Keynote: Mechanical Energy Harvesting Using Reverse Electrowetting by Professor Tom Krupenkin, Department of Mechanical Engineering, University of Wisconsin.

Abstract: Over the last decade electrical batteries have emerged as a critical bottleneck in portable electronics development. High-power mechanical energy harvesting can potentially provide a valuable alternative to the use of batteries, but, until now, its adoption has been hampered by the lack of convenient and efficient mechanical-to-electrical energy conversion technology. In this talk we discuss a novel approach to mechanical energy harvesting which is based on reverse electrowetting (REWOD). Reverse electrowetting is uniquely suited for high-power energy harvesting from a wide variety of previously inaccessible environmental mechanical energy sources, including human locomotion. Electrical energy generation is achieved through the interaction of arrays of moving microscopic liquid droplets with nanometer-thick multilayer dielectric films. Advantages of this process include the production of high power densities, up to $10^3$ Wm$^{-2}$; the ability to directly utilize a very broad range of mechanical forces and displacements; and the ability to directly output a broad range of currents and voltages, from several volts to tens of volts. We hope that the REWOD-based energy harvesting can provide a novel technology platform for a broad range of new electronic products and enable reduction of cost, pollution, and other problems associated with wide-spread battery use.

Understanding the Role of Surface Interactions on How Droplets Jump by Dr. Ryan Enright, Efficient energy transfer (net) Department, Bell Labs Ireland.

Abstract: Surface engineering that addresses both structure and chemical composition has emerged as a promising route towards further optimization of thermal and mass transport at the fluid/solid interface with implications for a wide range of applications. In particular, the implementation of surfaces engineered at the micro and nanoscale to enhance water condensation has been the focus of research in the last few years. We have seen a number of research studies performed in this area. However, what are optimal surface characteristics from a structural and chemical composition perspective? In this talk, I will focus on fundamental investigations of droplet jumping during water vapor condensation on superhydrophobic surfaces, as well as the criteria for nanodroplet water shedding. Through the use of modeling and experiments, we examined the role of surface structure and droplet morphology on departure characteristics via a coalescence-induced jumping mechanism. The insights gained from this fundamental study offer improved fundamental understanding of wetting and condensation on micro/nanostructures as well as practical implementation of these structures. They promise new surface engineering approaches to enhance the performance of various thermal management and energy production applications.
**Singular Capillary Microflows** by Professor James Sprittles, Mathematics Institute, University of Warwick.

Abstract: Drop formation, coalescence and dynamic wetting are all so-called 'singular' capillary flows, in which classical modelling approaches lead to infinite values of flow variables and computation becomes increasingly complex. In this talk, I will describe the mathematical models proposed for this class of flows and the techniques which have been used to obtain both analytic and computational results. In the case of wetting, I will explain how incorporating gas kinetic effects becomes essential for the description of recent experimental observations in both coating and drop impact. Simulations of the three microflows will reveal (a) the dominant physical mechanisms, (b) the accuracy of scaling laws proposed for them and (c) a number of new characteristics worthy of future investigation.

**Hybrid Superhydrophobic-Hydrophilic Materials for Dropwise Condensation and Nanoliter Dispensing** by Professor Alan Lyons, Department of Chemistry, City University of New York (CUNY).

Abstract: Low surface energy materials and high surface roughness topography are typically combined to form superhydrophobic surfaces. But, by incorporating high surface energy materials as well, anti-wetting properties can be combined with other chemical and/or physical characteristics that enhance the functionality of the surfaces. In the first part of my presentation, I will discuss a hybrid superhydrophobic-hydrophilic surface fabricated by inserting an array of hydrophilic metal needles through a superhydrophobic polymer film. Such surfaces were found to promote dropwise condensation (see photos at the end of this document), increasing the effective heat transfer of the surface by a factor of 2 over hydrophobic or superhydrophobic surfaces and a factor of 4 over solid copper. Water condenses preferentially on the hydrophilic needles as opposed to the hydrophobic polymer promoting rapid droplet growth and roll-off as well as preventing transitions from the Cassie to Wenzel state. In a second example, I will discuss the fabrication of a surface comprised on an array of glass pedestals that enable the transfer of precise quantities of nanoliter droplets of aqueous solutions. By chemically modifying the glass surface, biomolecules can be selectively adsorbed from the solution and detected by fluorescence microscopy or MALDI-TOF mass spectrometry. Evaporation of the droplets promotes convection and accelerates mixing within the droplets.

**Controlling Ice Formation on Nanostructured Superhydrophobic Surfaces** by Professor Tom Krupenkin, Department of Mechanical Engineering, University of Wisconsin.

Abstract: In this work we describe anti-icing properties of nanostructured superhydrophobic surfaces with well-defined regular arrays of micron and submicron surface features. Both open cell and closed cell structures are investigated. Dependence of ice formation dynamics on the temperature, details of the surface topography, substrate material, and other factors are investigated. We find that ice formation on those surfaces can be substantially retarded, with some of the surfaces showing no ice accumulation at temperatures as low as – 15 C. The obtained experimental results are in good quantitative agreement with the simple theoretical model based on classical heterogeneous nucleation theory. The results of the work provide new insight into design and optimization of anti-icing structures and coatings.
**Thermally Aware Superhydrophobic Surfaces for Icephobicity and Flow Condensation** by Professor Manish Tiwari, Department of Mechanical Engineering, University College London

Abstract: Durable hydrophobic surfaces offer a number of opportunities in phase change and heat transfer applications. In this talk, I will discuss the feasibility of rationally engineered superhydrophobic surfaces that can delay water freezing in severely supercooled conditions and sustain dropwise condensation of steam under strong vapour shear. In particular, I will highlight the importance of thermally conductive superhydrophobic surfaces for both anti-icing and flow condensation applications. Additionally, I will discuss a few strategies for careful nucleation control – of ice germs or droplets, respectively – using precise surface nanotexture and show our recent results on icephobic behavior down to -20 degrees Centigrade and flow condensation experiments for several days of sustained vapour shear. In addition, I will also discuss our recent results on surface designs for high speed droplet impact resistance which is pertinent to icing from supercooled droplets impacting on surfaces. Finally, I will share some personal perspective on future possibilities in this exciting area.

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**The Graetz-Nusselt Problem for Continuum Flows with Finite Slip** by Professor Jon Chapman, Mathematica Institute, University of Oxford.

Abstract: Graetz and Nusselt studied heat transfer between a developed, laminar fluid flow and a tube at constant wall temperature. Here we extend the Graetz-Nusselt problem to flows with partial wall slip. The amount of heat transfer is expressed by the local Nusselt number \( \text{Nu}(x) \), a dimensionless heat transfer coefficient. In the thermally developing regime, \( \text{Nu}(x) \propto (x/Gz)^{(-\beta)} \), where \( x \) is position down the tube and the Graetz number \( Gz \) is the ratio of axial advective to radial diffusive heat transport. In case of no-slip, the scaling exponent \( \beta \) equals 1/3. For no-shear (i.e., plug) flow, \( \beta = 1/2 \). We show that for partial slip, \( \beta \) transitions from 1/3 to 1/2 when \( 10^{-4} < b/R < 10 \), where \( b \) is the slip length and \( R \) the tube radius. The developed Nusselt number \( \text{Nu}(\infty) \) transitions from the classical limits 3.66 to 5.78 when \( 10^{-2} < b/R < 10^2 \). A mathematical and physical explanation is provided for the transition points for \( \beta \) and \( \text{Nu}(\infty) \).

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**Péclet and Brinkman Number Effects on Nusselt Numbers for Flow Between Textured Parallel Plates** by Mr. Georgios Karamanis, Department of Mechanical Engineering, Tufts University.

Abstract: We consider convective heat transfer for laminar flow of liquid between parallel plates that are textured with isothermal ridges oriented parallel to the flow. Two different configurations are analyzed: one plate textured and the other one smooth and adiabatic, and both plates textured with symmetrically aligned ridges. The liquid is assumed to be in the Cassie state on the textured surfaces, where a mixed boundary condition of no-slip on the ridges and no-shear along flat menisci applies. The thermal energy equation is subjected to a mixed isothermal-ridge and adiabatic-meniscus boundary condition on the textured surfaces. The effects of axial conduction and viscous dissipation are considered. We solve for the 3-dimensional temperature profile in an infinite domain resulting from a step change of the ridge temperature at the zero streamwise location assuming a hydrodynamically-developed flow, i.e., we consider the extended Graetz-Nusselt problem. Using the method of separation of variables, the thermal problem is essentially reduced to a 2-dimensional eigenvalue problem in the transverse coordinates, which is solved numerically. Expressions are found for the local and fully-developed Nusselt number in terms of the eigenvalues, eigenfunctions, Brinkman number and volumetric heat generation term.
**Effect of Meniscus Curvature on Thermal Transport in Microchannels with Ridged Walls at Constant Heat Flux** by Mr. Toby Kirk, Department of Mathematics, Imperial College London.

Abstract: It is well known that textured surfaces can reduce flow resistance in microchannels, but their effect on thermal transport in, e.g., direct liquid cooling of microprocessors, has only recently been considered. We investigate thermal transport in Poiseuille flow through a channel textured with periodic longitudinal ridges that are held at constant heat flux. We assume the liquid only makes contact with the tips of the ridges, reducing drag, but also the area for heat transfer. Accounting for curvature of the interfaces (menisci) that bridge each cavity, we consider two asymptotic limits: (i) small meniscus deflection from flat, using boundary perturbation; (ii) channel height large compared to ridge period, using matched asymptotics. In limit (i), the problem is reduced to dual series equations. If limit (ii) is also taken, we find explicit expressions for the effective slip length and Nusselt number. A remarkable finding is that the simple slip length expressions have exponentially small errors and so are accurate even for channel heights as low as half a ridge period.

**Local Hydrodynamics Close to Slippery Microstructured Surfaces** by Professor Clarissa Schönecker, Max Planck Institute for Polymer Research.

Abstract: Micro- or nanostructured surfaces can provide a significant slip to a fluid flowing over the surface, making them attractive for the development of functional coatings. This slip is due to a second fluid being entrapped in the indentations of the structured surface, like air for superhydrophobic surfaces or oil for so-called lubricant-infused surfaces (SLIPS). This talk addresses the flow phenomena within the lubricating layer and close to such surfaces, and demonstrates their implication on the effective slip length. Using an analytical model, that captures the influence of viscosity as well as surface topology on slippage, potential drag reduction in microchannels by employing superhydrophobic and other lubricating surfaces is discussed. It is shown that drag reduction is very sensitive to the viscosity of the lubricating medium. It furthermore crucially depends on the specific choice of the reference channel and its geometry. Furthermore, locally resolved measurements of the velocity field and slip length of a flow over a superhydrophobic surface are presented.

**New Theoretical Results for Longitudinal Flows over Superhydrophobic and Liquid-Infused Surfaces** by Professor Darren Crowdy, Department of Mathematics, Imperial College London.

Abstract: This talk will survey a number of recent theoretical results concerning the hydrodynamic problem of longitudinal low-Reynolds-number flow along unidirectional superhydrophobic and liquid-infused surfaces. In particular, we will focus two issues: how to account for the effect of non-zero meniscus curvature and the effects of additional subphase dissipation associated with the fluid trapped in the grooves. We will present some very new results highlighting the important and surprising role played by the idea of "reciprocity" in the theoretical study of these surfaces. The talk will be geared at opening up discussion of a wide range of possible extensions of the theoretical ideas presented.
Effect of Thermocapillary Stress on Slip Length for a Channel Textured with Parallel Ridges by Professor Marc Hodes, Department of Mechanical Engineering, Tufts University.

Abstract: Lubrication of flows in microchannels enabled by textured and superhydrophobic surfaces has received much interest in recent years. We compute the apparent hydrodynamic slip length, a measure of the effectiveness of lubrication in such flows, for (fully-developed and laminar) Poiseuille flow of liquid through a heated parallel-plate channel. One side of the channel is textured with parallel (streamwise) ridges and the opposite one is smooth. On the textured side of the channel, the liquid is the Cassie (unwetted) state, i.e., a lubricating layer of gas is trapped between menisci formed between ridges and the underlying substrate of the channel. No-slip and constant heat flux boundary conditions are imposed at the solid-liquid interfaces between the ridge tips and liquid and the menisci between ridges are considered flat and adiabatic. The smooth side of the channel is subjected to no slip and adiabatic boundary conditions. We account for the streamwise and spanwise thermocapillary stresses induced along menisci. When the latter are sufficiently small, Stokes flow may be assumed. Then, our solution is based upon a conformal map, albeit a cumbersome one. When, additionally, the ratio of channel height to ridge pitch is of order 1 or larger a less cumbersome, but equally accurate, solution is derived utilizing a matched asymptotic expansion. When inertial effects are relevant the slip length is numerically computed.

Three-Dimensional Effects on Momentum and Heat Transfer in Superhydrophobic Microchannels by Mr. Simon Game, Department of Mathematics, Imperial College London.

Abstract: Transport in microchannels can be enhanced by replacing flat, no-slip boundaries with boundaries etched with longitudinal grooves containing an inert gas, resulting in a flow exhibiting apparent (hydrodynamic and thermal) slip. Using a Chebyshev collocation (spectral) method, 3D effects are efficiently and accurately modelled, provided that channel length to hydraulic diameter ratio is sufficiently large. These effects include a non-constant meniscus curvature gradient found as part of the solution, as well as the transverse velocity field generated by the deformation of the meniscus. It can be shown that both of these effects are essential for the accurate prediction of the heat flux into a channel with constant temperature boundary conditions along solid-liquid interfaces. The efficiency of the method used allows for the Poiseuille and Nusselt numbers to be quickly calculated over a range of parameter values. This allows us to explore optimal channel configurations as well as determine the cases in which channels modified with longitudinal grooves are more effective than ordinary parallel plates.

Droplets of water condensed onto a hybrid superhydrophobic – hydrophilic surface prepared by inserting an array of needles through a superhydrophobic polymer. Courtesy of Professor Alan Lyons.