Order and Chaos:
Collective Behavior of Crowded Drops in Microfluidic Systems

Sindy Tang – Stanford University

Biography
Dr. Sindy KY Tang joined the faculty of Stanford University in September 2011 as an assistant professor in the Department of Mechanical Engineering. She received her Ph.D. from Harvard University in Engineering Sciences under the supervision of Prof. George Whitesides. Her lab at Stanford works on the fundamental understanding of fluid mechanics and mass transport in microfluidic systems, and the application of this knowledge towards problems in biology, rapid diagnostics for health and environmental sustainability. The current areas of focus include the hydrodynamics of concentrated emulsions in confinements, interfacial mass transport and self-assembly, and ultrahigh throughput opto-microfluidic systems for biochemical sensing and diagnostics, water and energy sustainability, and single-cell wound healing studies. Dr. Tang’s work has been recognized by multiple awards including the NSF CAREER Award, 3M Nontenured Faculty Award, and the ACS Petroleum Fund New Investigator Award. Web: http://web.stanford.edu/group/tanglab/

Abstract
Droplet microfluidics, in which micro-droplets serve as individual reactors, has enabled a range of high-throughput biochemical processes.[1] The talk will start with our recent application on using droplets to identify bacteria, specifically methane-metabolizing bacteria, for increasing the efficiency of generation of bioplastics.[2] This work, along with emerging applications to screen very large libraries of molecules or cells, has motivated us to investigate the physics and design criteria necessary for the further scaling-up of droplets technology.

Unlike solid wells typically used in current biochemical assays, droplets are subject to instability and can break especially at fast flow conditions. Although the physics of single drops has been studied extensively, the flow of crowded drops or concentrated emulsions—where droplet volume fraction exceeds ~80%—is relatively unexplored in microfluidics. The ability to leverage concentrated emulsions is critical for increasing the throughput of droplet applications, as it avoids the need to process large volumes of the continuous phase in order to process the same number of drops. Prior work on concentrated emulsions focused on their bulk rheological properties. The behavior of individual drops within the emulsion is not well understood, but is important as each droplet carries a different reaction.
This talk examines the collective behavior of drops in a concentrated emulsion by tracking the dynamics and the fate of individual drops within the emulsion. At the fast flow limit, we show that droplet breakup within the emulsion is stochastic (Figure 1).[3-6] This contrasts the deterministic breakup in classical single-drop studies. We further demonstrate that the breakup probability is described by dimensionless numbers including the capillary number and confinement factor, and the stochasticity originates from the time-varying packing configuration of the drops.[6]

To mitigate breakup, we design novel amphiphilic nanoparticles “F-SiO$_2$ NPs” (Figure 2a), and show they are more effective than surfactant molecules in preventing droplet breakup.[5] In addition, we show that these particles mitigate cross-talk of droplet content arising from inter-drop molecular transport, which is found to be mediated by reverse micelles in droplet systems stabilized by surfactants (Figure 2b).[7-11] The particles also form a solid-like interface that supports the adhesion and growth of adherent cells (Figure 2c). This capability is not possible in surfactant systems, and opens new opportunities for the use of droplets to study an increased range of cell types that require rigid surfaces for adhesion.

At the slow flow limit of the concentrated emulsion, we observe an unexpected order, where the velocity of individual drops in the emulsion exhibits spatiotemporal periodicity.[12] Such periodicity is surprising from both fluid and solid mechanics point of view. We show the phenomenon can be explained by treating the emulsion as a soft crystal undergoing plasticity, in a nanoscale system comprising thousands of atoms as modeled by droplets. Our results represent a new type of collective order not described before, and have practical use in on-chip droplet manipulation. From the solid mechanics perspective, the phenomenon directly contrasts the stochasticity of dislocations in microscopic crystals, and suggests a new approach to control the mechanical forming of nanocrystals.
Figure 2. (a) SEM image of F-SiO2 NPs stabilized droplets after evaporation of fluids. (b) Plots showing the time evolution of resorufin’s fluorescence intensity ratio between positive droplets (contains 220 µM resorufin at t=0) and negative droplets (without resorufin at t=0). (c) Optical image showing the spread and growth of anchorage-dependent mammalian cells (MCF-7) after 19 hours of cultivation at F-SiO2 NPs stabilized water/HFE-7500 interface.

Figure 3. Comparison of nanoparticles and surfactant as droplet stabilizer.
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