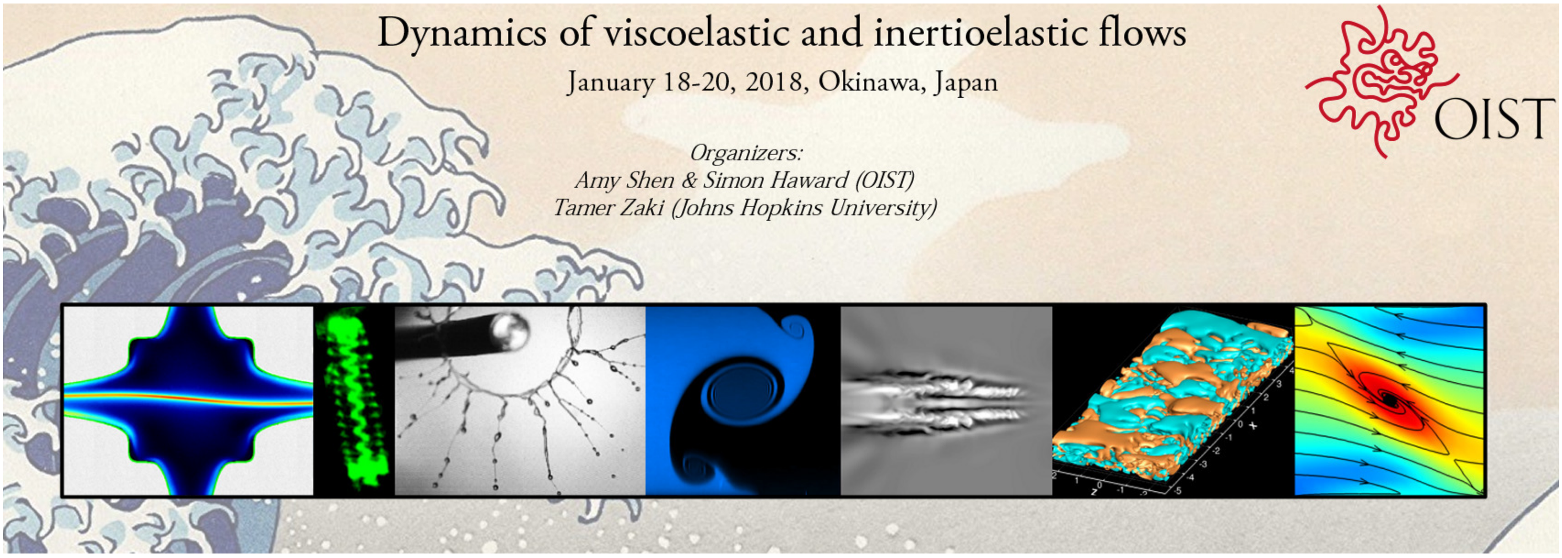
OIST

Okinawa Institute of Science and Technology Graduate University



Mini-symposium

BOOK OF ABSTRACTS

Jetting, spraying & splashing:
Free surface inertio-elastic flows

Gareth H. McKinley

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge MA 02139, USA

We investigate three different unsteady time-dependent flows in which nonlinear inertial and viscoelastic elastic effects in dilute polymer solutions also interact with a deformable free surface; (i) jetting and breakup of a high speed viscoelastic jet; (ii) the instability of a submerged viscoelastic jet propagating through a Newtonian medium; (iii) high-speed rotary atomization of a viscoelastic fluid sheet. In each case the nonlinear extensional rheology of the dilute polymer solution leads to marked changes to the dynamics observed with corresponding Newtonian fluids.

Exploring impacts of upstream nozzle kinematics on downstream droplet breakup and spray drift

Justin J. Cooper-White

School of Chemical Engineering, University of Queensland, Brisbane, Queensland, Australia

The physical properties of agrochemical spray solutions are known to influence droplet size distributions and spray drift outcomes. However, to date, it has proven difficult to accurately predict spray outcomes based on solution properties alone, even if they have been comprehensively characterised in terms of shear and extensional rheology, dynamic surface tension, and density. At the same time, variations in nozzle design are also known to have significant impacts on spray outcomes, and for complex fluids such as those used in agrochemical spraying, deciphering the relative contributions and interplay of each component of this complex parameter space remains a challenge. In this work, we probe the impacts of polymer chain dynamics and surfactant association on the onset of flow instabilities in microfluidic geometries mimicking those within standard agrochemical spray nozzles, exposing the complex inter-relationship between device geometry and in-nozzle flow kinematics, and downstream liquid jet break-up. Importantly, we show how these learnings can be used to tailor spray outcomes for reduced drift in pilot-scale spray tests within a wind tunnel. This work highlights that the mechanism of downstream breakup is substantially modulated by the flow dynamics upstream within the nozzle and upstream instabilities can be deterministic of resulting droplet size distributions and result in spray drift minimisation.

The spectral link in turbulent frictional drag (and implications for polymer-doped flows)

Pinaki Chakraborty

Okinawa Institute of Science and Technology Graduate University, Onna-son, Okinawa 904-0495, Japan

I will review the spectral link in turbulent frictional drag, the missing link between two aspects of turbulent flows have been the subject of extensive, but disjoint, research efforts: the frictional drag experienced by a turbulent flow over a wall and the turbulent spectrum. The standard theory of turbulent frictional drag, which is based on the pioneering work of Prandtl and von Karman, computes the frictional drag using an indirect approach and makes no contact with the spectrum. By contrast, the spectral link computes the frictional drag directly and expresses it as a functional of the turbulent spectrum. To illustrate the applications of the spectral link, I will obtain an analytical version of the arch-famous Nikuradse's diagram that is in minute qualitative agreement with the distinctive features in the diagram that have remained elusive to any theoretical elucidation. Thereafter, I will discuss unprecedented experimental measurements of frictional drag in turbulent soap-film flows over smooth walls and show how the results render the standard theory incomplete. Last, I will outline avenues for extending the spectral link to polymer-doped flows. This research is pursued in close collaboration with Gustavo Gioia (OIST); other collaborators include Nigel Goldenfeld (U. Illinois), Walter Goldburg (U. Pittsburgh), and Hamid Kellay (U. Bordeaux).

The nature of the maximum drag reduction asymptote

Björn Hof

IST Austria, Am Campus 1, 3400 Klosterneuburg, Austria

Small amounts of polymers severely alter the nature of turbulent flows and lead to significant drag reduction. I will present experimental and numerical results that show that the addition of polymers to turbulence can lead to complete relaminarisation. As shown, previous reports of a state of "hibernating turbulence" correspond to a reverse transition from fully turbulent flow back to puffs. While here average drag levels appear to capture the ultimate drag reduction limit flows have not reached the asymptotic limit and differ in nature. Flow structure are still Newtonian type in nature (i.e. puffs). Upon a further increase in polymer concentration (or Weissenberg number in simulations) the Newtonian structures entirely disappear and for select parameters the flow completely relaminarizes. At yet higher Weissenberg numbers an elasto inertial instability sets in that leads to a drag increase and an eventual approach to the maximum drag reduction asymptote.

Viscoelastic effects on roll cells in wall-bounded shear flow: Toward clarifications of DR and EIT

Takahiro Tsukahara

Department of Mechanical Engineering, Tokyo University of Science, 2641 Yamazaki, Noda-shi, Chiba 278-8510, Japan

An alternative step in understanding the flows of near-wall drag-reducing (DR) turbulence and elasto-inertial turbulence (EIT) can be examining the flow in well-organized streamwise vortex with a laminar background. Herein, we studied the flow behaviors of the Giesekus viscoelastic fluid in a rotating plane Couette flow system, which is accompanied by steady roll-cell structures. By fixing the Reynolds and rotation numbers at values that provide as steady wavy or 2D roll cells, i.e., an array of meandering/straight streamwise vortices, we performed parametric DNS study in terms of the Weissenberg number. We observed that, in the viscoelastic flows, the secondary flow (wall-normal and spanwise velocity fluctuations) are suppressed while the streamwise component is maintained, and the wavy roll cells are modulated into streamwise-independent straight roll cells. At high Weissenberg numbers, the viscoelasticity induces an unsteady flow state where the 2D roll-cell structure is periodically enhanced and damped with the time scale of the relaxation time of the additive, keeping the homogeneity in the streamwise direction. Such a pulsatile motion of the roll cell was caused by the delay in the response of the viscoelastic force to the change in the vortex development. We discuss the relevance to the DR phenomenon and EIT in the viscoelastic wall-bounded shear flows. In addition, we would focus also on the viscoelastic effect on the subcritical transition accompanied by oblique turbulent band in the rotating plane Couette flow, to study the robustness and limitation of the band in the viscoelastic fluid.

Elastic turbulence, inertial effect and drag reduction

Victor Steinberg

Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

Elastic turbulence (ET) is a chaotic state driven by elastic stresses alone and occurring in inertia-less flows. Turbulent drag reduction (TDR) is observed at high Reynolds number turbulent flows driven by inertial stresses. So far, the turbulence community sees ET and TDR as distinctly different turbulent forms of flow. Neither state enjoys the strong theoretical understanding than Newtonian turbulence has. A recently discovered another turbulent state, coiled elasto-inertial turbulence (EIT), occupying the Reynolds number space between ET and TDR, suggests that ET and TDR are linked and this link could be a significant piece missing in the theory of TDR. To search for direct relation between ET and TDR and prove of the aforementioned hypothesis, experiments we focused on a setup of a flow between two cylindrical obstacles in a micro-channel flow. In the same setup we intend to study the dynamics of ET, EIT and TDR in unbounded flow configuration. It allows first to investigate ET in fairly homogeneous vortex flow. Then by using polymer solutions of different viscosities in a wide range of their variations we are able to scan the Wi and Re parameter plane up to several hundred and to study the various turbulent states and transitions between them. This generalized approach to a flow of polymer solutions under an influence of an elastic stress field and inertia may provide a better understanding of ET, EIT and TDR and their relations.

Superhydrophobic and polymer drag reduction in turbulent Taylor-Couette flow

Gareth H. McKinley

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge MA 02139, USA

We use a newly-developed bespoke Taylor-Couette (TC) apparatus to study frictional drag reduction by dilute polymer solutions and superhydrophobic (SH) surfaces in turbulent flows for 15000 < Re < 86000. The TC geometry has a fixed outer cylinder and a rotating inner cylinder (radius ratio $\eta = 0.75$), and is mounted on a commercial controlled-stress rheometer enabling highly-resolved speed and torque measurements. By monitoring the scaling between torque and speed we show that the swirling flow becomes a featureless fully-turbulent motion above Re = 15000 and we focus on measurements in this regime. By applying SH coatings on the inner cylinder, we can evaluate the drag reducing performance of the coating and calculate the effective slip length in turbulent flow using a suitably-modified Prandtl-von Kárman (PvK) analysis [1]. We also investigate drag reduction by dilute solutions of various high molecular weight polymers, and show that natural biopolymers derived from plant mucilage can be an inexpensive and effective alternative to synthetic polymers in drag reduction applications and approach the same maximum drag reduction (MDR) asymptote. Finally, we explore combinations of the two independent drag reduction methods – one arising from wall slip and the other due to changes in turbulence dynamics in the bulk flow – and find that the two effects are not additive; interestingly, the effectiveness of polymer drag reduction is reduced in the presence of an SH coating on the wall.

[1] Srinivasan et al. (2015) Sustainable drag reduction in turbulent Taylor-Couette flows by depositing sprayable superhydrophobic surfaces, *Phys. Rev. Lett.* **114**: 014501

Elastic instabilities in planar elongational flows of polymer solutions

Simon J. Haward

Okinawa Institute of Science and Technology Graduate University, Onna-son, Okinawa 904-0495, Japan

Over the last decade there has been considerable interest among the experimental and computational rheology communities in the occurrence of a purely-elastic flow asymmetry in the cross-slot device [1,2]. The instability arises for low fluid inertia (i.e. low Reynolds number, *Re*) but for flow above a critical value of the Weissenberg number, *Wi*. In an effort to gain an improved understanding of the nature and onset conditions of such instabilities, here we use a combination of full-field birefringence imaging and time-resolved flow velocimetry to examine the behavior of well-defined viscoelastic polymer solutions flowing through a cross-slot-type microfluidic device that generates close to ideal planar elongation [3]. Our measurements reveal a new elastic instability for $Wi > Wi_{c1}$, which is characterized by lateral displacement and spatiotemporal fluctuation of the stagnation point along the outflowing symmetry axis. The often-reported flow asymmetry occurs subsequently for a higher Weissenberg number $Wi > Wi_{c2} > Wi_{c1}$. The progression of instabilities is mapped in *Wi*-*Re* parameter space for fluids with a range of elasticity numbers, $El = Wi/Re$. Further, we spatially evaluate a well-known dimensionless criterion for the onset of purely elastic flow instabilities [4] near the onset of the first instability at Wi_{c1}. The criterion well describes the geometric and rheological scaling for instability onset, providing good agreement with values previously reported for flows dominated by shearing kinematics. Our results suggest that the onset of elastic flow instabilities in this elongational flow field is driven by the accumulation of elastic tensile stress along strongly curved streamlines that pass close to the stagnation point.

[1] P. E. Arratia et al., *Phys. Rev. Lett.*, **96**, 144502 (2006).
[2] R. J. Poole et al., *Phys. Rev. Lett.*, **99**, 164503 (2007).
[3] S. J. Haward et al., *Phys. Rev. Lett.*, **109**, 128301 (2012).
[4] P. Pakdel & G. H. McKinley, *Phys. Rev. Lett.*, **77**, 2459 (1996).

Flow instabilities in the cross-slot geometry: Characterization, exploitation and cure

Robert J. Poole

School of Engineering, University of Liverpool, Brownlow Street, Liverpool L69 3GH, United Kingdom

The so-called "cross-slot" geometry, created by two channels mutually intersecting at 90 degrees to each other, has been well studied to its potential use as a rheometric device. Although in this regard it has been used to study elastic fluids or suspended particles/vesicles, or indeed individual DNA molecules, in extensional flow for a long time, it has only been relatively recently shown that the flow becomes unstable beyond a critical flowrate.

Even for purely Newtonian fluids the base flow has been shown to undergo a steady symmetry-breaking bifurcation. In the 2D limit this has been shown numerically to occur at a Reynolds number (Re) on the order of 1500 and result in a lateral displacement of the stagnation point. In contrast, the imposition of side-walls has shown that a different form of symmetry breaking can be observed at Reynolds numbers as low as 30 for aspect ratios (ratio of channel height: width) close to one. We show how this *purely-inertial* instability can be used to enhance heat transfer at the microscale. The effect of weak-elasticity on this inertial instability, through polymer addition to the base solution making the flow *inertio-elastic*, is shown to be destabilising. In the absence of inertia, a still different form of steady symmetry-breaking is observed for viscoelastic fluids due to a *purely-elastic* instability. This purely-elastic instability, which remains in the 2D limit, has been studied in detail and we show how the channel aspect ratio can be used to change the instability from a steady symmetry-breaking bifurcation into a time dependent instability as the channel height is reduced towards the Hele Shaw limit. We also show how different viscoelastic model parameters effect the onset conditions for these instabilities. In contrast to the *purely-inertial* instability, where the addition of elasticity was found to be destabilising, in the purely-elastic case the addition of weak inertia is shown to be stabilising (*elastic-inertio*).

Finally, we show how a passive control device (a circular cylinder added at the geometric centre of the device) can be used in the cross-slot to delay the onset flowrate for the purely-elastic instability to significantly higher flowrates. This geometric configuration also provides insight into the underlying physical mechanism responsible for the instability.

Inertioelastic flow instability at a stagnation point

Noa Burshtein

Okinawa Institute of Science and Technology Graduate University, Onna-son, Okinawa 904-0495, Japan

Recently it has been shown that flow of Newtonian fluids in cross-slot channels results in a steady spiral vortex instability as the Reynolds number, *Re*, is increased above a modest critical value Re_c (SJ Haward et al, Phys Rev E **93**: 031101, 2016). In this work we study how the onset and development of the spiral vortex is influenced when fluid elasticity is increased by the addition of high molecular weight poly(ethyleneoxide) (PEO) over a wide range of concentrations $0.0001 < c < 0.1$ wt%. The effects of fluid relaxation time λ; and viscosity ratio β; are decoupled by using solvents of various viscosity. Flow visualization is performed using quantitative micro-particle image velocimetry, from which vorticity fields in the cross-section of the spiral vortex are computed. The vorticity in the center of the spiral serves as a suitable bifurcation parameter to characterize the intensification of the instability with increasing *Re*. Our sensitive experimental set-up allows us to observe a significant change in Re_c at polymer concentrations as low as 0.0001 wt%, i.e. the concentration regime associated with polymer drag reduction (PS Virk & H Baher, Chem Eng Sci **25**: 1183, 1970). Our results show that as the polymer concentration is increased, Re_c and the intensity of the vortex are reduced. At sufficiently high polymer concentrations $c > 0.1$ wt%, we observe no vortex formation, but we encounter flow asymmetries due to the dominance of elastic effects at high Weissenberg numbers (*Wi*). Our data can be collapsed to describe a stability boundary in dimensionless *Wi*-*Re*-β; parameter space. Our results are supported by numerical simulations and constitute new data on stability of low to moderate elasticity fluids in elongational flow fields. Our experimental configuration allows direct and prolonged examination of a single steady vortex, providing new insight into the effects of drag-reducing concentrations of polymer on vortex formation and dynamics.

Microscopic investigation of vortex breakdown in a dividing T-junction flow

San To Chan

Okinawa Institute of Science and Technology Graduate University, Onna-son, Okinawa 904-0495, Japan

Axisymmetric vortex breakdown, the development of bubble-like regions inside which the flow recirculates, is possible when flow deceleration and vorticity decay are present in a swirling flow. Recently, it has been discovered that vortex breakdown also occurs in a dividing T-junction flow configuration, when the inlet Reynolds number *Re* exceeds the critical threshold Re_c [1,2]. Here, we microscopically investigate this phenomenon using a novel glass microfluidic T-junction device. First, by micro-Particle Image Velocimetry (μPIV), we visualize at the channel cross-section the formation of a pair of counter-rotating vortices, and explain it through the Dean instability. Second, by a method that enables high-contrast imaging of recirculating streamlines, we show that outflow imbalances of even just a few percent can significantly alter both the Re_c and structures of the vortex breakdown. Complementary numerical simulation reveals that these effects are due to variations in the net pressure difference across the two outlets. Our study highlights the risk of microfluidic design failure due to vortex breakdown, and implies that one can engineer the position and dynamics of recirculation within a dividing T-junction simply by varying the imbalance between the two outflows. Finally, we outline very recent preliminary work involving balanced outflows, but higher *Re*, demonstrating the onset of symmetry breaking between the vortex breakdown bubbles within the two outlet channels.

[1] Vigolo D, et al. (2014) Proc Natl Acad Sci 111: 4770

[2] Ault J T, et al. (2016) Phys Rev Lett 117: 084501

Development of measurement techniques using microscopy for spherical particles in microchannels

Marie Oshima

Institute of Industrial Science, The University of Tokyo, Tokyo, Japan

Behavior of red blood cells affects flow features, which leads to the non-Newtonian characteristics in the microcirculation. In order to measure the effects of red blood cells in a blood vessel whose diameter is less than 300 µm, it is important to capture their dynamic behavior in the 3-D (Dimension). The authors have been developing measurement techniques using microscopy. These technique can capture 3-D complex, random and unsteady flow.

The presentation consists of two parts for preliminary study using spherical particle instead of red blood cells. The first part investigates the secondary flow structures induced by fluid inertia in microscale channel geometries. Three different types of stepped microchannels are measured using the bright-field microscopy to examine the effects of various geometric parameters and the Reynolds number on the focusing behavior of spherical particles. The second parts develops a new particle detection method using DHM-PTV (Digital Holographic Microscopy – Particle Tracking Velocimetry) based on phase information. The present DHM consists of interferometer, laser, objective lens and a camera. The phase information is reconstructed numerically using interference fringes recorded on the camera. A new algorithm for particle detection is developed and is applied to a 3-D flow field. Precision of the present particle detection method is evaluated.

High throughput viscoelastic ordering of particles in a straight microfluidic channel

Francesco Del Giudice

Okinawa Institute of Science and Technology Graduate University, Onna-son, Okinawa 904-0495, Japan

Microfluidics has revolutionized many applications in biomedical engineering, such as particle/cell counting and sorting. Among these applications, interrogation of single particles/cell has recently been achieved by encapsulating cells and functionalised particles in a single picoliter droplet. Unfortunately, in many cases particles and cells can not be encapsulated in the same droplet. This problem could be potentially solved if particles and cells are equally spaced prior the encapsulation, so that the frequency of droplet formation can be synchronized with the frequency of particles and cells entering the encapsulation area.

In this work, we show that particles can be equally spaced, i.e. ordered, in a simple straight channel by introducing viscoelasticity in the suspending liquid. We study the effect of flow rate, channel length, particle concentration, and fluid rheology on the particle ordering. We employ two hyaluronic acid solutions at different concentrations in phosphate buffer saline (PBS). The first testing fluid is elastic with almost constant-viscosity, while the second fluid exhibits both elastic and shear-thinning features. We find that particles of 20 μm in diameter flowing at 50 μl/min and 100 μl/min in a straight square-shaped microchannel with height of 100 μm can be equally spaced only when suspended in the shear-thinning liquid, at a given particle concentration. We do not observe viscoelastic ordering at low particle concentrations since particles cannot interact with each other. Particles suspended in the near constant-viscosity liquid focus both on the centerline and the wall, thus preventing particle ordering. Since both particle concentration and flow rate are relatively high, a throughput up to ~15000 particles/s is also achieved, offering great potentials for rapid healthcare applications.

Numerical analysis of viscoelastic models

Hirofumi Notsu

Faculty of Mathematics and Physics, Kanazawa University, Kanazawa 920-1192, Japan

In order to investigate the viscoelastic material property, high-quality numerical schemes are often required. In the talk we present finite element schemes for the Maxwell viscoelastic model and the Peterlin viscoelastic fluid model, and prove error estimates of the schemes under some assumptions. For the Maxwell viscoelastic model, we show that the model has a gradient flow structure and that the structure is preserved in the scheme. As for the Peterlin viscoelastic fluid model, the finite element scheme to be studied is based on the method of characteristics and is called the stabilized Lagrange-Galerkin method. We establish error estimates of the scheme not only for the velocity and conformation tensor but also for the pressure. Numerical results are presented and discussed in the last part of the talk.

[1] M. Lukacova-Medvidova, H. Mizerova, H. Notsu and M. Tabata. Numerical analysis of the Oseen-type Peterlin viscoelastic model by the stabilized Lagrange-Galerkin method, Part I: A nonlinear scheme. ESAIM: M2AN, Vol.51 (2017), pp.1637-1661.

[2] M. Lukacova-Medvidova, H. Mizerova, H. Notsu and M. Tabata. Numerical analysis of the Oseen-type Peterlin viscoelastic model by the stabilized Lagrange-Galerkin method, Part II: A linear scheme. ESAIM: M2AN, Vol.51 (2017), pp.1663-1689.

Natural transition and turbulence in viscoelastic channel flow

Tamer A. Zaki

Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218, USA

Transition to turbulence in viscoelastic channel flow is studied using direct numerical simulations of a FENE-P fluid. The computations start from infinitesimally small Tollmien–Schlichting (TS) waves and track the development of the instability from the early linear stages through nonlinear amplification, secondary instability and full breakdown to turbulence. In the early stage, the two-dimensional TS waves can be regarded as spanwise vorticity perturbations against the background of mean shear. As the TS waves become three-dimensional, they elongated and their legs become streamwise aligned vortices that generate streaky perturbations. Finally, hairpin vortices are spawned and break down to turbulence. Perturbation theory, and the vorticity-torque equations are invoked to explain these stages of laminar-to-turbulence transition, and some of the phenomenology observed in the fully turbulent state. In order to analyze the associated changes in the polymer conformation, a new mathematical framework is proposed, and scalar measures that quantify the perturbation to the polymer conformation are defined and evaluated.

Characterizing elastic turbulence in parallel shear flows

Paulo E. Arratia

Department of Mechanical & Applied Mechanics, University of Pennsylvania, PA 19104, United States

In this talk, I will discuss recent experiments in characterizing the flow of a viscoelastic fluid in a parallel shear geometry at low Reynolds number. We find that as the flow becomes unstable via a nonlinear subcritical instability, velocimetry measurements show non-periodic fluctuations over a broad range of frequencies and wavelengths, consistent with the main features of elastic turbulence. Using the same experimental setup, these features are compared to those in the flow around cylinders, which is upstream of the parallel shear region; significant differences are found in power spectrum scaling, intermittency statistics, and flow structures. A simple mechanism to explain the growth of velocity fluctuations in parallel shear flows is proposed based on polymer stretching due to fluctuations in streamwise velocity gradients.

Dynamics and structures of viscoelastic turbulence in channel flow: From MDR to micelles

Michael D. Graham

Department of Chemical & Biological Engineering, University of Wisconsin-Madison, 1415 Engineering Drive, Madison, WI 53706, USA

In the first part of this talk we describe direct numerical simulations (DNS) of channel flow turbulence in a FENE-P fluid. At Reynolds numbers very close to transition, the flow first relaminarizes upon increasing Weisenberg number (Wi) or polymer concentration, but then becomes turbulent again, displaying features of elasto-inertial turbulence (EIT). At higher Reynolds number, the flow evolves as Wi increases from displaying intermittency and streamwise vortex structure characteristic of Newtonian flow to EIT, while at intermediate Wi, a spatiotemporal mixture of the two structures is observed. We also show results at two parameter sets that display indistinguishable mean velocity profiles that lie in the maximum drag reduction (MDR) regime, but one set displays predominantly streamwise vortex structure and a nonzero Reynolds shear stress (RSS) while the other has an EIT structure and negligible RSS. Thus in polymer solutions, virtually identical mean velocity profiles can arise from very different turbulence production mechanisms.

The second part of the talk turns to development of a molecularly-based constitutive model for dilute wormlike micellar solutions. The fluid is treated as a dilute suspension of rigid Brownian rods whose length varies dynamically. Flow-induced alignment of the rods promotes increase of rod length that corresponds to the formation of flow-induced structures observed in experiments. If the rate constant for flow-induced growth is sufficiently large, the model predicts a multivalued relation between stress and deformation rate in agreement with experimental results. The model is simple enough to serve as a tractable constitutive relation for studies of turbulence.