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Modeling and Experimental Study on the Design of Separators for Water/Oil Separations using Electric Fields

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Abstract

The efficient elimination of water from water/oil emulsions has been an important issue in the industry for many decades. This paper reports simulation and experimental study on different designs of the separator and their effects on the separation time of water/oil. The separator with a cylindrical design is found to have shorter separation time when compared to the separator using flat-plates design. The effects of the size of the separator and design of the center electrode (i.e., thickness, length, and air-gap) on electric field are also studied by computational simulation, and the results can be used to explain the experimental tests. It is found that the decrease in the thickness and the air-gap of the central electrode, as well as the diameter of the separator, can significantly increase the electric field in the emulsion. In addition, the elongation of the center electrode can also enhance the electric field. The results of this reported study can be used to design an efficient water/oil separator for various applications.

Keywords: Water/Oil; Emulsions; Electrode; Petroleum and chemical industries

Introduction

The separation of water droplets from water/oil emulsions has been a significant subject in petroleum and chemical industries [1,2]. Many different techniques have been developed to solve this issue. One of the most efficient methods for the water-oil separation is the electric field assisted coalescence. This method uses electric fields to enhance the water droplet coalescence in emulsions [2]. In electric fields, water droplets can move toward the electrodes and collide with each other. The dipole-dipole force and the dielectrophoretic (DEP) force are two major electric forces that affect the droplet movement. The dipole-dipole force represents the attractive force between two polarized droplets, while DEP force is the result of the unbalanced electric forces on the polarized particles in non-uniform electric fields. The droplets can collide and/or coalesce with the interactions of these electric forces. The coalesced droplets can be settled due to the gravitational force.

The droplet movements in electric fields with various temperatures have been investigated theoretically [3-8]. The electric field separation can be accelerated by increasing the operating temperature due to the reduced viscosity of the oil at the elevated temperature, which speeds up the coalescence of the water droplets [2,9]. In this experimental setup, electric fields are applied to the emulsion with elevated temperature to enhance the water/oil separation speed. Different shapes (i.e., flat plates and cylindrical) of separators are designed to compare the influence of the configuration. The effects of the thickness and length of the centre electrode, and the air-gap between the centre electrode and its insulated capillary tube have been investigated. In addition, the influence of the separator's diameter has been studied.

Theoretical considerations

In the separation process of the water-in-oil emulsion using electric fields, two different forces are considered to be the main driving forces: the dipole-dipole force and dielectrophoretic (DEP) force. The dipole-dipole force can be created both in uniform and non-uniform electric fields. It represents the attractive force between the polarized droplets at the positive end and negative end. This attraction is only effective at close distances between polarized droplets because the dipole-dipole force decreases rapidly as the distance between droplets increases. Therefore, if the droplets are located far away, this single effect is not enough to enhance droplet coalescence in electric fields [10]. This dipole-dipole force between two identical droplets in electric fields can be expressed in equation 1, where is the permittivity of the oil phase, E_0 is the electric strength, is the radius of the water droplet, and is the distance between the droplet centers [3].

$$F_{el} = \frac{24\pi E_0^2 a^6}{l^4} \quad (1)$$

In non-uniform electric fields, the electric fields near the centre electrode are much stronger than those in the far-field region. As a result, the polarized droplets can be pushed or pulled by the electric fields as illustrated in Figure 1. This introduced motion can drive the dipole-dipole interaction when the droplets approach other neighbouring droplets, which would also expedite the droplet coalescence [10]. The driving force of this motion is called DEP force and can only be created in non-uniform electric fields. Non-uniform electric fields can enhance the coalescence of water droplets compared to the uniform fields because the combined dipole-dipole and DEP forces act on the particles simultaneously [2,11,12].

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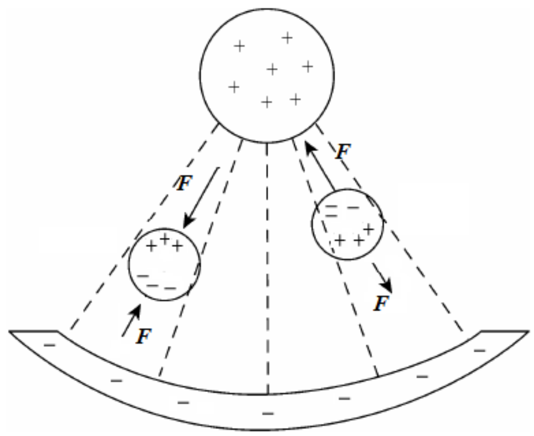

Figure 1: Schematic diagram of non-uniform electric fields and dielectrophoresis (DEP) forces exerted on droplets.

The magnitude of DEP force can be expressed in equation 2, where is a droplet radius, is the permittivity of the medium surrounding oil, is the permittivity of water droplets, and is the gradient of the root-mean-square of the applied electric field.

$$F_{DEP} = 2\pi a^3 \varepsilon_m \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m} \nabla \left|\vec{E}\right|^2 \text{ (2)}$$

As indicated in equation 2, the DEP force is highly influenced by the gradient of electric field , and becomes zero in the uniform electric field. Therefore, we decided to use non-uniform electric fields in the separation system, which would introduce not only the dipole-dipole force but also the DEP force to promote the moment and coalescing of water droplets. The coalesced water droplets by electric fields can deposit by gravitational force. The force of gravity (F_g) exerted on the water is expressed in equation 3, where is a droplet radius, ρ_w is water density, and ρ_0 is a density of continuous oil phase [4].

$$F_g = \frac{4}{3}\pi a^3 (\rho_w - \rho_0) g \text{ (3)}$$

Computational simulations

The influence of the design of cylindrical separator is investigated by computational simulation. The ANSYS Maxwell, which is a high-end interactive tool using Finite Element Analysis (FEA) for electric and magnetic modeling, simulates variables such as the radius of the separator, length of the central electrode, and the air-gap between the centre electrode and its insulated capillary tube. As illustrated in the last section, when water droplets are placed in electric fields, the electrostatic force acting on them can be calculated by integrating the dipole-dipole and DEP forces over their close surfaces [13-15]. The dipole-dipole force is in proportion to the square of the electric field strength as shown previously in equation 1.

Figure 2 shows the magnitude map of electric fields in the separator with a 5 kV voltage applied to the central electrode. The left figures show the models before simulation, while the right ones show the results of mapping. As can be seen in Figure 2, a very strong electric field is generated within the 0.075 mm air-gap between the copper wire and the insulated capillary tube. This strong electric field would result in a great drop of electric potential, thus reducing the strength of electric field in the emulsion area. Therefore, reducing or even eliminating the air-gap may be an effective way to increase the magnitude of electric fields in an emulsion. In contrast to the air-gap, the electric field within the insulated capillary tube is relatively week, which may result from its large relative permittivity (i.e., ~5.5 for glass).

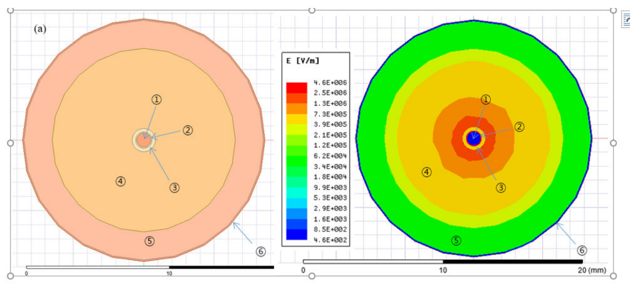

Figure 2(a): Simulation of the magnitude of electric field distribution top-view. Sectional front view. In the figure shows the configuration (left) and the mapping (right):(1) central electrode (5 kV applied), (2) Air gap, (3) Insulating glass layer, (4) Emulsion, (5) Glass tube, (6) Copper foil (ground).

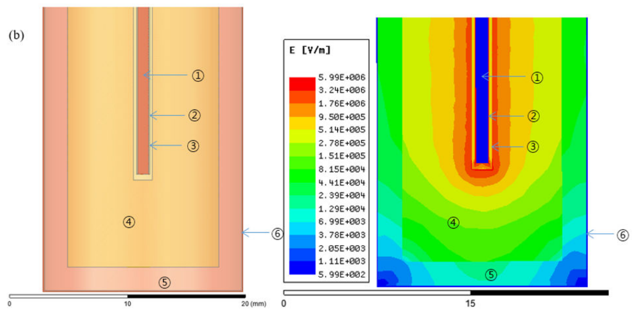

Figure 2(b): Simulation of the magnitude of electric field distribution top-view. sectional front view. In the figure shows the configuration (left) and the mapping (right): (1) Central Electrode (5 Kv applied), (2) Air gap, (3) Insulating glass layer, (4) Emulsion, (5) Glass tube, (6) Copper foil (Ground).

Besides the dipole-dipole force, DEP force is exerted on the droplets in the separator with the non-uniform electric fields. DEP force is proportional to the square of the gratitude of the electric field. Figure 3 plots the magnitude of over the emulsion. One notable observation in Figures 2 and 3 is that both the electric field strength and gradient decreases significantly with an increase of radius. It is consistent with Gauss' law as equation 4 and 5, where δ is the charge per unit length on the central electrode, r is radius (i.e., the distances to the central axis), and ε is the permittivity of the medium [16-18].

$$E(r) = \frac{\delta}{2\pi\varepsilon r} \text{ (4)} \left|\frac{dE(r)}{dr}\right| = \frac{\delta}{2\pi\varepsilon r^2} \text{ (5)}$$

As a result, the water droplets in the areas near the central electrode will experience a much higher dipole-dipole force and DEP force, thus resulting in a higher separation rate in those regions. In addition, as the electric field declines very fast with the increasing of radius, the separation speed will be reduced if the radius of separator becomes larger.

In Figures 2b and 3b, a region with much lower electric field strength and gradient is also observed below the central electrode (i.e., ~10% comparing to the magnitude in other region). This indicates that the electric fields in the separator are mostly distributed in the radial direction. Therefore, more emulsion will be cover in the strong electric field region if the length of central electrode is increased, which would lead to an enhanced separation performance.

Experimental Setup

The configuration (e.g. plate or cylinder) of the separator is a key factor to affect the separation time. In this paper, two different separation tubes equipped with flat plates or cylindrical electrodes are fabricated to conduct the water/oil separation tests. The schematic diagrams of these two separate systems are indicated in Figure 4. The flat plate electrodes would create uniform electric fields, while cylindrical electrodes generate non-uniform radial electric fields. The separation test is conducted in the temperature-controlled oven.

The flat-plate separator is built using two copper flat-plates as electrodes which are fixed in a glass bottle and facing each other. The cylindrical separator is built using a copper wire as a central electrode which is fixed in a cylindrical glass tube, and a copper foil. The separator is surrounded by a copper foil which plays a role as a ground electrode. The electrodes of these two systems are insulated to prevent electric short-circuits. Insulated electrodes have an electrical breakdown strength to sustain the high voltage. This can reduce electrical potential at the electrode emulsion interface [19-25] and enhance separation speed [26]. In this test, two flat electrodes are covered by PFA Teflon bags, while the central electrode and thermocouples are insulated by glass capillary tubes.

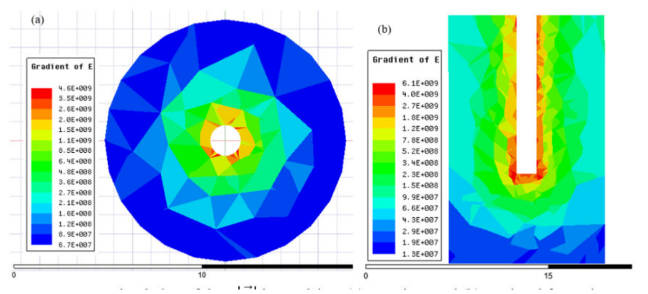

Figure 3: Simulation of the in emulsion: (a) Top-view, and (b) Sectional front view.

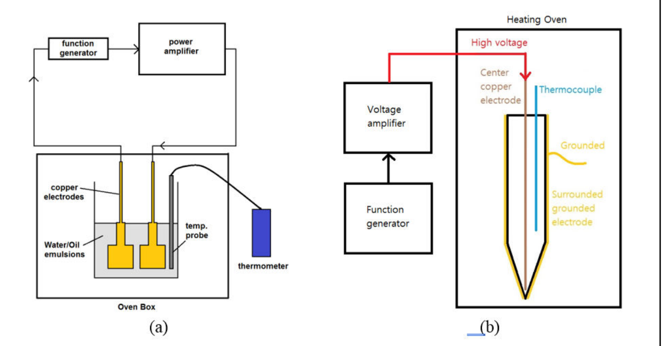

Figure 4: Schematic of water-in-oil emulsion separation setup: (a) Flat plates electrode separation system, (b) Cylindrical electrode separation system.

A function generator and a voltage amplifier are used to supply voltage to the electrodes, and thermocouples are immersed in the emulsion during the test for temperature measurement. The function generator can generate various electric fields (e.g. DC, AC, and pulsed DC) with different wave shapes (e.g. sine, square, and arbitrary). A square wave of pulsed DC is used for all the tests because this wave may produce the highest separation speed [2,27]. The voltage amplifier can amplify the input voltage to 2000 times higher. The maximum voltage and frequency generated from this equipment are 10 kV and 7.5 kHz.

Results and Discussion

In this experimental process, water-in-oil emulsion is heated to the targeted temperature. Once the emulsion reaches the temperature, a voltage is applied to the system. The pictures of water/oil separation at different time are taken after the emulsion is exposed to the high electric fields.

Comparison between flat plates and cylindrical electrodes

In this test, two different separators, which use flat plates and cylindrical electrodes respectively, are designed to perform water/oil separation tests. The flat plate separator is used to create uniform electric fields, while the cylindrical separator is used to provide the non-uniform electric fields. In this test, 1 kV of voltage is applied with 50 Hz of frequency, and the operating temperature is 80°C.

The progress of the water/oil separation for these two separating systems is shown in Figures 5 and 6. The separation speed of water-in-oil emulsion using a cylindrical tube can be much expedited when compared to those using flat plate electrodes as shown in Figure 5. After the 10-minutes test, the white deposit of the water droplets still exists in the flat plate separator, while the emulsion is completely separated in the cylindrical separator. This result indicates that the cylindrical water/oil separation system, which generates non-uniform electric fields, is more efficient for water/oil separation compared to the flat plate's separation system.

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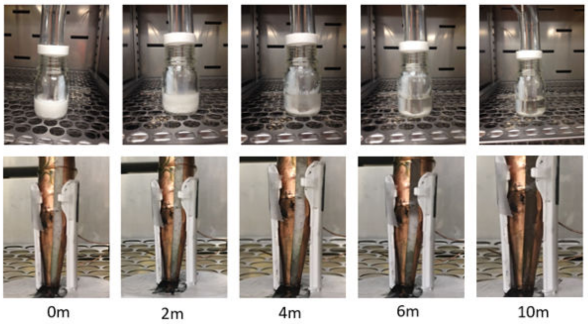

Figure 5: Comparison of water/oil separations between flat plates (top) and cylindrical electrodes (bottom).

Based on this result, a further investigation regarding the design of the cylindrical electrodes will be performed by changing the thickness of the centre electrode and the capillary tube. Also, the effect of the length of the centre electrode and the gap between the electrode and the insulated glass layer will be determined.

Thickness of the centre electrode

The thickness of the centre electrode may influence the separation time of the water/oil due to its effects on the strength and gradient of electric fields. As validated in the simulation, the strength and gradient of the electric field inside the separator increase as the radius decreases. The thickness effect of the centre electrode on the water/oil separation is investigated by performing water/oil separation tests using two centre electrodes with different thicknesses. As shown in Figure 6, two separators are used in the test. Both separators have an inner diameter of 17 mm and an outer diameter of 25 mm. The separator on the left has a thicker (7 mm) central electrode, while the one on the right has a thinner (1.65 mm) centre electrode. There is a 15 mm gap between the edge of the centre electrode and the bottom of the separators. High voltage is applied to the two separation tubes at the same time. The applied voltage and frequency are 5 kV and 5 kHz with a square wave and the operating temperature is maintained at 90°C. As indicated in Figure 6, the reduced thickness of the centre electrode can expedite the separation speed of the emulsion.

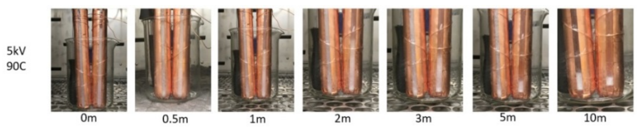

Figure 6: Comparison of water/oil separation with two different thicknesses of the center electrodes: 7 mm (left) vs. 1.65 mm (right).

Length of the centre electrode

The length of the central electrode can affect the separation time of the water-in-oil emulsion. Several tests for water/oil separation are executed to determine the length effect of the centre electrode. Two identical cylindrical separation tubes are used in this test. The separation tube on the left-hand side has a shorter central electrode (105 mm), which results in a 15 mm gap to the bottom of the tube. The separation tube on the right-hand side has an extended length (120 mm) of the centre electrode, which results in a minimal gap to the bottom of the tube. The use of this elongated centre electrode may enhance the electric fields in the separator, especially around the bottom area. The thickness of the centre electrode is 0.65 mm for both separation tubes. Two different voltages and temperatures are used in this test. The applied voltage is 5 kV or 10 kV with 5 kHz of frequency, and the operating temperature is 90°C or 100°C.

The simulation shows that the extended length of the centre electrode should enhance separation. It is verified by our experimental tests. As can be seen in Figure 7, the extended length of the centre electrode can promote the separation speed. Especially, huge differences are observed around the lower part of the separators. The white layer, which indicates incompletely separated emulsion, remains on the left side tube after the 10-minutes test, while the emulsion is completely separated after several minutes on the separator which has an extended centre electrode. That phenomenon may result from the enhanced electric field around the bottom area of the separator by using the elongated central electrode.

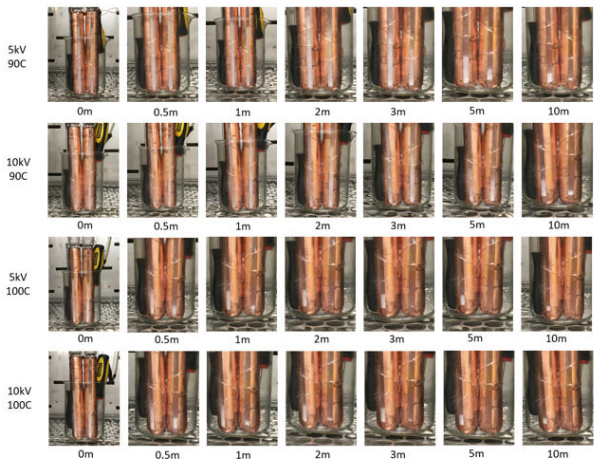

Figure 7: Comparison of water/oil separations with two different lengths of the centre electrodes at different temperatures and voltages: 105 mm (left) vs. 120 mm (right).

Air-gap between centre electrode and capillary tube

In the separator, insulated electrodes are used to prevent electric short-circuits. This design is achieved by inserting the copper wire into a thin capillary glass tube. As a result, there would always be a thin air-gap between the copper wire and the insulated capillary tube. From previous tests, it has been determined that the thickness and length of the centre electrode can affect the separation speed. However, it remains unclear whether the air-gap has an influence on the separation performances.

In this test, the effect of the air-gap between the centre electrode and its insulated capillary tube is investigated. Two different thicknesses (0.2 mm and 0.65 mm) of the copper wire are used with the same capillary tube that has an inner diameter of 1.15 mm and an outer diameter of 1.65 mm. It results in the air-gap of 0.475 mm and 0.25 mm respectively. The separator on the left has a thinner central electrode (0.2 mm) which leads the extended air-gap, while the separator on right has a thicker central electrode (0.6 mm). The applied voltage is 5 kV or 10 kV with 5 kHz of frequency, and the operating temperature is 90°C or 100°C.

The simulation implies that the reduced air-gap can enhance the electric field strength as shown in Figure 2a. This increased electrical strength can expedite the separation speed of the water-in-oil emulsion. The separations of water and oil phases are indicated in Figure 8. From the results of this test, it is experimentally verified that the reduced air-gap between the centre electrode and the capillary tube can expedite the separation speed.

Diameter of the separation tube

The diameter of the separation tube can influence the strength and gradient of the electric field which determine the separation time of the emulsion. Theoretically, the dipole-dipole forces and DEP forces rapidly decrease as the radius increases, as shown in Figures 2 and 3. In this experiment, two different dimensions of cylindrical separators are used for the water/oil separations. The inner and outer diameters of the larger separation tube are 30 mm and 34 mm, while the smaller one has 13 mm and 17 mm respectively. The applied voltage is 1 kV with 50 Hz, and the operating temperature is 90°C. The dimensions of the centre electrode and its capillary tube are identical for both separators.

The difference of the separation depending upon the diameter of the separator is shown in Figure 9. The upper pictures represent the separations by the larger separation tube, while the lower pictures show the smaller tube separation. As indicated in Figure 9, the reduced diameter of the separator can exceedingly expedite the separation speed of the emulsion by over 2 times. Therefore, the computational simulation accurately predicts the enhancement of the separation by reducing the diameter of the separator.

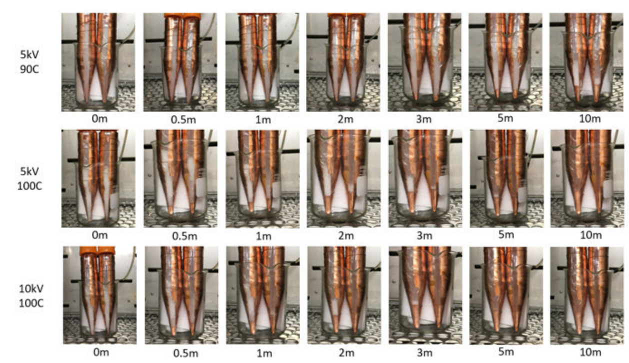

Figure 8: Comparison of water/oil separation with the effect of air-gap between the center electrode and its capillary tube: 0.475 mm (left) vs. 0.25 mm (right).

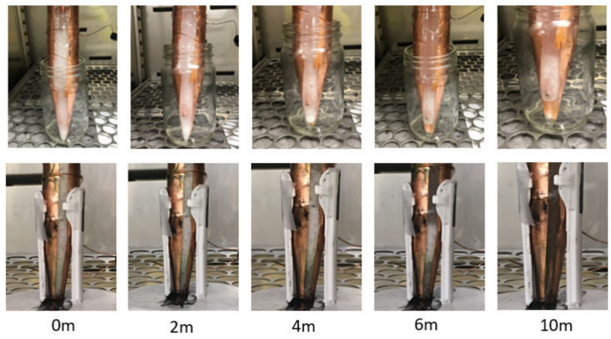

Figure 9: Comparison of water/oil separation with the effect of the tube size (inner-diameter): 30 mm (top) vs. 13 mm (bottom).

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Conclusion

In summary, the design of the water/oil separator is investigated theoretically and experimentally. The separator with cylindrical design shows a higher separation speed compared to the separator using flat-plate electrodes because of the generation of non-uniform electric fields inside. Non-uniform electric fields are generally considered more efficient than uniform electric fields because it introduces both dipole-dipole forces and DEP forces on water droplets, while only dipole-dipole forces can be created in uniform electric fields.

In addition, the effects of the thickness and length of the centre electrode, air-gap between the centre electrode and insulated capillary tube, and the diameter of the separator are investigated theoretically and experimentally. Both the simulation and experiments show that the electric field strength and gradient in emulsions would be enhanced by narrowing the air-gap, extending the centre electrode, and reducing the diameter of the separation tube, which enhance the separation speed.

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