Joao Cabral: Spinodal Clustering of Nanoparticle-Polymer Mixture in Thin Films We report the spinodal clustering in polymer-nanoparticle mixtures in thin films of polystyrene (PS) and fullerenes C60. Supported PS-C60 blend fims annealed above Tg develop surface undulations with dominant wavelength lambda 1-10 micrometer, which depends on film thickness h (20-500 nm), molecular mass Mw, temperature T and time t. The initial wavelength scales with h and coarsen- ing kinetics follow $\lambda\ t^{\alpha}$. The morphology eventually pins at long times (t$\sim$72 h), while dewetting does not take place in this time frame. Power law exponents are found to be alpha=1/3 for large thick- nesses (h $\sim$ 170 nm) and to decrease effectively to zero as h $\rightarrow$ 20 nm. The spinodal morphology occurs for PS Mw $>$ 10 kg/mol while dewetting suppression and film stability is observed for lower Mw ($\sim$2 kg/mol). The emergence of a spinodal topography in high-Mw PS-C60 thin films results from the interplay between particle-particle and particle-substrate attraction.

Hsueh-Chia Chang: A Micro-Scale Electrokinetic Instability: Selection of the Over-Limiting Current We show experimentally and theoretically that the overlimiting DC current across a membrane or an electrode with a diffusion-limited electron-transfer reaction is determined by a hydrodynamic instability related to miscible fingering. An ion-depleted zone develops on one side of the membrane and propagates into the bulk as a diffusion front. However, the diffusion front destabilizes at a particular distance from the membrane, which is determined with a spectral theory specific to the self-similar diffusion front, and selects the depletion layer thickness to determine the ion flux density at the overlimiting current region.

Richard Craster: Rupture and interfacial deformation of electrokinetic thin films We investigate the evolution of an electrolyte film surrounding a second electrolyte core fluid inside a uniform cylindrical tube and in a core-annular arrangement, when electrostatic and electrokinetic effects are present. The limiting case when the core fluid electrolyte is a perfect conductor is examined. We analyse asymptotically the thin annulus limit to derive a nonlinear evolution equation for the interfacial position, that accounts for electrostatic and electrokinetic effects and is valid for small Debye lengths that scale with the film thickness, that is charge separation takes place over a distance that scales with the annular layer thickness. The equation is derived and studied in the Debye-Hückel limit (valid for small potentials) as well as the fully nonlinear Poisson-Boltzmann equation. These equations are characterised by an electric capillary number, a dimensionless scaled inverse Debye length and a ratio of interface to wall electrostatic potentials. We explore the effect of electrokinetics on the interfacial dynamics using a linear stability analysis and perform extensive numerical simulations of the initial value problem under periodic boundary conditions. Allied nonlinear analysis is carried out to investigate fully singular finite-time rupture events that can take place. Depending upon the parameter regime, the electrokinetics either stabilise or destabilise the film and, in the latter case, cause the film to rupture in finite time. In this case, the final film shape can have a ring or line-like rupture; the rupture dynamics are found to be self-similar. In contrast, in the absence of electrostatic effects, the film does not rupture in finite time but instead evolves to very long-lived quasi-static structures that are interrupted by an abrupt re-distribution of these very slowly evolving drops and lobes. The present study shows that electrokinetic effects can be tuned to rupture the film in finite time and the time to rupture can be controlled by varying the system parameters. Some intriguing and novel behaviour is also discovered in the limit of large scaled inverse Debye lengths, namely stable and smooth non-uniform steady state film shapes emerge as a result of a balance between destabilising capillary forces and stabilising electrokinetic forces.

Brian Duffy: Quasi-steady spreading of a thin ridge of fluid with temperature-dependent surface tension on a heated or cooled substrate We derive an implicit solution of the thin-film equations for the free-surface profile of the ridge, and use this (along with a Tanner law for the moving contact lines) to examine the possible forms that the ridge's evolution may take. In some cases we find that there may be three (qualitatively different) stable ”stationary” states. This is joint work with G. J. Dunn, S. K. Wilson and D. Holland.

Jan Eijkel: The generation of sub-micrometer droplets in a microfluidic system and their self-organization into 3D lattices We generated O/W droplets at the interface between a nanochannel (100-900 nm high) and a microchannel (10 micrometer high). Droplets with a diameter downto 700 nm were produced. Under certain conditions the droplets spontaneously organized into a 3D lattice inside the microchannel. The droplet formation mechanism at the nanochannel/microchannel interface involves the formation of thinning oil filaments extending to the interface, and at present is not understood.

Eliot Fried: Derivation of a dynamical equation for the contact line of an evaporating sessile drop During the early 1950s, J.D. Eshelby developed a framework for the defective crystal lattices. Central to that framework is the notion of configurational force. Whereas Newtonian forces are linked to the motion of material particles, configurational forces are associated with defects that may move with respect to material particles. For crystals, examples of such objects include impurities, dislocations, cracks, and phase interfaces. Eshelbys approach involved a creative synthesis and extension of ideas appearing in J.L. Lagranges work on generalized coordinates and forces, J.W. Gibbs work on the equilibrium of heterogeneous substances, J. Larmors work on the luminiferous aether, and E. Noethers work on conservation laws arising from the invariance of functionals. In Eshelbys approach, the configurational force acting on a defect is determined by computing the variation of the total energy with respect to changes in the configuration of the defect. Eshelbys contributions set the stage for many important contributions to the study of defects in solids, perhaps the most celebrated of these being to fracture, where the relevant configurational force acts at the tip of a crack and is the J-integral derived independently, and without knowledge that Eshelby had done so previously, by G.P. Cherepanov and J.R. Rice.

Being variational, Eshelbys approach is predicated on the provision of constitutive relations. Further, it allows for at most infinitesimal departures from equilibrium and accounts only artificially for dissipative mechanisms which generally accompany the motion of defects. Beginning in the early 1990s, M.E. Gurtin constructed a theory that frees Eshelbys framework of these restrictions. This approach distinguishes carefully between basic laws, which hold for large classes of materials, and constitutive relations, which distinguish between different classes of materials. Configurational forces are treated as primitive and are assumed to obey a balance distinct from the conventional balances of linear and angular momentum. Further, power expenditures associated with the motion of defects are accounted for properly in the statement of the energy balance and the entropy imbalance is used to determine physically reasonable restrictions on constitutive relations. A major advantage of Gurtins theory is that objects such as the J-integral arise independent of constitutive assumptions and encompass not only to the standard elastic case but also to cases where inelastic effects are present.

Recently, Gurtin's approach has been used to develop a theory for evaporation and other fluid-fluid phase transformation, with focus on interfacial equations. In this talk, that theory is extended to yield a dynamical equation the contact line of an evaporating sessile drop. In addition to bulk and interfacial excess quantities, this equation accounts naturally for the energy of the contact line and for frictional terms that have previously been included on an ad hoc basis.

Michael Graham: Transport and collective dynamics in suspensions of swimming microorganisms A suspension of swimming organisms is an example of an active complex fluid. At the global scale, it has been suggested that swimming organisms such as krill can alter mixing in the oceans. At the laboratory scale, experiments with suspensions of swimming cells have revealed characteristic swirls and jets much larger than a single cell, as well as increased effective diffusivity of tracer particles. This enhanced diffusivity may have important consequences for how cells reach nutrients, as it indicates that the very act of swimming toward nutrients alters their distribution. The enhanced diffusivity has also been proposed as a scheme to improve transport in microuidic devices and might be exploited in microuidic cell culture of motile organisms or cells.

The feedback between the motion of swimming particles and the fluid flow generated by that motion is thus very important, but is as yet poorly understood. In this presentation we describe theory and simulations of hydrodynamically interacting microorganisms that shed some light on the observations. In the dilute limit, simple arguments reveal the dependence of swimmer and tracer velocities and diffusivities on concentration. As concentration increases, we show that cases exist in which the swimming motion generates dramatically enhanced transport in the fluid. This transport is coupled to the existence of long-range correlations of the fluid motion. Furthermore, the mode of swimming matters in a qualitative way: microorganisms pushed from behind by their flagella are predicted to exhibit enhanced transport and long-range correlations, while those pulled from the front are not. A physical argument supported by a mean eld theory sheds light on the origin of these effects. These results imply that different types of swimmers have very different effects on the transport of nutrients or chemoattractants in their environment; this observation may be related to the evolution of different modes of swimming.

Michael Gratton: Suppressing van der Waals driven rupture through shear. An ultra-thin viscous film on a substrate is susceptible to rupture instabilities driven by van der Waals (London dispersion) attractions. When a unidirectional “wind” shear τ is applied to the free surface, the rupture of instabilities in two dimensions is suppressed for τ greater than a critical value τ_c and is replaced by a new, permanent, finite amplitude structure, a Dispersion-Capillary Wave that travels at approximately the speed of the surface. If three-dimensional disturbances are allowed, the shear is decoupled from disturbances perpendicular to the flow, and line rupture would occur. In this case, replacing the unidirectional shear with a new shear whose direction rotates with angular speed $\hat{\omega}$ suppresses the rupture if $\tau >\sim 2\tau_c$. For the maximizing wave number, $\tau_c \approx 10^{-2}\,\mathrm{dyn\,cm^{-2}}$ at $\hat{\omega} \approx 1\,\mathrm{rad\,s^{-1}}$ for a film with physical properties similar to water at a thickness of $100\,\mathrm{nm}$.

Anette Hosoi: Low temperature solvent annealing of organic thin films These are films made of organic materials for use in electronics and LCD panels. In order to increase mobility, it is necessary to convert the amorphous state to a crystalline one. I will discuss both experimental results and models describing the annealing process.

Serafim Kalliadasis: Influence of spatial heterogeneities on contact line dynamics We consider contact line motion over spatially heterogeneous substrates by using a two-dimensional droplet of a partially wetting fluid spreading over such substrates as a model system. The spreading dynamics is modelled under the assumption of small contact angles where the long-wave expansion in the Stokes-flow regime can be employed to derive a single equation for the evolution of the droplet thickness. Through a singular perturbation approach, the flow in the vicinity of the contact line is matched asymptotically with the flow in the bulk of the droplet to yield a set of two coupled differential equations for the spreading rates of the two droplet fronts. Analysis of these equations for deterministic substrates reveals a number of intriguing features that are not present when the substrate is flat. In particular, we demonstrate the existence of multiple equilibrium states whichallows for a hysteresis-like effect on the apparent contact line. Further, we demonstrate a stick-slip-type behaviour of the contact line as it moves along the local variations of the substrate shape and the interesting possibility of a relatively brief recession of one of the contact lines. Finally, our formalism is used to investigate droplet equilibria in the presence of small-scale, random substrate variations. Using an appropriate stochastic representation for such substrates, we provide a rational definition of ”substrate roughness” and we assess the statistics of droplet equilibria and dynamics of droplet spreading via a perturbation approach.

R. Krechetnikov: On Marangoni-driven interfacial singularities and their resolution In this talk I will discuss the origin and physical mechanisms of Marangoni-driven singularities at fluid interfaces, in particular in the context of tip-streaming problems, and the development of a mathematical theory aimed at their resolution.

Satish Kumar: Stretching and Slipping of Liquid Bridges near Plates and Cavities The dynamics of liquid bridges are relevant to a wide variety of applications including high-speed printing, extensional rheometry, and floating-zone crystallization. Although many studies assume that the contact lines of a bridge are pinned, this is not the case for printing processes such as gravure, lithography, and microcontacting. To address this issue, we use the Galerkin/finite element method to study the stretching of a finite volume of Newtonian liquid subject to contact line slip and confined between (i) two flat plates, one of which is stationary and the other moving, and (ii), one moving flat plate and a stationary cavity.

Eric Lauga: Small-scale swimming: Physical and mathematical constraints Fluid mechanics plays a crucial role in many cellular processes. One example is the external fluid mechanics of motile cells such as bacteria, spermatozoa, and essentially half of the microorganisms on earth. In this talk we discuss the basic fluid mechanics processes relevant for cell locomotion.

Charles Maldarelli: The Self-Propulsion of a Droplet in a Two-Dimensional Microchannel Driven by a Gradient in the Superhydrophobicity of the Channel Walls Methods for the propulsion of aqueous droplets through a network of microfluidic channels is central to the development of lab-on-chip technologies for chemical analysis. These technologies use the coordinated trafficking and combination of droplets moving through the microfluidic network to execute the fundamental steps of dilution, reaction and separation which are involved in a chemical study. The dominance of capillary forces on the microfluidic length scale suggests their use in devising mechanisms for the droplet motion that would be self-propelling, and would therefore not require off-chip sources of power to actuate the motion. This study examines the hydrodynamics of contact angle propulsion of droplets in microfluidic channels. We consider the propulsion of a single droplet which occludes a two dimensional channel filled with air. The arcs representing the interfaces (menisci) of the droplet intersect the inside surface of the channel at finite contact angles with the magnitude of the angle and hence the curvature of the arcs determined by the surface energy of the walls. In contact angle propulsion, the capillary pressure in the liquid under the menisci on either end of the droplet is used to propel the droplet down the channel. If the channel walls are modified so that the contact angle of an aqueous phase in contact with the channel wall changes with position down the channel, a drop situated in this gradient will experience a difference in the curvatures and capillary pressures between its two ends which can propel the droplet. We consider the case in which gradients in the contact angle are generated on a microtextured surface. Aqueous droplets in contact with hydrophobic, microtextured surfaces trap air in the gaps between the solid parts of the texture creating very large (super hydrophobic) contact angles (Cassie-Baxter wetting) relative to the plane of the wall. A gradient in contact angle along a channel wall created by a gradient in microtexture is ideal for propelling droplets because the droplet liquid moves with reduced friction over the cushions of trapped air, and the larger contact angles allow drops to roll, which prevents liquid from being left behind a moving drop. A simple model of a surface embedded with a uniform microtexture is constructed consisting of contiguous half disks of a given radius and surface energy with the disk centers arranged in a straight line parallel to the plane of the wall. Low Reynolds number solutions for the pressure driven movement of a semi-infinite slug through the channel are obtained to identify the conditions for Casie-Baxter wetting. Gradients in the microstructure are also constructed to study propulsion. Microtexture gradients are obtained by increasing the radius of the disks in the direction down the channel while keeping the height of the disks relative to the plane of the wall constant. Solutions are obtained for the velocity of droplets along these surfaces as a function of the microtexture parameters and surface hydrophobicity.

Omar Matar: Interfacial flows in the presence of additives The presence of additives, which may or may not be surface active, can have a dramatic influence on interfacial flows. The presence of surfactants alters the interfacial tension and drives Marangoni flow that leads to fingering instabilities in drops spreading on ultra-thin films. Surfactants also play a major role in coating flows, foam drainage, jet breakup and may be responsible for the so-called "super-spreading" of drops on hydrophobic substrates. The addition of surface-inactive nano-particles to thin films and drops also influences the interfacial dynamics and has recently been shown to accelerate spreading and to modify the boiling characteristics of nanofluids. These findings have been attributed to the structural component of the disjoining pressure resulting from the ordered layering of nanoparticles in the region near the contact line. In this talk, we present a collection of results which demonstrate that the above-mentioned effects of surfactants and nano-particles can be captured using long-wave models.

M.J. Miksis: Dynamics of Lipid Bilayer Vesicles in Viscous Flow The dynamics of a lipid bilayer vesicle in a Stokes flow is studied. The model accounts for the bending resistance of the membrane, the transport of lipids along the monolayers, and the slip between the monolayers. Small amplitude perturbations from a spherical vesicle are considered and at leading order, a nonlinear system of equations for the dynamics of the interface and the mean lipid density is found and studied.

Sushanta Mitra: Capillary Flow for Microfluidic Applications Capillary flow is often used in various microfluidic devices like Lab-on-a-Chip (LOC) to transport biomolecules, chemicals, and analytes from the inlet reservoir to different locations within the device. The talk will discuss the mechanism of capillary transport in microchannels in presence of a finite reservoir volume. The influence of microbead suspension on the capillary flow will also be discussed. Often electrical fields are also used in a LOC to manipulate analytes of interest. A mathematical framework to investigate the combined electroosmotic and capillary flow will be presented. The talk will end with an application of capillary transport through a microfluidic device with integrated pillars.

Susan J. Muller: Experiments in microfluidic stagnation point flows: opportunities for trapping, deforming, and analyzing DNA, vesicles & other microscale objects We have designed and fabricated a series of microdevices that create stagnation points at which microscale objects may be trapped and subjected to flow forces. In the simplest of these, the cross-slot, microscale objects such as DNA may be trapped and stretched to a steady-state extension that is determined by the flow strength, as demonstrated by the pioneering work of Chu and co-workers (Science, 276, 1997). We will present three extensions of this idea: 1) the design and use of more complex devices to allow the systematic variation of flow type as well as flow strength near the stagnation point (the microfluidic four-roll mill) , 2) the use of stagnation point flows for single molecule studies of enzyme binding kinetics and sequence detection in DNA, and 3) the use of stagnation point flows for studies of the dynamics of vesicles.

A. Pascall: Induced charge electrokinetics over controllably contaminated electrodes Experimental data on induced charge electro-osmosis (ICEO) and related phenomena have shown that the standard theory consistently overpredicts slip velocities by up to a factor of 1000. Here we present experiments in which we controllably ‘contaminate’ the metallic surface with a thin dielectric film or Au-thiol self assembled monolayer, and derive a theory for ICEO that incorporates both dielectric effects and surface chemistry, which both act to decrease the slip velocity relative to a ‘clean’ metal. Data for over a thousand combinations of electric field strength and frequency, electrolyte composition, dielectric thickness and surface chemistry show essentially unprecedented quantitative agreement with our theory.

D.T. Papageorgiou: Electrostatically induced instabilities in interfacial flows. Several problems will be discussed where electric fields are used to either enhance or reduce interfacial instabilities found in a wide class of viscous flows. For example, electric fields can destabilise two-layer shear flows or falling film flows at small Reynolds numbers, and can increase the deformation of viscous drops suspended in a Couette device. In the case of axisymmetric liquid jets, we predict a stabilisation of the capillary pinching event accompanied with the formation of liquid microthreads. We use a combination of asymptotically derived evolution equations and direct numerical simulations in order to analyse such probelms.

Sumita Pennathur: Fundamental transport of electrolyte solutions in nanofluidic channels with finite wall charge In this talk, I would like to present both theoretical and experimental results pertaining to electrolyte flow in nanofludic channels. This will include channels of different heights, electric double layer thicknesses, and surface wall charge composition, as well as different electrolyte fluids. Both pressure-driven and electroomostic flow will be investigated.

Nikos Savva: Three-phase contact line at small scale We investigate the area around an equilibrium three-phase contact line at a small scale by using a density functional approach. A typical system is made of a planar wall in contact with a Lennard-Jones gas below the critical temperature. The wall exerts an attractive force on the fluid molecules so that a thin film can usually form between the wall and the gas. We focus on two cases. When the chemical potential is smaller than its coexistence value and the system presents a phase transition with respect to the film thickness, we examine the area between the two equilibrium film thicknesses. It appears to be smooth and several molecular diameters long. When the chemical potential is at its coexistence value, computations of the equilibrium density profiles show a well formed contact angle whose value follows closely the Young equation. A deviation from this equation is observed in the immediate vicinity of the contact line.

Eric S.G. Shaqfeh: The Microfluidics of NonSpherical Colloidal Particles and Vesicles with Application to Blood Additives Many dispersions of colloidal particles with application in materials processing, biological assays, or medicine, contain elongated particles (e.g. ellipsoidal disks, rods, etc.) Recently these particles have been used in drug delivery applications because of the inability of leukocytes to easily rid them from the circulation. Moreover such particles are useful at the nanoscale for application in cancer therapies, either for detection of tumor vasculature or for the delivery of anti-cancer agents to tumor endothelial cells. Thus, the study of anisotropic particulate flows with adhesion in microchannels especially in mixtures with vesicle flows (i.e. red blood cells) has taken on a particularly important set of engineering applications. We will review our computer simulations of these processes with a view toward virtual prototyping and engineering these therapies.

Amy Shen: Complex fluids under confinement and flow The flow of complex fluids in confined geometries produces rich and new phenomena due to the interaction between the intrinsic length-scales of the fluid and the geometric length-scales of the device. In this talk, I will choose two model systems to illustrate the idea. First, I will focus on a micellar solution system that yields a novel route to synthesizing bio-compatible nanoporous sol-gels. Through a combination of experiment and modeling I will show how self-assembly, confinement, and flow can be utilized to control fluid microstructure and system phase transitions, and thus to enhance the controlled synthesis of bio-compatible new materials. Second, I will illustrate how confinement and flow can modify the self-assembly of supramolecular hydrogels and their subsequent thermal properties.

Mike Siegel: A hybrid numerical method for fluid interfaces with soluble surfactant

We address a significant difficulty in the numerical computation of fluid interfaces with soluble surfactant that occurs in the practically important limit of large bulk Peclet number Pe. At thigh values of Pe in typical fluid-surfactant systems, there is a transition layer near the interface in which the surfactant concentration varies rapidly. Accurately resolving this layer is a challenge for traditional numerical methods but is essential to evaluate the exchange of surfactant between the interface and bulk flow. We present recent work that uses the slenderness of the layer to develop a fast and accurate ‘hybrid’ numerical method that incorporates a separate analysis of the dynamics in the transition layer into a full numerical solution of the interfacial free boundary problem.

Todd Squires: Microrheology of phospholipid monolayers: direct visualization of stretching, flowing, yielding and healing While the static properties of fluid-fluid interfaces have long been studied – and continue to be – the dynamic properties of interfaces have proven more elusive. I will describe a new technique we have developed to measure the interfacial rheology – the viscous and elastic properties – of fluid-fluid interfaces, typically laden with some surface-active species (molecular surfactants, copolymers, colloids, etc.). Using microfabrication techniques, we make ferromagnetic, amphiphilic microdisk probes that are ideally suited for active interfacial microrheology. By applying an oscillatory torque using electromagnets, and measuring the resulting (oscillatory) displacement, we create a small-scale Couette interfacial rheometer that is exceedingly sensitive to the rheology of the interface. A novel feature is our ability to directly visualize the interface during the measurement, which allows us to directly correlate the microstructural deformation with the measured response. In particular, we explore the linear and nonlinear rheology of a monolayer of the phospholipid DPPC in the liquid-condensed phase, which our experiments reveal to have a far richer dynamical response than has been previously reported. In particular, we demonstrate viscoelasticity, history-dependence, yielding, aging and a surprisingly long-lived recoil, which we relate directly to deformation and cooperative motion of individual LC domains.

Kathleen Stebe: Orientation and Assembly of anisotropic particles by capillary interactions There is significant scientific and technological potential if reliable means are developed to assemble anisotropic particles into ordered structures. Capillary attraction holds promise as a means of orienting, assembling and positioning particles. Capillary interactions arise spontaneously between partially wet particles at fluid interfaces. Particles at interfaces deform the interface to satisfy their wetting boundary conditions. The deformations expand the area of the interface relative to a planar case. The product of this excess area and the surface tension is an excess energy associated with the particle. Capillary attractions arise when deformation fields from neighboring particles overlap; the excess area created by the particles decreases as the particles approach each other. Capillary interactions are remarkably large; the surface tension of an aqueous-air interface is 72 mN/m or 18 kT/nm2, so the elimination of even 1 nm2 of surface area translates into significant energy reduction in particle assembly. Here, particles with shape anisotropy create undulations with excess area that can be locally elevated at certain locations around the particle. The local elevation of excess area (and therefore excess energy) makes these sites locations for preferred assembly, causing particles to orient and aggregate in preferred orientations. We present means to dictate object orientation, alignment, and the sites for preferred assembly, including means of promoting registry of features on particles. We also demonstrate that particle deformation fields interact with background interface shape to assume preferred alignments. These ideas are developed for the example of a right circular cylinder using analysis, experiment and numerics. A series of other shapes are then studied to illustrate the generality of the concepts developed.

Paul Steen: Vibrations of a constrained cylindrical interface Pinning a cylindrical liquid/gas interface along an axial line stabilizes the Plateau-Rayleigh instability, as is well-known. We generalize this kind of constraint to include partial contact of the liquid with a conforming solid support, and study the stability limits and the inviscid capillary oscillations of the interface, as both depend on the extent of constraint.

Jean-Luc Thiffeault: Nonlinear dynamics of phase separation in thin films We present a long-wavelength approximation to the Navier-Stokes Cahn-Hilliard equations to describe phase separation in thin films. The equations we derive underscore the coupled behaviour of free-surface variations and phase separation. We introduce a repulsive substrate-film interaction potential and analyse the resulting fourth-order equations by constructing a Lyapunov functional, which, combined with the regularizing repulsive potential, gives rise to a positive lower bound for the free-surface height. The value of this lower bound depends on the parameters of the problem, a result which we compare with numerical simulations. While the theoretical lower bound is an obstacle to the rupture of a film that initially is everywhere of finite height, it is not sufficiently sharp to represent accurately the parametric dependence of the observed dips or 'valleys' in free-surface height. We observe these valleys across zones where the concentration of the binary mixture changes sharply, indicating the formation of bubbles. Finally, we carry out numerical simulations without the repulsive interaction, and find that the film ruptures in finite time, while the gradient of the Cahn–Hilliard concentration develops a singularity.

Dmitri Tseluiko: Electrified liquid films When applied, an electric field affects the stability of a liquid film and can either reduce or promote irregularities in the film surface, both of which can be desirable for applications. I will consider various situations when an electric field acts of liquid films flowing down flat plates or over topographical features.

Jean-Marc Vanden-Broeck: The influence of electric fields on nonlinear free surface flows Nonlinear free surface flows in the presence of electric fields are studied. Both inviscid and viscous fluids are considered. The mathematical problem involves solving the fluid mechanics equations coupled with the Maxwell equations. Fully nonlinear solutions are obtained by boundary integral equation methods and asymptotic solutions are derived for thin films.

Thomas Ward: Droplet production in a microfluidic flow focusing device via interfacial saponification chemical reaction Microfluidic flow-focusing technology will be used to investigate the production of a surfactant via an interfacial chemical reaction. In the absence of a chemical reactions the drop shapes remain constant from the time of break up at the flow-focusing nozzle until they exit the channel. In the presence of the chemical reaction there is modification of the shape depending on the reactant concentrations. These values are measured for a variety of flow conditions with observable trends that seem to depend on the reaction rate, suggesting that the Damköhler number may be the most suitable parameter for characterizing these types of flows.

Stephen Wilson: Theoretical and Experimental Studies of Droplet Evaporation Combined programme of physical experiments and mathemtical theory has cast new light on the ubiquitous problem of droplet evaporation, in particular the key role the substrate and the atmosphere play in this physically important problem. In this talk I'll review our recent work in this area and highlight directions for future study.

Leslie Yeo: Peculiar Interfacial Phenomena Driven by Surface Acoustic Waves The fluid-structural coupling arising from the large substrate accelerations, typically up to 10 million g's, associated with surface acoustic waves give rise to peculiar microscale colloidal and interfacial phenomena. Interesting free surface colloidal patterning dynamics are observed at the low power spectrum whereas interfacial destabilization leading toward long slender jets and even drop atomization is observed at the high power spectrum. These unique phenomena provide ample opportunities for further investigation, particularly with regards to the fundamental physicochemical mechanisms governing the poorly understood behaviour and their application for ultrafast microfluidic actuation and manipulation.

Hong Zhao: Direct numerical simulation of vesicle dynamics in shear flow and generalized linear flows The dynamics of vesicle in shear flow and generalized linear flows is of intense research interest. Besides the tank treading and tumbling motions that are predicted by the classic Keller–Skalak theory, the vesicle can undergo a third "trembling" motion as observed in experiment. There have been several perturbation theories for explaining the phenomena and predicting the boundaries of flow regime transition. We herein perform high–fidelity direct numerical simulations that are based on Stokes–flow boundary integral equations, where the vesicle is modeled as a bending–resisting two-dimensional incompressible fluid that is commonly accepted and used in perturbation theories. The tank-treading angles obtained numerically agree well with experiments. Under different flow parameters, all three motion patterns (tank–treading, tumbling and trembling) are obtained unambiguously from our deterministic simulations. The transition boundaries between flow regimes are determined for vesicles of several reduced volumes, and are compared with both experiments and perturbation theories.

4 The programme

Table 1: Monday, 8th February, 2010:
Morning **Dewetting & Phase Phenomena**
Afternoon **Substrate effects and contact lines**,

08.45-09.00	Welcome to BIRS	BIRS Station Manager
09.00-09.25	J-L. Thiffeault	Nonlinear dynamics of phase separation in thin films
09.25-09.50	E. Fried	Derivation of a dynamical equation for the contact line of an evaporating drop
09.50-10.15	S. Wilson	Theoretical and experimental studies of droplet evaporation
10.15-10:45	Coffee	
10.45-11.10	A. Hosoi	Low temperature solvent annealing of organic thin films
11.10-11.35	B. Duffy	Quasi-steady spreading of a thin ridge of fluid
11.35-12:00	M. Gratton	Suppressing van der Waals driven rupture through shear
12.00-13.30	Lunch	
13.30-14.00	Group Photo	
14.00-14.25	C. Maldarelli	The self-propulsion of a droplet in a two-dimensional microchannel
14.25-14.50	K. Breuer	Droplet formation and contact line flows
14:50-15:20	Coffee	
15.20-15.45	N. Balmforth	First contact in a viscous fluid
15.45-16.10	N. Savva	Influence of spatial heterogeneities on contact line dynamics
16.10-16.35	S. Kalliadasis	Three-phase contact line at small scale
16:35-17:00	Discussion	
17.30-19.30	Dinner	

Table 2: Tuesday, 9th February, 2010:
Morning **Dispersed systems: droplets and particles**,
Evening **Interfacial flows and thin films**

09.00-09.25	K. Stebe	Orientation and assembly of anisotropic particles by capillary interactions
09.25-09.50	J. Eijkel	The generation of sub-micrometer droplets in a microfluidic system
09.50-10.15	T. Ward	Droplet production in a microfluidic flow focusing device
10.15-11:00	Coffee	
11.00-11.25	S. Anna	The impact of surfactant sorption kinetics on microscale tipstreaming
11.25-11.50	J. Cabral	Spinodal clustering of nanoparticle-polymer mixtures in thin films
12.00-13.30	Lunch	
13.30-14.30		Guided tour of Banff Centre
14.30-17.30	Free Afternoon	Discussion/ Group meetings
17.30-18.30	Dinner	
18.30-18.55	P. Steen	Vibrations of a constrained cylindrical interface
18.55-19.20	S. Kumar	Stretching and slipping of liquid bridges near plates and cavities
19.20-19.45	L. Yeo	Peculiar interfacial phenomena driven by surface acoustic waves
19.45-20.10	R. Braun	Models for the dynamics of the human tear film
20.10-20.35	S. Mitra	Capillary flow for microfluidics

Table 3: Wednesday, 10th February, 2010:
Morning **Bio-Microfluidics** ,
Afternoon **Complex Fluids and Marangoni flows**

09.00-09.25	E. Shaqfeh	The microfluidics of non-spherical colloidal particles and vesicles
09.25-09.50	H. Zhao	Direct numerical simulation of vesicle dynamics in shear flow
09.50-10.15	M. Miksis	Dynamics of lipid bilayer vesicles in viscous flow
10.30-11:00	Coffee	
11.00-11.25	S. Muller	Experiments in microfluidic stagnation point flows
11.25-11.50	E. Lauga	Hydrodynamic interactions in small-scale swimming
12.00-13.30	Lunch	
13.30-13.55	O. Matar	Interfacial flows in the presence of additives
13.55-14:20	M. Graham	Transport and collective dynamics in suspensions of swimming microorganisms
14.20-14:45	A. Shen	Complex fluids under confinement and flow
15.00-15.30	Coffee	
15.30-15.55	R. Krechetnikov	On Marangoni-driven interfacial singularities and their resolution
15.55-16.20	M. Booty	Surfactant solubility effects
16.20-16.45	M. Siegel	A hybrid numerical method for fluid interfaces with soluble surfactant
17.30-19.30	Dinner	

Table 4: Thursday, 11th February, 2010:
Morning and Evening **Electrokinetics: dynamics and instabilities**,

09.00-09.25	T. Squires	Microrheology of phospholipid monolayers
09.25-09.50	S. Pennathur	Fundamental transport of electrolyte solutions in nanofluidic channels
09.50-10.15	A. Pascall	Induced charge electrokinetics over controllably contaminated electrodes
10.30-11:00	Coffee	
11.00-11.25	D. Tseluiko	Electrified liquid films
11.25-11.50	J-M. Vanden-Broeck	The influence of electric fields on nonlinear free surface flows
12.00-13.30	Lunch	
13.30-17.00	Afternoon	Discussion
17.30-18.30	Dinner	
18.30-18.55	H-C. Chang	A Micro-Scale Electrokinetic Instability
18.55-19.20	R. V. Craster	Rupture and interfacial deformation of electrokinetic thin films
19.20-19.45	D. T. Papageorgiou	Electrostatically induced instabilities in interfacial flows