Discharges Between Charged Particles in Oil

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Abstract: A new method of plasma processing is under investigation which involves the generation of plasma within oil by means of mobile charge carriers controlled by an external electric field. Discharges are initiated when conducting particles, such as water droplets or metal balls, gain charge at an electrode immersed in the oil and then collide with one another. The interesting electrodynamics of this system provides a controllable method for the chemically processing of liquids. Three different discharge modes were identified including gas bubble discharges, microspark discharges and long spark chain discharges. These modes of electrical discharge can initiate non-thermal, thermal and hydrocracking chemical mechanisms in the oil and may be a useful method of gasification or reforming.

Keywords: Discharges, Plasma, Breakdown, Oil, Liquid

1. Introduction

The dynamics of charged particle in dielectric media has been described by several authors [1, 2]. Particle motion in these heterogeneous fluids, where the particles can be either gas, liquid, or solid, can be explained by either electrophoresis, forces on charged particles due to a uniform electric field, or dielectrophoresis, forces on dielectric particles due to a changing field. Although the dynamics of these systems are well known the collisional charge exchange mechanisms between particles have not been described. In this work we explore the electrical discharges which form when charge carriers collide. Depending on the circumstances of the collision including initial particle charge, time between adjacent collisions, and fluid motion during collision various types of electrical discharges were observed. Discharge modes can also depend on the external circuit responsible for generating the electrical field and variations are considered. The different characteristics of observed discharge modes can provide some idea about the expected properties of the plasma. High power sparks can dissipate kilojoules per pulse while lower power pulses dissipate energy on the order of joules per pulse and can be incomplete discharges [3]. Micro and nano-scale plasmas can be generated by limiting the power to only millijoules [4]. Ballasted discharges can create sustained non-thermal but warm glow discharges inside of bubbles.

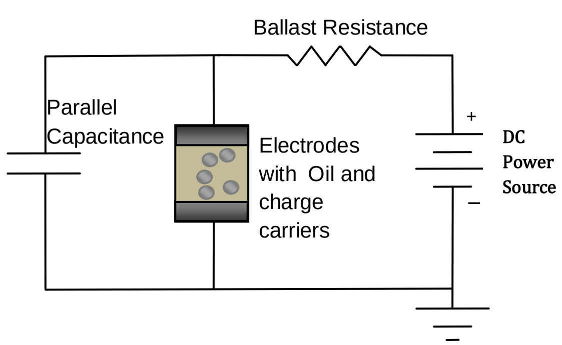


Figure 1: Experimental Circuit

2. Experimental Setup

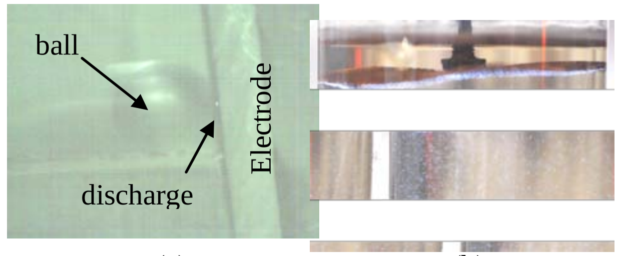
The experimental setup consists of a dc power source connected in series through a ballast resistance to two parallel electrodes submerged in dielectric oil maintaining a gap of several centimeters between them. A capacitance in parallel to the electrodes can control the time response of the circuit. Conducting particles are placed between the electrodes to act as charge carriers. Several charged carriers were investigated including water droplets and metal beads ranging in size from 0.8mm to 6.4 mm. Voltages were typically in the 10-30 kV range.

Parallel capacitances were varied from parasitic levels (~5 pF) to hundreds of nanofarads. The ballast resistance of 2Mohm was not always necessary and was used to isolate the output capacitance of the power supply from the circuit. A general circuit diagram is shown in Figure 1.

Discharges phenomena were observed using several imaging cameras: for long exposure images and those similar to observable by eye a Nikon D90 with macro lense was used; microscopic images were taken with a CCD attached to an Amscope microscope; high speed video imaging was performed using a Phantom V7.3.

3. Results

When the conductive particle is initially touching the electrode it acts as an extension of that electrode acquiring the same potential as the electrode. However as the charge carrier is not fixed to the electrode it feels an electrostatic repulsive force and moves away from the initial electrode and is accelerated to the oppositely charged electrode. Particle acceleration is reduced by fluid drag and some of its charge is lost by leakage into the fluid. However if the initial particle charge is sufficient the particle is able to cross the electrode gap. When the charged particle approaches another particle in the fluid or an electrode with a different charge a strong electric field develops between the charged surfaces and eventually an electrical breakdown will occur. An image of the discharge between a 3.2 mm ball and electrode is shown in Figure 2a. Breakdown occurs at almost every collision. Breakdown in liquids is described by the dielectric strength; for mineral oil this number is about 200 kV/cm. A minimum voltage below which breakdown will not occur is probably on the order of several hundred voltages and was not observed here since applied voltages were always in excess of 10kV. Two possible (though not definitively observed) exceptions to the occurrence of discharges are: 1) when two particles coming from the same electrode with a slight difference in charge collide and 2) when a particle leaks a substantial amount of its charge into the oil.



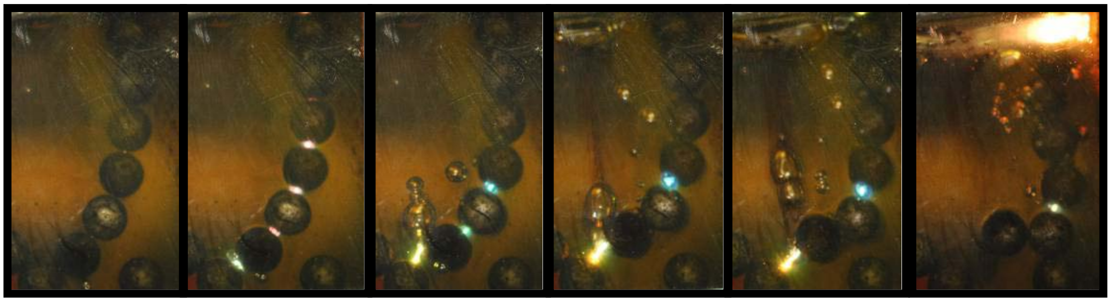
(a) (b)

Figure 2: a) Single charge carrier discharge with electrode b) Several charge carriers with discharges between each other and the electrode taken at 30 sec exposure time.

The characteristics of the electrical breakdown depend upon how much energy is transferred and the time over which that transfer occurs. In general three types of discharges were observed and these could be controlled by changing the particles and external circuit. First were short duration (<1μs) low power (<`mJ) microsparks. Second were long duration (usually 10's ms to almost steady state) steady current (~ 1 mA) gas bubble discharges. Last were high current short duration spark discharges which occurred between particles in chain.

3.1 Microsparks

When low power discharges are initiated just before a charged particle collides with an object of different charge as shown in Figure 2a. These discharges can occur even when the charge of the particle is very small and a lower voltage limit for breakdown has not yet been observed. The distances at which these discharges occur are typically very short (<10 μm) and the discharge is small, on the order of a few microns, and decreases with amount of charge transferred during the collision. The initial charge on the particle can be controlled by the size and the applied voltage to the particle. Total charge on the particles is on the order of nanocoulombs and the charge transfer during breakdown occurs on the microsecond timescale. Based upon the size, energy, and duration of the discharge they are likely highly non-equilibrium in nature similar to nanoscale corona discharges observed [4] using similar power discharges. When several charge carriers are present between the electrodes the charge carriers can transfer charge either by colliding with the electrodes or another charge carrier. When a low



0 s 4 s 6 s 12 s 14 s 20 s

Figure 3: Gas Bubble Discharge Chain

viscosity fluid is used and high electric fields the charge carriers bounce around in a chaotic manner resulting in multiple discharges occurring throughout the fluid as seen in the 30 second exposure photo in Figure 2b.

3.2 Gas Bubble Discharge Chain

When multiple charge carrier are present the charge carriers have a tendency to self-organize into chains as illustrated in Figure 3.The self arrangement into chains occurs because the higher electric field in the gaps between particles draws other particles into that region. When the particle velocity is high these structure are less likely to form and motion is more chaotic so they are more often seen in viscous fluids, for large particles, and at lower voltages. When the particles arrange into a chain they can effectively bridge the gap between the two electrodes. Since there is some chaotic particle and fluid motion and since the electrode gap is not an integral number of particle diameters the chain meander somewhat. Between particles in the chains electrical discharges occur as charge is transferred from one electrode to the other along the chain of particles.

If the external circuit has a low capacitance in parallel with the electrode a nearly sustained current flow is observed and the discharges form gas bubbles from reforming of the oil. An example of this is shown in Figure 3. The bubbles grow continuously throughout the duration of the discharge pushing the charge carriers away from one another until the bubble is removed from between the charge carriers. This can be seen happening at around 6 seconds in Figure 3. Once the bubble leaves often a new bubble will form or the chain may break apart and soon form a new chain. The discharge inside of the bubble appears to be a DC microglow discharge [5]. Discharge current can be controlled which can affect the type of plasma generated.

3.3 Spark Discharge Chain

If a capacitor is placed in parallel to the electrode when particle chain formation occurs it is possible to avoid gas bubble discharges. Adding the capacitor to the circuit provides high power pulses when the chains are formed resulting in spark chains as can be seen in Figure 4. These discharges are short in duration and often cause the chains to break apart immediately after breakdown is initiated.

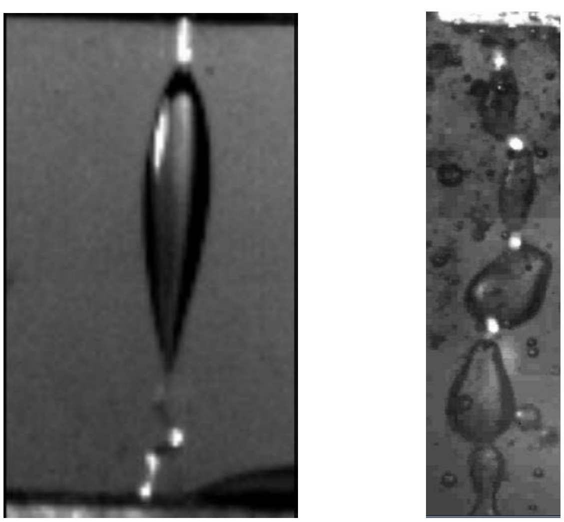
In Figure 4 the short duration, high intensity of the discharge is noticeable as the many balls moving in the fluid appear frozen (like in a strobe photo). The energy released in the spark discharge is very large however the duration is very short these allows for high temperature non-equilibrium chemistry. Transitioning from gas bubble discharges to spark chains is possible by varying the capacitance. If the power supply is not ballasted

Figure 4: Spark Discharge Chain

current is only limited by the capacitance that is present due to the electrical wires and the internal capacitance of the power supply; this is typically on the order of a few picofarads. In this case spark chains can occur. However more control is possible by using a ballast and varying the external capacitance, typically between picofarads and nanofarads. This results in control of the transition from the longer duration gas bubble discharge mode to the shorter duration spark plasma formation mode.

3.4 Deformable Charge Carriers

As mentioned previously gas, liquid and solid charge carriers are all possible. The solid charge carriers are able to transfer charge by moving through the fluid. Additionally, liquid charge carriers can deform, initially forming taylor cones and jets [6]. The jets can then act as the charge carrier which can transfer charge instead of moving the entire drop through the fluid. The jets can also break up into smaller drops creating several charge carriers. This type of taylor cone breakdown can be seen in Figure 5a. Several liquid charge carriers are present in the fluid they can also form chains which can initiate breakdown between the drops as shown in Figure 5b depending on the capacitance spark chains as shown here or gas bubble discharge chains can form.



(a) (b)

Figure 5: Taylor cone breakdown of a water drop in oil b) Liquid chain breakdown of water drops in oil

4. Conclusions

Several modes of breakdown between charge carriers in liquid have been observed and described here. Microspark discharges are low power micro scale short duration plasmas that favor low viscosity and high electric fields which cause chaotic motion between particles. These discharges are thought to be highly non-equilibrium. Charge carriers can self-organize into chains and two types of discharge are observed. Gas bubble discharges are longer in duration and produce bubbles that grow continuously between charge carriers. They occur when current is limited by a ballast supplying a steady current to the discharge. Gas bubble discharges occur more often in higher viscosity fluids. Transitioning to spark chains is possible by introducing a capacitor to the external circuit. The capacitor provides high power pulses resulting in short duration sparks. The short duration release of a high amount of energy may lead to a high temperature non-equilibrium plasma state. Spark chains occur much faster than gas bubble discharges. Lastly, water drops in oil can act as charge carriers with the added complexity of bubble deformation. Taylor cone breakdowns were observed as well as bubble chains.

Acknowledgements

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References

[1] Melcher, James R. Continuum Electromechanics. Cambridge, MA: MIT Press, 1981.

[2] Jones, Thomas B. Electromechanics of Particles. Cambridge University Press 1995.

[3] Locke, B. R., Sato, M., Sunka, P., Hoffmann, M. R., Chang, J.–S., 2006, *Ind. Eng. Chem. Res.,* **45**, 882.

[4] Staack, D., Fridman, A., Gutsol, A., Gogotsi, Y. and Friedman, G. 2008, *Angew. Chem., Int. Ed.* **47**, 8020.

[5] Staack, D., Farouk, B., Gutsol, A., and Fridman, A., 2008, *Plasma Sources Sci. Technol.***17**, 13

[6] W. Ristenpart, J. bird, A. Belmonte, F. Dollar, H. Stone, 2009, *Nature*, **461**, 377.