Poster titles and abstracts

Boyle, Christopher (University of Strathclyde)

Investigation into fluctuations in jammed suspensions

Fluids can have unexpected responses to induced flow: shear thickening fluids have increasing viscosity with shear stress, shear thinning have decreasing viscosities. Particle suspensions often exhibit these Non-Newtonian rheological behaviours. Shear thickening can even be dramatic enough that the fluid starts to act like a solid, an effect termed shear jamming [1]. In the Wyart-Cates friction model [2], upon increasing stress, above some critical value, the shear overpowers lubrication of the fluid and the particles move into frictional contact, causing the jam.

Jammed fluids under shear have been seen to have fluctuating shear rates [3,4] at fixed stresses. The statistics of these fluctuations has been studied in a previous work using a sensor consisting of a piezoelectric transducer with an attached probe, termed the Piezoelectric Needle Device (PND).

A rheometer is currently being designed and built to be used with the PND to provide the simultaneous collection of PND and rheological data. This will also provide a modular and extensible apparatus for future investigations. To gain a better understanding of local measurements of the fluctuations, we compare the PND sensor data to simultaneous global rheological measurement.

[1] E. Brown & H. Jaeger, Shear thickening in concentrated suspensions: phenomenology, mechanisms, and relations to jamming, Reports on Progress in Physics, 77 1--23 (2013).
[2] M. Wyart & M. Cates, Discontinuous shear thickening without inertia in dense non-Brownian suspensions, Physical Review Letters, 112(9), 1--5 (2014).
[3] C. Forsyth, 2015, Complex flow of concentrated suspensions. PhD, University of Strathclyde, Glasgow UK.
[4] M. Hermes, B. Guy, W. Poon, G. Poy, M. Cates & M. Wyart, Unsteady flow and particle migration in dense non-Brownian suspensions, Journal of Rheology, 60, 905--914 (2016).

Houston, Gemma (University of Strathclyde)

Viscoelastic effects for mixing enhancement in multiphase flows

Gemma Houston and Mónica S. N. Oliveira (University of Strathclyde)

The small length-scales typical of microfluidics, in which surface effects are enhanced, enable the generation of flows with high deformation rates and accentuate the role of elasticity to levels far beyond those typical at conventional scales, while keeping inertia low. These unique conditions result in the ability to promote elastic-driven instabilities and turbulence even when there are no inertial effects. These instabilities and "turbulent-like" characteristics can be used to promote mixing enhancement under adverse conditions, like in the case of very viscous systems or flows at small scales, as turbulent flows are known to mix things much more efficiently.

In this work, we make use of experimental microfluidic platforms and aim to obtain fundamental insight into the impact of instabilities triggered by elasticity and assess the mixing effectiveness of elastic turbulence in multiphase flow systems (where two immiscible liquids are present). Different geometrical configurations are used in the experiments, but here we focus on the flow-focusing device, composed of four orthogonal channels (three inlets and one outlet), which generates a strong extensional flow. Two immiscible fluids are used in the inlet streams, an aqueous polymeric solution that exhibits a viscoelastic rheology and an oleic fluid. Fluorescence microscopy is used to visualise the flow and we investigate the effects of geometrical parameters, velocity ratio between the lateral and main central streams and interfacial tension on the flow dynamics and the onset of the instabilities.

Kelly, Nathaniel (University of Bath)
Measurement of secondary flow in blood analogue fluids using relative torque

Introduction: Multiphase by nature, blood is a complex fluid. Containing cells and proteins suspended in a viscous fluid it has shear-thinning flow behaviour. An assumption often made is that it is Newtonian across all shear rates, which can cause inaccuracies when investigating transition to turbulence. Commonly used for viscometric tests a rheometer can be used to study turbulence of fluids [1] of different rheologies. The aim of this study is to explore the development of turbulent secondary flow of a Newtonian and a shear-thinning blood analog using a rotational rheometer.

Methods: A TA Instruments (DHR2) rheometer was used for steady shear tests (primary flow) and for the development of turbulence (secondary flow). Two blood analog samples were prepared, a 60:40 wt% of water-glycerine solution for Newtonian blood analog, and a 67.9:32 wt% of water-glycerine with 0.06 wt% of xanthan gum added to replicate shear-thinning blood. A 2° cone with 40mm radius was used to conduct all tests. A steady shear test at 25°C was conducted over a range of 0-1500s-1 for primary flow. Shear rate was then increased to 20000s-1 to initiate secondary flow of both analogues. We define a Reynolds number (Re*) using a ratio of centrifugal forces (product of the cone angle and radius as the characteristic linear dimension and angular velocity) and viscous forces (viscosity).

Results: Steady shear tests showed that the Newtonian analog exhibited a constant dynamic viscosity across all shear rates, with a value of 0.00349 Pa.s. When the angular velocity was increased, the Newtonian analog begins to develop non-tangential flow behaviour, noted by an increase in relative torque (ratio of measured torque to torque measured with purely tangential flow) at Re* =1, this was in reasonable agreement with [1]. Viscometric tests of the shear-thinning blood analog showed decrease in viscosity with increase of shear rate. Regarding secondary flow, the shear-thinning fluid demonstrated more complex behaviour with a high relative torque at low Re*. Compared to the Newtonian blood analog this may demonstrate that the flow is not purely tangential at the critical Re* and does not reach a steady state behaviour.

Conclusions and Future Work: Non-tangential flow can be established in a cone and plate rheometer when Re* reaches a critical Re* = 1 for Newtonian blood analogs. Shear-thinning fluids show a substantial difference in relative torque with changes in Re*, but whether this behaviour is non-tangential flow still needs to be investigated. Future plans include investigations of the variation in relative torque with Re* for multiphase fluids. In addition a rig is currently being designed for visualisation and quantitative assessment of the onset on turbulent flow in a cone and plate device, where single phase and multiphase fluids, whole blood, and blood plasma will be examined.

References

[1] Sdougos, H., Bussolari, S. and Dewey, C. (1984). Secondary flow and turbulence in a cone-and-plate device. Journal of Fluid Mechanics, 138(-1), p.379.

[2] Ellenberger, J. and Fortuin, J. (1985). A criterion for purely tangential laminar flow in the cone-and-plate rheometer and the parallel-plate rheometer. Chemical Engineering Science, 40(1), pp.111-116.

Mukhopadhyay, Aditi (University of Strathclyde)
The influence of boundary conditions on the shear thickening of a system

Shear thickening can be found in a diverse variety of situations and processes ranging from quicksand to body armour; an everyday example being cornstarch in water [1]. On a macroscopic scale, shear thickening can be defined as the increase in viscosity upon the application of a shear stress. Recent work shows that discontinuous shear thickening is observed at a specific shear stress value, called the critical onset stress, which is independent of concentration. The degree of thickening, above the onset stress, that is witnessed within a system however, is dependent on the concentration of the suspension [2].

The impact of the physical boundary conditions under which shear thickening occurs forms the basis of this investigation. Many reports discuss the importance of dilation in thickening samples, where particles push into boundaries in order to reduce the local packing fraction [3]. A TA DHR-2 rheometer was used to measure the rheology of varying concentrations of cornstarch in a glycerol-water mixture in contact with surfaces of different softness. To mimic a soft surface environment, a thin plastic film layer (parafilm) was adhered onto a standard peltier parallel plate geometry in the rheometer. As well as this, the effect of varying the rheometer gap sizes (400μm and 600μm) under these conditions will be investigated and compared to explore the possible role of slip.

Preliminary results convey that the use of a soft boundary results in shear thickening at significantly greater stress values, in comparison to hard surfaces. Such a shift in the onset stress at which shear thickening is witnessed, if confirmed, would potentially enable improvements in how thickening is dealt with in applications. To clarify the role of slip, the next step will be to rheologically test the suspensions under both roughened and soft boundaries.

[1] E. Brown and H. M. Jaeger, "Shear thickening in concentrated suspensions: Phenomenology, mechanisms and relations to jamming," Reports Prog. Phys., vol. 77, no. 4, 2014.
[2] B. E. Guy, M. Hermes, and W. E. E. Poon, "Towards a Unified Description of the Rheology of Hard-Particle Suspensions," Phys. Rev. Lett., vol. 115, no. 8, 2015.
[3] M. E. Cates, M. D. Haw, and C. B. Holmes, "Dilatancy, jamming, and the physics of granulation," J. Phys. Condens. Matter, vol. 17, no. 24, 2005.

Murphy, Shona (Malvern Panalytical)

Using Creep testing as an alternative to Multiwave Oscillation for determining the true gel point of network polymers

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The most common method for monitoring gelation dynamics with a rotational rheometer is to perform Small Amplitude Oscillatory Shear (SAOS) testing at a single fixed frequency while continually monitoring the evolution of G' and G'' with time or temperature - the point of gelation being defined as the time or temperature at which G' and G'' cross. Winter has shown, however, that with the exception of stoichiometrically balanced network polymers and networks with excess cross-linker the true gel point does not coincide with the intersection of the dynamic moduli and is more accurately identified as the time or temperature at which $G'(\omega)$ and $G''(\omega)$ become parallel and the loss tangent ($\tan\delta$) frequency independent [1], the so called Winter-Chambon criteria [2]. Hence, to accurately determine the gel point using SAOS testing requires measurements to be made at multiple frequencies and at various stages of the gelation process. A common approach is to perform Fourier Transform Mechanical Spectroscopy (FTMS) or Multiwave Oscillation whereby the frequency dependent moduli are determined simultaneously at several discrete frequencies by applying a complex waveform consisting of a fundamental frequency and several harmonics [3]. While the approach can significantly reduce the time required to obtain a frequency spectrum and hence assist in the determination of the true gel point it is still, however, limited by the time required to perform a full or partial oscillation at the lowest frequency, which can be substantial. Hence, the approach is only really valid for relatively slow curing systems. Furthermore, the sum of the stress or strains applied at each frequency must be within the Linear Viscoselastic Region (LVR) thereby increasing noise to signal ratio (harmonic distortion) compared with a single frequency test.
In this paper we propose and demonstrate an alternative to Multiwave Oscillation that overcomes many of the limitations cited above. The approach is based on creep testing and the subsequent transformation of $J(t)$ to $G'(\omega)$ and $G''(\omega)$ using the method proposed by Duffy et al [4], since $J(t)$ contains information about all oscillation frequencies, not just the discrete harmonics used in a multiwave test. Furthermore, it is possible to determine a frequency spectrum in a fraction of the time required for multiwave without the same stress or strain limitations, potentially allowing more weakly structured and faster gelling systems to be evaluated.

1. HH Winter; *Can the gel point of a cross-linking polymer be detected by the G'–G "crossover?*, Polymer Engineering & Science 27 (22), 1698-1702 (1987)

2. HH Winter, F Chambon; *Analysis of linear viscoelasticity of a crosslinking polymer at the gel point*, Journal of Rheology 30 (2), 367-382 (1986)
3. EE Holly, SK Venkataraman, F Chambon, HH Winter; *Fourier transform mechanical spectroscopy of viscoelastic materials with transient structure*, Journal of non-newtonian fluid mechanics 27 (1), 17-26 (1988)
4. JJ Duffy, CA Rega, R Jack, S Amin; *An algebraic approach for determining viscoelastic moduli from creep compliance through application of the Generalised Stokes-Einstein relation and Burgers model*, Appl. Rheol. 26:1 (2016)

Radhakrishnan, Rangarajan (University of Edinburgh)
Study of oscillatory shear rheology of dense suspensions using particle based simulations.

Dense suspensions of non-Brownian spheres suspended in a Newtonian liquid are widely used in a variety of formulated products, such as paints, foods and cements. Understanding the transient rheology can be crucial in many of these applications. Using discrete element method simulations of particles, we study the response of such suspensions under oscillatory shear, one of the most widely used method to study the transient shear rheology of materials. We find that the pre-shear protocol has a significant impact when the oscillatory amplitude is moderate. Our simulations predict that the spatial asymmetry in the microstructure induced due to pre-shear protocol can lead to asymmetric stress response between the forward and reverse parts of the oscillatory cycle. This implies that rheological models based on a single scalar microstructural parameter are inadequate to capture the transient shear rheology of dense suspensions.

Reynolds, Carl (Birmingham University)
Polymer rheology in the medium amplitude oscillatory shear regime

While large amplitude oscillatory shear (LAOS) rheology has been a significant area of interest in recent rheological studies, there is still difficultly in assigning a physical interpretation to the higher harmonics that appear in the response at these higher strain amplitudes. A key factor in this problem is that the response in LAOS is highly dependent on the experimental conditions, complicating the interpretation of the results. Hence the use of intermediate, medium amplitudes (MAOS rheology) is key, as with careful control, the higher harmonics can be studied, while maintaining the behaviour of the first harmonic (and hence G′/G′′) that is expected in the linear regime. Here, we report MAOS frequency sweeps including the phase and magnitude of the third harmonic, for a range of polymers, and suggest, based on comparisons with the Rolie-poly model, that the behaviour of the third harmonic is dependent on the Rouse time of the polymer.

Roberts, Tirion (Aberystwyth University)
The flow of a yield-stress fluid through vein-like geometries
Tirion Roberts & Simon Cox
Veins become varicose when the one-way valves within them become ineffective which leads to a reduced blood flow. This increases the pressure within the vein, leading to swelling, which can cause discomfort for the individual, with the potential to cause further medical complications. There are several treatments available, with the least invasive method consisting of the injection of a surfactant-laden foam directly into the affected vein. The foam displaces the stagnant blood, and the surfactant treats the walls, causing the vein to collapse and eventually dissolve.

Foam is used for several reasons: its yield stress prevents gravity override and aids the displacement of blood; and less surfactant is required to coat the walls compared to the injection of pure surfactant.

We will describe numerical simulations of a 2D flow of a Bingham fluid through various channel geometries. The output is compared with analytic velocity profiles in simple geometries to validate the simulations. We then describe the fields of velocity, stress and pressure for more complicated geometries.

In fact, both blood and foam can be considered as yield-stress fluids. In the future, we will therefore consider the displacement of one yield stress fluid by another. The shape and stability of the fluid-fluid interface will be a critical prediction of the modelling. The influence of gravity will be considered, since the angle at which a patient holds their leg during the treatment may reduce its effectiveness.

Rycroft, Ewan (University of Strathclyde)
The effects of fluid viscosity and elasticity on the swimming velocities on a flagellated alga
Ewan Rycroft, Mark Haw and Mónica S. N. Oliveira ((University of Strathclyde)

The motility and the swimming behaviour of microorganisms is greatly influenced by the interactions with the medium in which they live. An understanding of their swimming dynamics in complex media is key for the enhancement of applications such as artificial swimming, micro-robotics and targeted drug delivery. In this work, we examine the effect of rheological characteristics, such as viscosity and viscoelasticity, of the medium on the swimming dynamics of a eukaryotic bi-flagellated puller alga, Dunaliella salina. We make use of dilute algae suspensions, in which alga-alga interactions are not important. To visualise the algae swimming behaviour, we employ microfluidic chambers of rectangular cross-section and rely on microscopy and image analysis to quantify the swimming kinematics. We observe analogous algae swimming velocities in both Newtonian (Ficoll PM400) and viscoelastic (Polyacrylamide) solutions across a significant range of fluid viscosities. In both cases, swimming velocities decrease as the viscosity is increased up to a point where velocities plateau, exhibiting an approximately constant velocity for high viscosity solutions. Further, we examine the algae behaviour in a second Newtonian fluid (Glycerol). In this case the behaviour is significantly different, with a more pronounced decrease in swimming velocities as the viscosity is increased and a defined point of non-motility, which was not observed in Ficoll and Polyacrylamide solutions.

Thompson, Richard (Durham University)
Structural evolution of graphene nanoplates under controlled flow
S. C. Boothroyd, D. W. Johnson, Michael P. Weir, C. D. Reynolds, J. M. Hart, A. J. Smith, N. Clarke, R. L. Thompson, and K. S. Coleman

Translating the exceptional properties of graphene to the corresponding polymer composites remains a significant and largely unsolved challenge. The limited improvements in mechanical properties are understood to arise partly from poor control over dispersion and orientation during processing. By combining shear rheology and stress relaxation measurments with simultaneous small-angle X-ray scattering or dielectric spectroscopy, we have been able to determine the relationship between flow regimes and the structural evolution of the graphene nanoplates and carbon black. While carbon black shows relatively simple trends in behaviour that can be associated with dispersion under flow and reaggregation when flow stops, graphene nanoplates show a fascinating, non-monotonic range of behaviour. We attribute this to the aggregation process having multiple stages that have different characteristic timescales. Exfoliation and orientation are induced by flow. After cessation of flow, impedance falls, then rises before falling again, because of the hierarchical nature of reaggregation. The initial fall in impedance arises from reorientation of exfoliated plates to form a percolating path.

This path then is lost as aggregation of plates to form small disparate aggregates takes place. In the final slowest stage, these aggregates can then diffuse to form a network of aggregated platelets. Understanding the response of graphene fillers to flow and relaxation is an important stage in realising the potential of these materials.

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Vitasari, Denny (Aberystwyth University)
Prediction of bubble dynamics during foam flow through a constricted microfluidic channel

Foam is used as a displacement fluid in improved oil recovery and soil remediation. Knowledge about the mechanisms of foam generation in porous media is therefore important in determining appropriate process conditions. We modify the viscous froth model[1] by adding the disjoining forces between bubble interfaces to allow simulation of "wet" foam in a two-dimensional microfludic channel. The system consists of foam flowing though a gradual constriction, designed to resemble the shape of channels in porous media. The bubbles form a staircase structure at the upstream. Beyond the constriction, three different responses are observed: the structure returns to initial state, reorientation in which the bubbles undergo topological rearrangement and bubble pinch-off in which a bubble is divided into two smaller bubbles. Our simulations examine the effect of foam driving velocity, bubble size, constriction size and liquid fraction on this behaviour. Bubble reorientation is more likely to occur when the bubbles are larger, while bubble pinch-off is more likely to occur at high velocity (high capillary number). The likelihood of bubble reorientation and pinch-off decreases with increasing liquid fraction and constriction gap width. The reorientation into 1-bubble foam (bamboo foam) is favourable as the structure gives a better displacement efficiency, while the bubble pinch-off leads to foam generation.

[1] Kern, et al., Phys. Rev. E 70(4):041411, 2004

Zhou, Qi (University of Edinburgh)
Peculiar RBCs distribution in a dilute suspension flowing in microfluidic devices: experiments and simulations

Red blood cells (RBCs) are an essential component of whole blood. These deformable particles have key biological functions, such as the delivery of oxygen to tissues around the body, and are one of the main responsible for the complex behaviour of blood. In recent years, several studies have focused on the RBC dynamics in microfluidic channels, in particular for cell separation from plasma in the context of point-of-care diagnosis. In this work, we focus on the spatial-temporal dynamics of dilute RBC suspensions, where cell-cell interactions are weak, under conditions of negligible inertia. The flow of a dilute suspension of animal RBCs in a Dextran solution (cell volume fraction, Hct = 1%) in a straight microfluidic channel of rectangular cross-section is studied for a range of capillary numbers. We found an apparently counterintuitive cell distribution across the channel width, even at short distances away from the channel inlet, where the cells tend to accumulate at equilibrium positions in the channel. The distribution resembles the Segré-Silberberg effect (observed when inertial lift forces are important), even though the characteristic Reynolds numbers in our experiments are much lower than 1 ($Re << 1$). In order to elucidate on the collective behaviour of the cell suspension, leading to such peculiar cell distributions, complementary numerical simulations were performed using the immerse-boundary-lattice-Boltzmann method (IB-LBM). Overall there is a qualitative agreement between experiments and simulations. We analyse the evolution of the cell density profiles along the channel length, the development of the cell-free-layer close to the channel walls, and the kinematics, and conclude that such cell distributions are mainly a combined effect of hydrodynamic lift and the lack of cell-cell interaction in such dilute suspensions. The peculiar density profiles persist for distances as large as 45Dh in experiments and 28Dh in simulations (where Dh is the hydraulic diameter), demonstrating the importance of local and transient characteristics when working with dilute suspensions in microfluidics.