Introduction and Background This research project studies electrocoalescence, the process of forcing the coalescence of water droplets in an oil or petroleum crude by the application of an electric field across the droplets. The field polarizes the droplets, creating a dipolar attraction which results in the droplets merging. The focus of the study is to study the role of colloidal particles, present in the oil phase, and adsorbed onto the water/oil interfaces of the droplet, on the coalescence. The particles provide a steric barrier to the coalescence, requiring a larger field to merge the droplets. The objectives are: (i) to use microfluidics to directly visualize the electrocoalescence of an emulsion in two dimensions, identify coalescence events, and measure the event frequency as a function of the applied electric field, the surface chemistry of the colloids (hydrophobic/hydrophilic) and the particle suspension density, (ii) design a microfluidic arrangement to measure the dielectric properties of colloidal particles by examining the motion of the colloids driven by dielectrophoretic forces, and (iii) simulate the hydrodynamics of colloids trapped at, and moving along an interface, and (iv) the electrostatics and hydrodynamics of the electrocoalescence process to predict merging events, in emulsions without and with particles. Progress on the first two objectives are reported below.

Research Progress

(i) A Microfluidic Cell to Visualize and Measure Electrocoalescence Rates in Two Dimensions

The microfluidic cell, which is fabricated using soft lithography to imprint channels in an elastomer, polydimethylsiloxane, is shown in Fig. 1. A monodisperse train of water droplets (approximately 40 μm in diameter) suspended in a crude oil is generated by flow focusing streams of crude and water. The train is directed to a holding chamber (width \( W = 3 \text{ mm} \) and length \( L = 10 \text{ mm} \)) in which the droplets arrange themselves in an arbitrary configuration to form the 2D emulsion, and in which the electric field is applied. The height of the channels and chamber is \( H = 60 \mu \text{m} \) which is small enough for the crude to be transparent. For the field generation, planar electrodes are situated parallel to the chamber, and an AC field (500 hz) is applied across the chamber. Once the field is energized, a video of the coalescence dynamics in the chamber is recorded from the moment the potential is applied. Fig. 2 shows an illustrative sequence of images of the drop generation at the orifice, and the 2D emulsion in the chamber. The scale bars are 50 μm.

The microfluidic cell, which is fabricated using soft lithography to imprint channels in an elastomer, polydimethylsiloxane, is shown in Fig. 1. A monodisperse train of water droplets (approximately 40 μm in diameter) suspended in a crude oil is generated by flow focusing streams of crude and water. The train is directed to a holding chamber (width \( W = 3 \text{ mm} \) and length \( L = 10 \text{ mm} \)) in which the droplets arrange themselves in an arbitrary configuration to form the 2D emulsion, and in which the electric field is applied. The height of the channels and chamber is \( H = 60 \mu \text{m} \) which is small enough for the crude to be transparent. For the field generation, planar electrodes are situated parallel to the chamber, and an AC field (500 hz) is applied across the chamber. Once the field is energized, a video of the coalescence dynamics in the chamber is recorded from the moment the potential is applied. Fig. 2 shows an illustrative sequence of images of the electrocoalescence events in the chamber, over a period of approximately 1/2 s, for a field strength \( E_{\text{electrode}} = 250 \text{ V/mm} \). The sequence includes droplet pairs coalescing, as well as events in which groups of three and four droplets coalesce. Also evident (lower right hand side of figure) is a cascading event where two droplets merge, and the combined drop merges with a neighbor brought closer due to the prior electrocoalescence event. The coalescence events are clearly between droplets close enough so that they are a few tenths of a radii apart. Typically, coalescing droplets are aligned in the field direction, but not always precisely in that direction. These results demonstrate that the electrocoalescence process can be visualized on the scale of the droplets, and coalescence events can be recognized and recorded.
Figure 2: Image sequence of the electrocoalescence of droplets in the chamber at times of 1.94 - 2.56 s, referenced from the moment (t=0) the field is energized. In the first configuration, at 1.94 s, no droplets have yet coalesced. Scale bar is 50 µm. The field is applied top-to-bottom with $E_{\text{electrode}} = 250 \text{ V/mm}$. 

(ii) Microfluidic Measurement of the Dielectric Constants of Colloids by Dielectrophoretic-Driven Motion

To understand the motion of colloids adsorbed onto the emulsion droplet interfaces during electrocoalescence, the dielectric properties of the particle are required. In this study the dielectric constant is measured in a microfluidic arrangement by subjecting the particle flowing in a microfluidic channel (Fig. 3) to a non-uniform dielectric field imposed by a “V”-shaped electrode across the channel. The field induces a dipole moment in the particle in proportion to the dielectric constant, and the nonuniform field acts on the dipole, creating an electrostatic force which drives the particle along the direction of the gradient in the electric field and towards the wall. The migration is tracked by video recording and compared to simulations of the hydrodynamic trajectory which account for the viscous lubrication forces as the particle approaches the wall. By matching the simulations to the experimental trajectories, the dielectric constant can be obtained shown in Fig. 3 for polystyrene particles as a model system.

Figure 3: The microfluidic measurement of the in-situ dielectric constant of a colloid particle in oil. The particles are spherical polystyrene particles, 9.1 µm in diameter in a viscous mineral oil. The particles are convected by a channel flow, and migrate to the channel wall due to a dielectrophoretic force caused by the “V” shaped electrode. Modelling of the hydrodynamic trajectory in the perpendicular direction allows measurement of the dielectric constant of the particle.

One doctoral and one undergraduate student worked on this project. The doctoral student graduated and is employed in a microfluidics company and the undergraduate student went on to graduate school.