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Performance of an Electrowet-Coalescer

Ashish Bandekar, George G. Chase

Abstract: ***Water in diesel fuel can cause corrosion and reduce engine performance. Mechanical separators are most effective when water in the fuel is in the form of drops larger than about 100 microns but often fuels contain emulsified drops smaller than 100 microns. Pre-coalescence of the emulsified drops to larger drops can improve separation performance of mechanical separators such as coalescing and membrane filters. In this work, a thin-slit radial-flow electrowet-coalescer device was experimentally tested and statistically analyzed to evaluate the performance. The effects of the slit gap distance, the diesel fuel flow rate, and the applied electric potential were evaluated. Application of a full quadratic statistical model and the response optimizer method in Minitab™ shows the applied potential and the gap distance had greater impacts on the average drop size exiting the device than did the flow rate. The analysis determined the best performance occurred with the applied potential of 380V, gap distance of 0.0007m and flow rate of 2ml/s. At these conditions the average drop size increased from 33 microns in the inlet stream to 120 microns in the exit stream. The electric power required to operate the device was less than 1 milliwatt.***

Keywords: Electro wetting, Coalescence, Oil-water separation.

I. INTRODUCTION

Water in diesel fuel can cause corrosion and can plug engine components that contribute to reduction of engine performance and operating life [1-4]. Diesel fuels are often contaminated by low concentrations of water during routine handling and storage [5-6]. Fuel flow through centrifugal fuel transfer pumps and vibrations from equipment can disperse the water into emulsions of drops smaller than 100 microns. The emulsified drops tend to resist mechanical methods of separation. To separate dispersed water drops from diesel fuels a number of methods have been developed including adsorbent filters, hydrocyclones and gravity settlers [7-8]. In general these methods perform better with larger drops than smaller drops. Coalescing filters [9-12] are often used to enlarge the drops to improve performances of the separators. An alternative method to coalesce the drops is to apply electrowetting. To our knowledge, the use of electrowetting for this application is unique.

In our prior work an electrowet-coalescer (EWC) device was fabricated in which a water droplet emulsion in Ultra Low Sulfur Diesel (ULSD) fuel passed through a gap between two disc shaped electrodes (Figure 1) [13]. For electrowetting phenomena to occur, the two discs were sequentially dip coated with a dielectric polymer and a hydrophobic polymer.

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***** Correspondence Author (s)
Ashish Bandekar, Department of Chemical and Bio-Molecular Engineering, The University of Akron, OH 44325, USA.
George G. Chase, Department of Chemical and Bio-Molecular Engineering, The University of Akron, OH 44325, USA. E-mail: gchase@uakron.edu

Parameters controlling the dip coating of the two polymers on the electrodes were evaluated and the device was operated for proof of the concept as reported in the prior work [13].

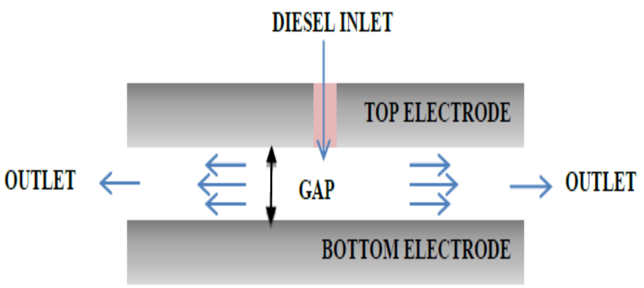

Figure 1. Schematic side-view of the slit flow between two disc-shaped electrodes.

In this work the operation of the EWC was evaluated to determine the effects of the gap distance, applied potential difference, and the ULSD flow rate. A combination of the three parameters was expected to result in an optimal performance of the EWC to produce the largest drops in the exit stream. The average drop size in the exit flow stream was selected as the objective function for the statistical analysis [14].

The gap distance between the electrodes and the applied potential difference between the electrodes control the intensity of the electric field between the electrodes that induce electrical forces on the drops to cause the drops to move towards the electrodes and to spread on the electrode surfaces [15-20]. The gap distance and the volumetric flow rate of the ULSD control the local velocity of the ULSD and thus control the drag force of the ULSD to transport the drops through the slit. The shear of the fluid flowing through the slit may contribute to drop coalescence or drop breakup [21-22] and was evaluated by operating the EWC with the electric power turned off.

If the gap distance is too small, the flow shear and drag of the ULSD may prevent coalescence and increase the pressure needed to push the flow through the gap. For a drop to experience the electric forces, the distance between the two electrodes needs to be relatively small [23-24]. If the gap distance is too large the electrical field may not be strong enough to enhance the coalescence. In the prior work the gap distance of 1 mm was tested. In this work the gap distance was varied from 4mm to less than 0.5 mm to determine where the best performance occurred. If the electric potential difference is too large the electric field may exceed the breakdown potential for the dielectric and make the dielectric ineffective as an insulator. The dielectric material used in this work had a breakdown potential of 1400 V/mm.

The voltage power supply used in this work provided a maximum potential difference 380 V. At the maximum potential, the electric breakdown of the dielectric would occur if the gap distance was less than 0.27 mm. Experiments were run with a larger gap distance than 0.27 mm to avoid breakdown.

The ULSD flow rate and the gap distance determined the flow velocity profile which controlled the shear stress of the flowing ULSD on the drop that dragged the coalesced drops out of the slit between the electrodes. For these experiments the flow rate was varied from 1 to 4 ml/s. This flow range is comparable to the fuel consumption rate of small diesel engines in sport utility vehicles, automobiles, and small trucks that range in fuel consumption from about 15 to 40 miles per gallon at 60 miles per hour.

II. DESCRIPTION OF EXPERIMENT

2.1. Electrowet-Coalescer Device

Two stainless-steel discs were used as the electrodes with a thin-slit gap between the electrodes. The discs were positioned so that the flow through the thin slit was horizontal. The top disc was 0.048 m in diameter and 0.014 m thick. The bottom disc was 0.036m in diameter and 0.014m thick. The two discs were dip coated (as described in reference [13]) with a dielectric coating polymer solution composed of 15 wt% of polymer in a polymer/toluene mixture and the polymer was Poly (styrene-co-methyl methacrylate) (PS/PMMA, Aldrich, MW: 100,00~150,000, styrene ~ 40 mol%) (ACS reagent 99.5%, MW: 92.14 g/mol). The electrodes were dried for 48 hrs (± 15 minutes), then similarly coated with the commercial polymer; Fluropel™ 1601V (Cytonix, Maryland) as the hydrophobic layer [25]. The Fluropel™ was provided in liquid form and used as provided without further modification.

The discs were assembled in the electrowet-coalescer device shown in the diagram in Figure 2 and in the photo in Figure 3. In this device the water-ULSD dispersion entered at the top through the center of the top disc, flowed through the thin-slit gap between the two discs, and exited from the bottom of the assembly. The gap distance between the two discs was adjustable by rotating a threaded rod attached to the lower disc. The two discs were prevented from contacting each other to maintain independence of electrical potential. The two discs were connected via wires to a power supply (Model IP 17, Heathkit Regulated High Voltage Power Supply, Benton Harbor, Michigan) for application of the potential difference between the discs. The outer wall of the EWC was a transparent non-conductive Lexan cylindrical tube. The top and bottom of the EWC was capped and sealed with machined Plexiglas ends.

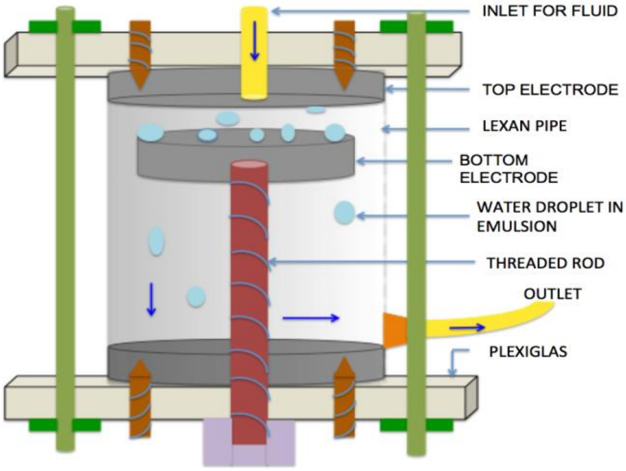

Figure 2. Schematic of the Electrowet-Coalescer Device.

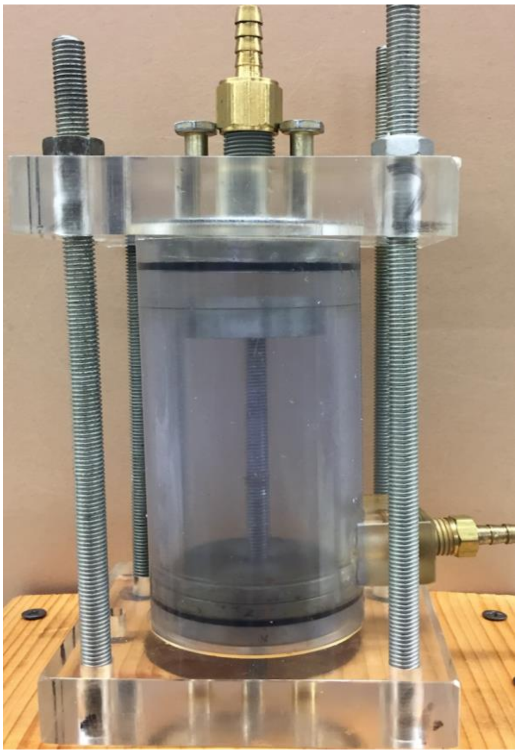

Figure 3. A photograph of the Electrowet-Coalescer Device.

2.2. Coalescence Experiment

ULSD purchased locally (McIntosh Oil, Akron, Ohio) was used in the experiments without modification. Chemical composition and additives in the ULSD can vary but no attempt was made to characterize the ULSD composition.

A dispersion of 0.24 vol% of water drops in the ULSD was created by blending 24 ml of water into 10 liters of ULSD and pumping the mixture through a recycle flow loop with a 3500 RPM fuel transfer pump (E3309, Airtex) as indicated in Figure 4. Part of the flow stream was diverted from the recycle line and sent through the EWC. The performance was assessed by comparing the drop size distributions in the inlet stream to the exit stream. Upstream and downstream ULSD samples were taken at 20 minute intervals from the inlet and outlet flow lines.

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Particle size distributions (number count per ml) were measured using a particle counter (Accusizer 780/SIS, Particle Sizing Systems Port Richey, FL, USA) from which the average particle sizes were determined on a number count basis.

III. RESULTS AND DISCUSSION

All experiments were run at the maximum voltage potential of the power supply, at 380 V. Experiments were run in triplicate. The data below are the average values and the error bars are one standard deviation of the averaged points.

In an experiment of constant flow rate of 4.0 ml/s, the gap distance between the two electrodes was varied in the range of 0.0003m to 0.004m. The results plotted in Figure 5 show the largest outlet average drop size, about 114 µm, occurred when the gap distance between the two electrodes was in the range of 0.0006m to 0.001m. Gap distances larger than 0.001 m caused a gradual decrease in the average drop size as.The electric field became less effective at attracting the drops to the disc surfaces due to the reduced field strength. For gap distances less than 0.0006 m the average drop size decreased rapidly as distance decreased due to the rapid increase in fluid velocity.

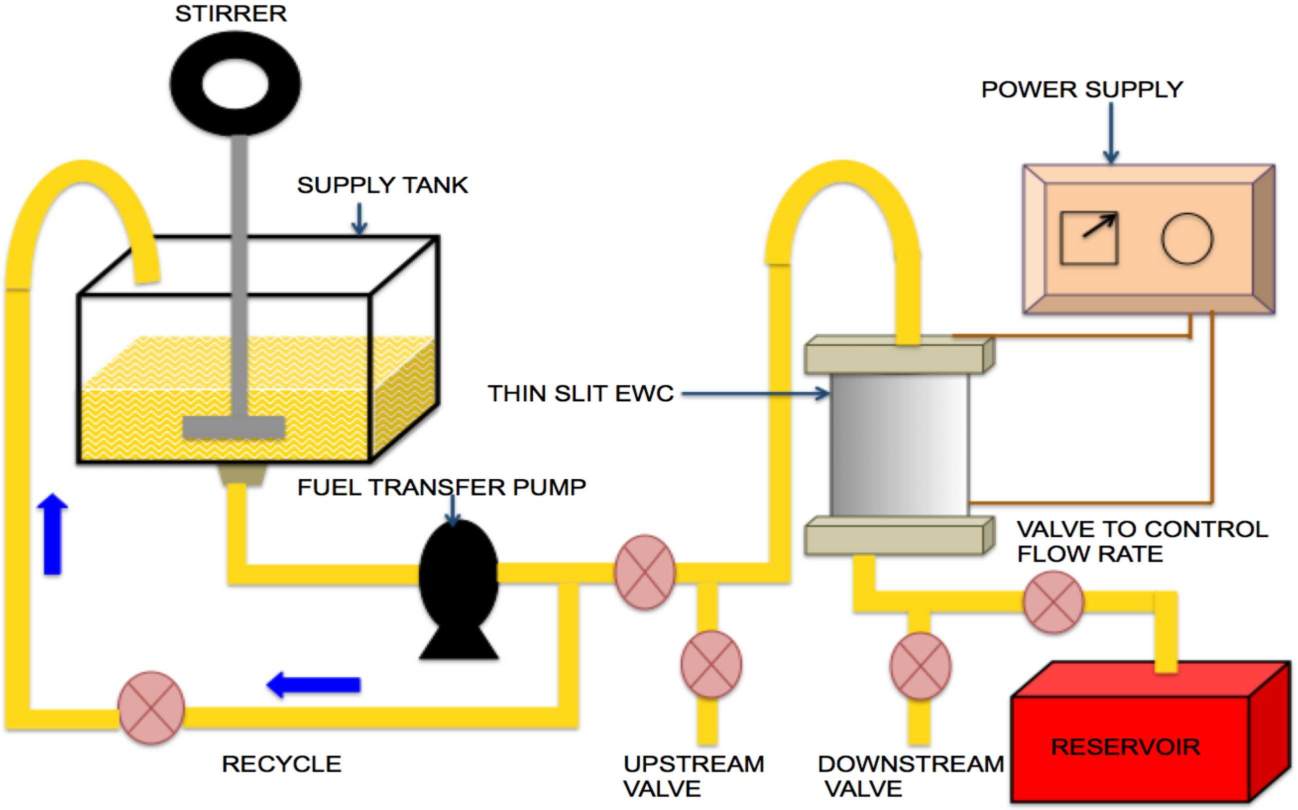

Figure 4. Schematic of the Coalescence Experiment Setup

The rapid increase in velocity with gap distance occurred due to the mass continuity. Based on the slit geometry and mass continuity the calculated average velocities (volumetric flow rate / area of flow) at the center and at the outside edge of the circular thin slit are plotted in Figure 6.

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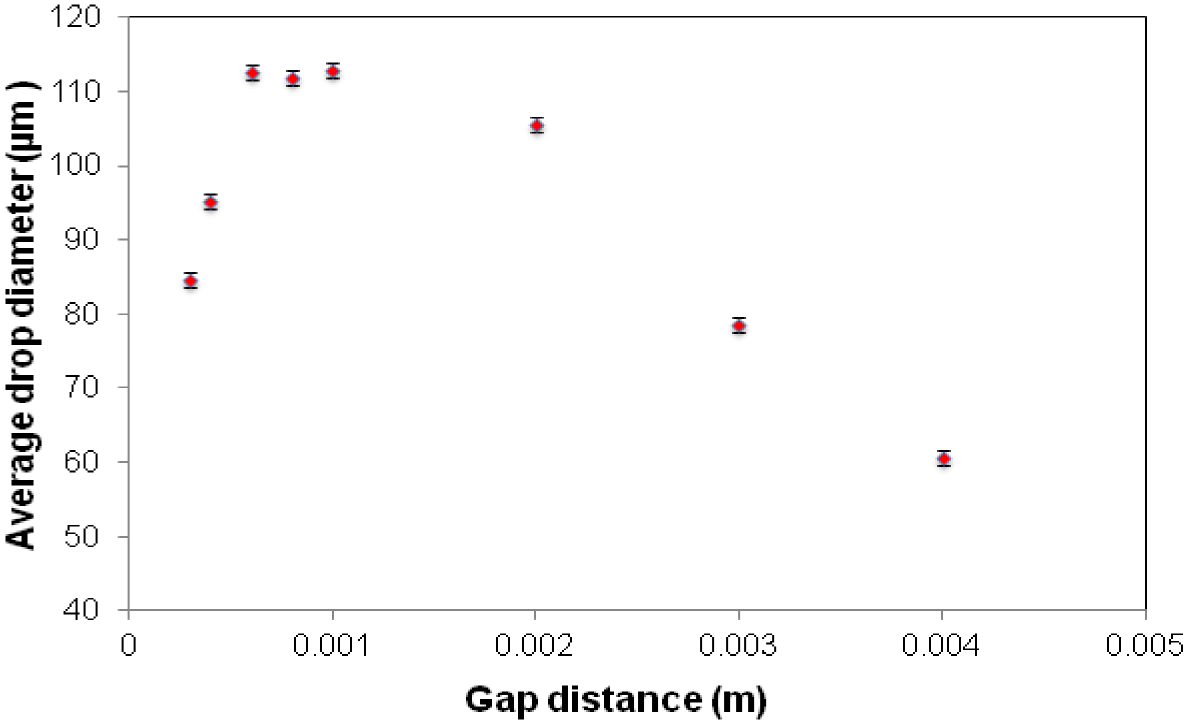

Figure 5. Impact of Varying Gap Distance on the Average Drop Size Distribution While Holding the Applied Potential at 380 Volts and the Flow Rate at 4.0 ml/s.

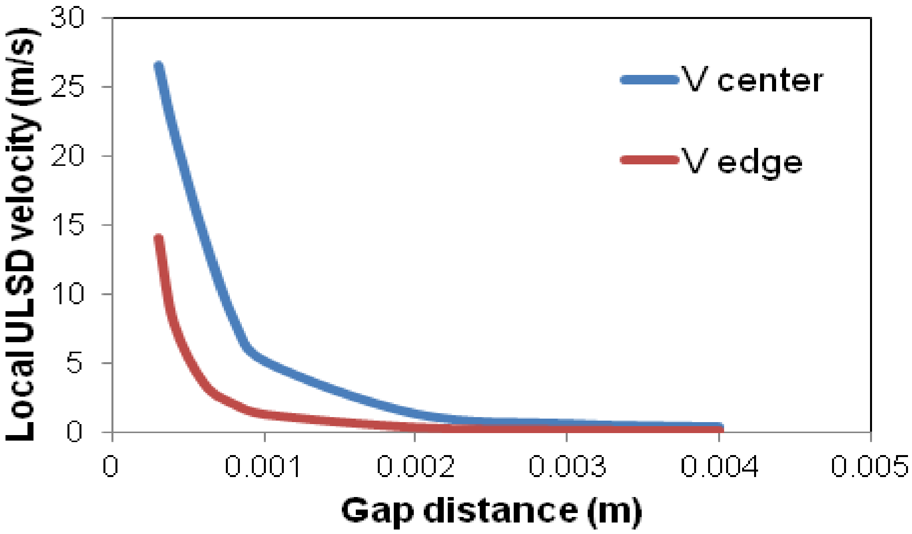

Figure 6. Plot of calculated average fluid velocity within the slit between the two discs at constant volumetric flow rate of 2 ml/s. The two curves show the average velocity near the center of the disc and near the edge of the disc. The velocity was calculated by dividing the volumetric flow rate by the slit area for flow in the radial direction.

As expected, at the same flow rate, the average velocity at the center of the disc is larger than at the outer edge. The plots show that as the gap distance decreases below about 0.0006 m both center and edge velocities increase rapidly. This is significant because the drag force of the flowing ULSD on a drop sitting on the surface of disc is roughly proportional to the average velocity, thus at gap distances smaller than about 0.0006 m the drag of the ULSD flow does not allow the drops to remain on the disc surfaces to collide and coalesce with drops in the fluid, and hence the EWC performance decreases.

From the data in Figure 5 the optimal gap distance is 0.001 m. Using this gap distance, experiments were conducted while varying the flow rate. The plot in Figure 7 shows the largest average drop diameter of about 126 μm occurred at ULSD flow rate of 2.0 ml/s and is an improvement compared to the prior work. Figure 7 also shows the measured pressure drops across the EWC device for different flow rates and gap distances between the discs.

In the prior work [13] the flow through the slit without applied electric potential resulted in a modest increase of average drop size to 40 μm (for gap distance 0.001 m and flow rate of 4 ml/s) compared to 115 μm at an applied potential of 350 V.

This showed the application of the electric potential contributed significantly to the droplet coalescence. The average coalesced drop size of about 115 µm in the prior work was within 1 standard deviation error bar of the 114 µm value plotted in Figure 5 for 380 V which suggests that the effect on average drop size by the applied potential may reach plateau. The prior work did not systematically investigate the effects of gap distance and flow rate, as is done here. Also, the prior work did not assess the operating power consumption.

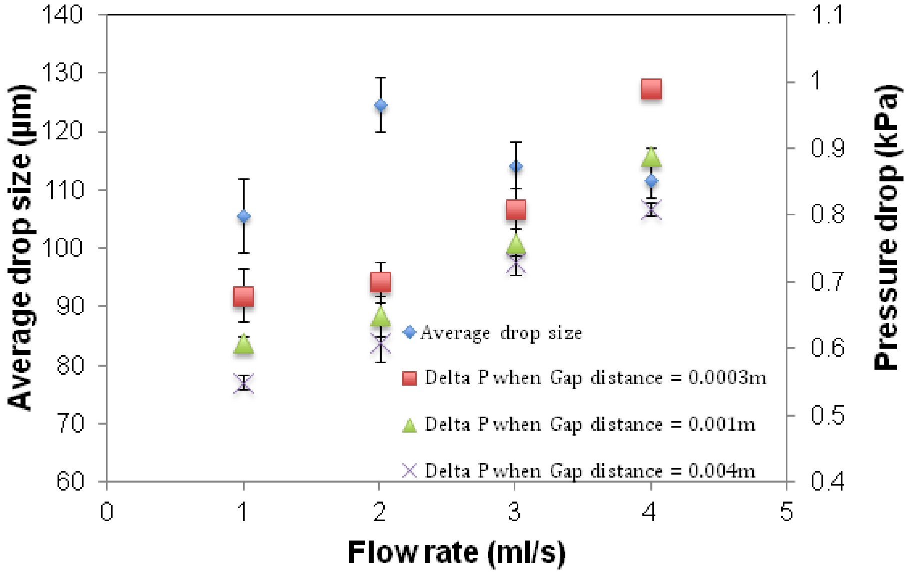

Figure 7. Impact of varying flow rate on the average drop size distribution while holding the applied potential at 380 V and gap distance at 0.001m. The highest average drop diameter of 126 µm occurred with flow rate of 2.0 ml/s. Also plotted are the measured pressure drops (Delta P) for different flow rates and gap distances.

The power consumption is due two parts: (1) the power required by the fluid to compensate for the friction loss of the ULSD to flow through the EWC and (2) the electric power consumed due to the current flowing through the device. The fluid power was calculated as the pressure drop times the flow rate through the EWC. The pressure drop across the EWC was measured using an electronic differential pressure gauge connected to the upstream and downstream lines entering and leaving the EWC. Figure 7 shows the pressure drop depended on the gap distance and the flow rate. At the optimal gap distance of 0.001 m and the optimal flow rate of 2.0 ml/s, the pressure drop was 772 Pa and the calculated power for the fluid flow was 1.50 mW.

The electric power to operate the EWC was calculated as voltage potential difference times current. The electric current flowing through the EWC was measured using a Keithley meter (Keithley 2400 SourceMeter, Beaverton, OR) during an experiment with the gap distance of 0.001 m and applied potential of 380V. The measured current through the EWC when filled with stagnant ULSD (no water drops) was 631.12 nanoamperes. When the ULSD-water emulsion flowed through the EWC at 2 ml/s the electric current increased slightly to 631.79 nanoamperes and remained constant throughout the experiment. The slight increase in the current may have been due to a slight increase in ULSD conductivity due to the presence of the water drops. From the applied potential and measured current the power was calculated to be 0.240 mW. Hence the total power required to flow ULSD through the EWC and operate the EWC at the optimal conditions (380 V, 0.001 m gap, and 2 ml/s flowrate) was 1.50 + 0.240 = 1.74 mW. This shows the required power was very reasonable.

The question of durability of the EWC is how well the EWC performs over repeated experiments. The same sets of discs were mounted in the setup and the experiments were performed 12 times. After each experiment the discs were removed, examined for water drop contact angle, and replaced in the holder for the next experiment. The water contact angles varied between 114 and 116 deg with no obvious trend or pattern. The coalescence experiments were run at the same operating conditions for each experiment (applied potential of 380 Volts, gap distance of 0.001 m, and continuous ULSD flow rate of 2.0 ml/s). Over the experiments the average drop size in the inlet streams ranged from 32 to 39 microns and the average drop size of the outlet stream ranged from 118 to 124 microns. The variations in the average drop sizes did not show obvious trends and were consistent with the variability observed in prior experiments. Hence over the 12 repeated experiments the EWC did not show a decline in performance and the discs could be used in further tests.

IV. STATISTICAL ANALYSIS

For statistical analysis of the parameters affecting the average drop size, a full quadratic model was applied to the three main parameters (applied potential, gap distance and flow rate). Model coefficients were estimated using the Design of Experiments (DOE) Response Surface platform of MINITAB 17 software. Quadratic plots depicting main effects for average drop size are shown in in Figure 8. All of these plots were obtained by the response optimizer method in MINITAB 17. The plots verify that drop size is strongly related to the applied potential and gap distance but the flow rate had a small effect on the outcome.

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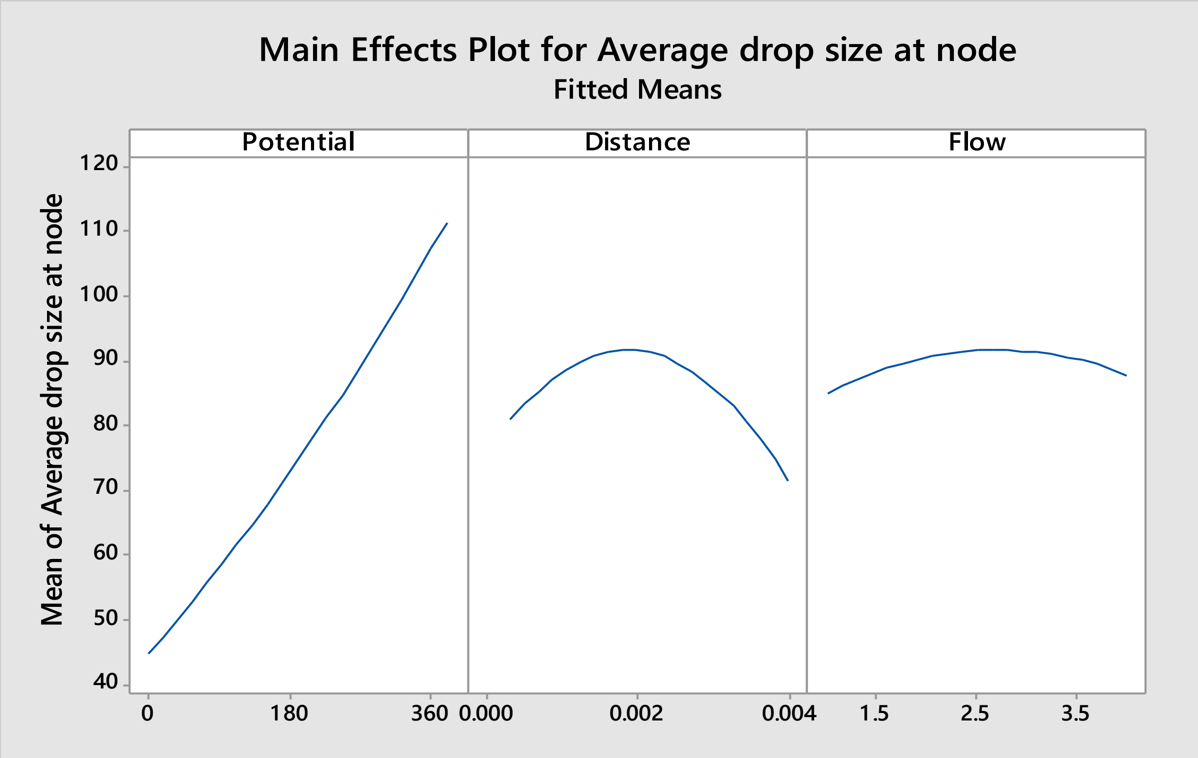

Figure 8. Main Effects Plot for Drop Size.

P-values for each of the coefficients of the quadratic models for predicting drop size are shown in Table 1. These were obtained from the variance table produced using the Response Surface Regression functionality of Minitab 17. Normally, in case of P-values, P<0.05 is referred as statistically significant. Table 1 gives the P-vales for the quadratic model coefficients based on analysis on variance. From Table 1 it can be seen that in case of liner model the parameters of Applied potential and gap distance are statistically significant and the parameter of flow rate is statistically insignificant as in this case P-value is >0.05. In case of all the 3-types of model, all flow rate terms are statistically significant. In quadratic modeling relating to drop size, none of the model terms involving the flow rate were statistically significant. However, both applied potential and gap distance were significant. The interaction between applied potential and gap distance was also significant related to drop size as indicated by the interaction plots in Figure 9.

Table 1. P-Values for Quadratic Model Coefficients based on Analysis of Variance.

Model	Parameter	P-value
Linear	Applied potential	0.002
	Gap Distance	0
	Flow rate	0.656
Square	Applied potential * Applied potential	0.159
	Gap Distance * Gap Distance	0.096
	Flow rate * Flow rate	0.313
2-Way Interaction	Applied Potential* Gap Distance	0.028
	Applied Potential*Flow rate	0.735
	Gap distance*Flow rate	0.976

After determining that flow rate was a statistically insignificant parameter, Minitab analysis was performed using only applied potential and gap distance as the parameters. The P-values for this case are shown in Table 2. From these values we learned that, P-values in this case were statistically more significant than in the latter case. In Table 2, all the interactions were statistically significant which was not the case in Table 1.

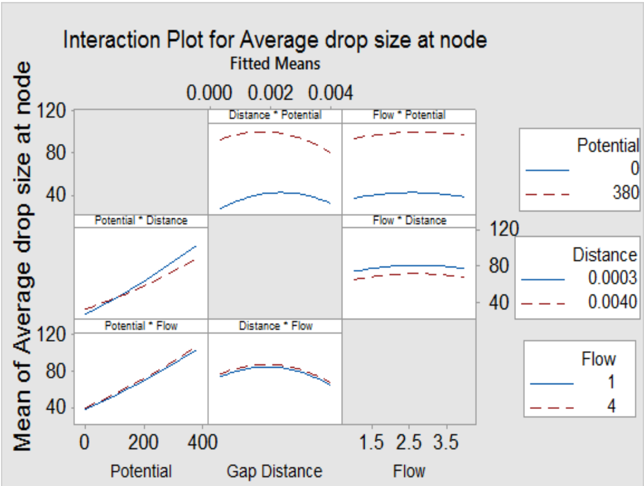

Figure 9. Interaction plots.

Table 2. New P-values for Quadratic Model Coefficients based on Analysis of Variance.

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Model	Parameter	P-value
Linear	Applied potential	0.001
	Gap Distance	0
Square	Applied potential * Applied potential	0.007
	Gap Distance * Gap Distance	0.041
2-Way Interaction	Applied Potential* Gap Distance	0.028

V. CONCLUSION

The designed electrowet-coalescer device was tested at a maximum voltage potential of 380V to determine its performance to coalesce drops for different flow rates and gap distances. The best performance gap distance of 0.001 m and ULSD flow rate of 2.0 ml/s enlarged the drops from average size of about 30 to 126 µm. The power required to operate the EWC, both for fluid flow and electric, was only 1.74 mW. Repeated tests with the same discs showed negligible change in the surface properties of the discs after 12 repeats. Statistical analysis showed the applied potential and the gap distance were the statistically significant parameters controlling the performance.

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