New Methods of Application of Electrostatic Fields

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Abstract:

Desalting combines three key steps to achieve efficient salt removal. Fresh water mixing provides dilution, coalescence to promote droplet growth and phase separation to remove the contaminants. Typically, the coalescence step is accomplished by an electrostatic field to maximize the droplet growth. However, as oils become more difficult, traditional electrostatic processes fail to achieve adequate droplet coalescence for efficient desalting. Recent developments in electrostatic power supplies provide important tools for dealing with difficult crude oils. These oils include those with high conductivity, low API gravity, and high viscosity. While improvements in the hydraulic performance of an electrostatic dehydrator or desalter have successfully improved capacities, only the application of aggressive and conformable electrostatic fields has the potential to obtain the droplet growth necessary to achieve efficient dehydration at these increased oil fluxes. This paper describes the generation and application of multi-frequency electrostatic fields and the advantages realized.

Introduction:

Efficient desalting in both field and refinery applications is an essential process to reduce corrosion, control metal content and improve wastewater treatment. Electrostatic dehydrators are used almost exclusively in these desalting applications because of their high efficiency. Electrostatic desalting of crude oils is a process of three steps consisting sequentially of fresh wash water dispersion, coalescence between the connate brine and wash water and finally dehydration of the oil by phase separation. Fresh water dispersion is typically accomplished in the oil inlet piping ahead of the desalter and utilizes pipe distributors, static mixers, and mixing valves. Coalescence of the brine water and wash water is accomplished inside the desalter vessel by establishing an environment to induce collisions (coalescence) between these dispersed waters. Effective phase separation is achieved when the water droplets achieve sufficient diameter to separate rapidly. (Warren, Sams and Nakayama, 1998)

The optimum desalter environment includes an iso-kinetic oil flow to reduce short-circuiting and eliminate flow recycling and an aggressive electrostatic field capable of energizing the smallest dispersed water droplets and promoting water droplet growth. Establishing iso-kinetic flow requires reduction of the oil momentum as it exits the oil distributor orifices, redirection of the oil to achieve a uniform flow field throughout the vessel and uniform oil collection to achieve maximum utilization of the desalter volume. (Sams and Wallace, 2001) An aggressive electrostatic field consists of several key components to maximize the electrostatic forces, induce rapid droplet coalescence and enhance droplet growth to maximize phase separation. (Urdahl, Nordstad, Berry, Wayth, Williams, Bailey and Thew, 2001)

Electrostatic Fields:

Dehydrator manufacturers rely on three fundamental types of electrostatic fields to enhance coalescence of the dispersed water droplets, namely direct current (DC) fields, alternating current (AC) fields and combined AC/DC fields. DC fields are highly efficient but can promote electrolytic corrosion. Therefore, they are not used in crude oil desalting applications, but only to dehydrate refined oils having low conductivity. On the other hand, AC fields are used by all manufacturers due to their tolerance of high water cuts and non-electrolytic nature. Finally, combined AC/DC fields provide the high water tolerance of the AC field with the high efficiency of the DC field. (Burris, 1977)

AC dehydrators range from electrostatic fields utilizing one AC transformer energizing a single, horizontal electrode suspended below a grounded (earth) electrode as shown in Figure 1. A weak AC gradient is established between the energized electrode and the oil / water interface and a strong AC gradient is established between the energized and earth electrode. Wet oil entering the vessel just above the water interface is rapidly coalesced by the lower AC field and is then further coalesced and dehydrated by the upper field. Once the oil is above the earth electrode additional electrostatic coalescence is impossible since an electrostatic field can not exist above it.

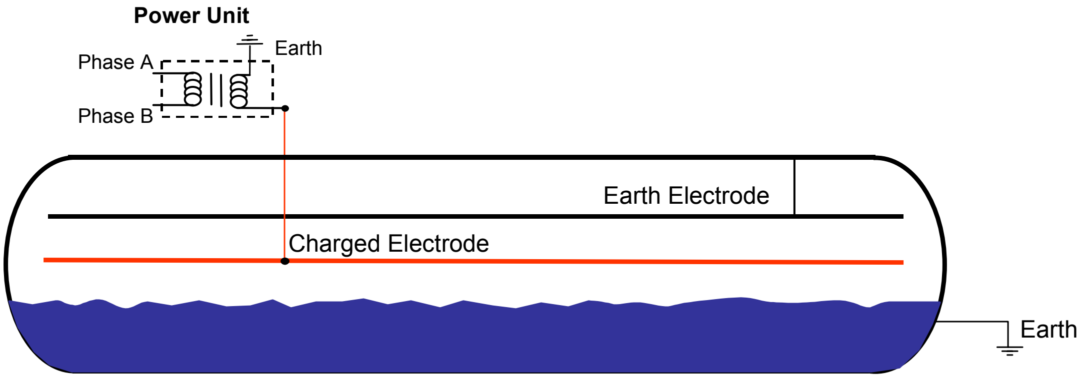

Figure 1: Conventional AC Dehydrator / Desalter

A more efficient AC desalter utilizing three AC transformers and three electrodes is shown in Figure 2. These are commonly referred to as Deep-field AC processes because they establish an AC field between the oil / water interface and the oil collector. The wet oil enters just above the interface where the low AC field promotes initial coalescence and separation. Higher AC field gradients are established between the three electrodes where additional coalescence and separation achieve the desired performance.

An aggressive electrostatic process utilizes a combination AC / DC fields. These desalters consist of an array of vertical, parallel electrodes generally positioned diametrically across the vessel just above the

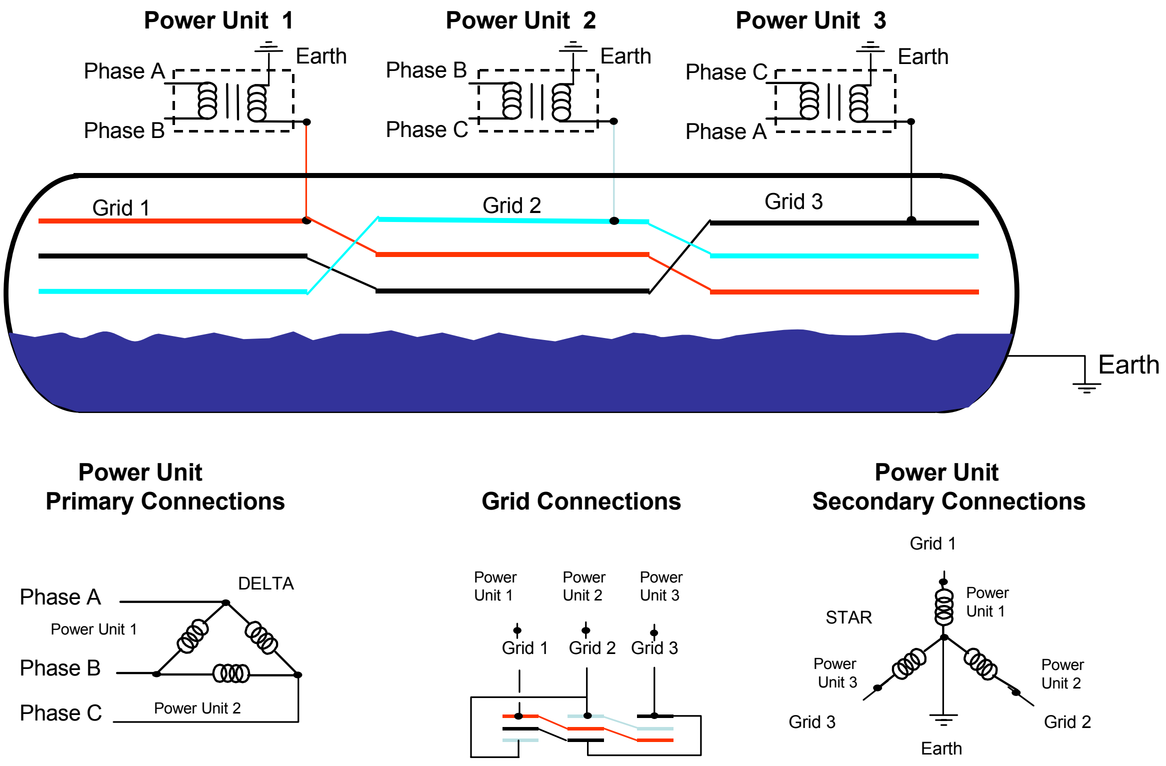

Figure 2: Deep Field AC Dehydrator / Desalter

centerline as shown in Figure 3. These desalters utilize from one to three transformers containing a pair of reversed diodes to establish a DC field between adjacent electrodes as shown in Figure 4. For a combination AC/DC desalter, an AC field is established between the bottom of the electrodes and the oil/water interface. Just like the AC desalter, this lower AC field gradient promotes initial droplet coalescence in the high water cut environment just above the interface.

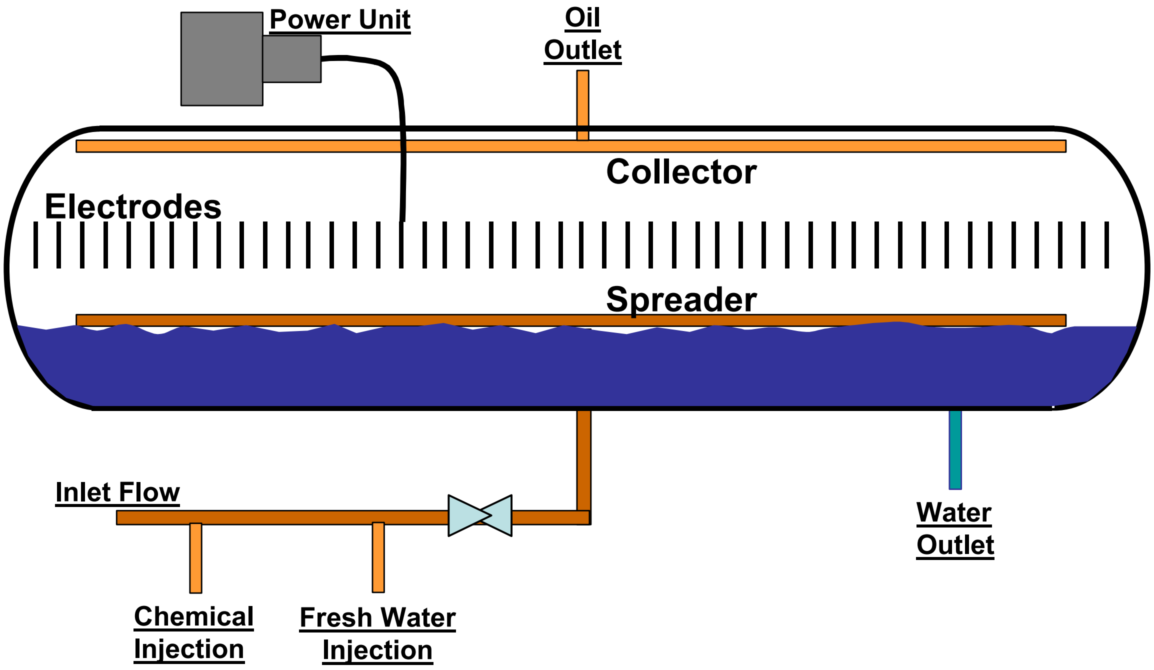

Figure 3: Combined AC/DC Desalter

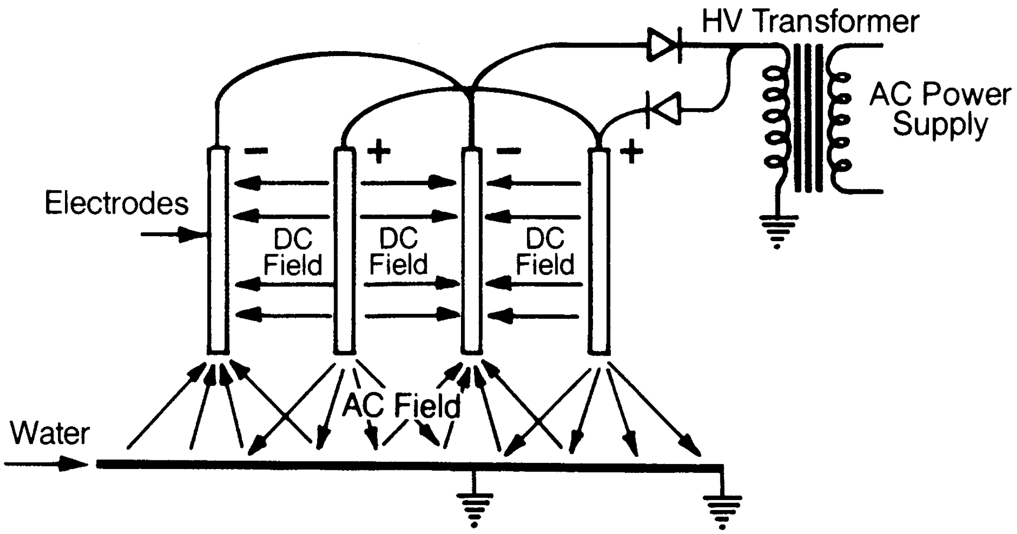

Figure 4: Combined AC/DC Wiring

Electrostatic Forces:

A water droplet suspended between a pair of electrodes is acted upon by five forces as indicated in Figure 5. (Draxler and Marrs, 1993) Two of these five forces are gravitational and hydraulic. Gravitational forces equal to the weight of the droplet act to move the water droplet toward the bottom of the vessel. Drag forces imposed by the rising oil moving pass the water droplet act to lift it toward the oil outlet. If the water droplet is larger than the Stokes' droplet diameter as calculated by the equation in Figure 6, the weight is greater than the drag and the water droplet will be separated from the oil.

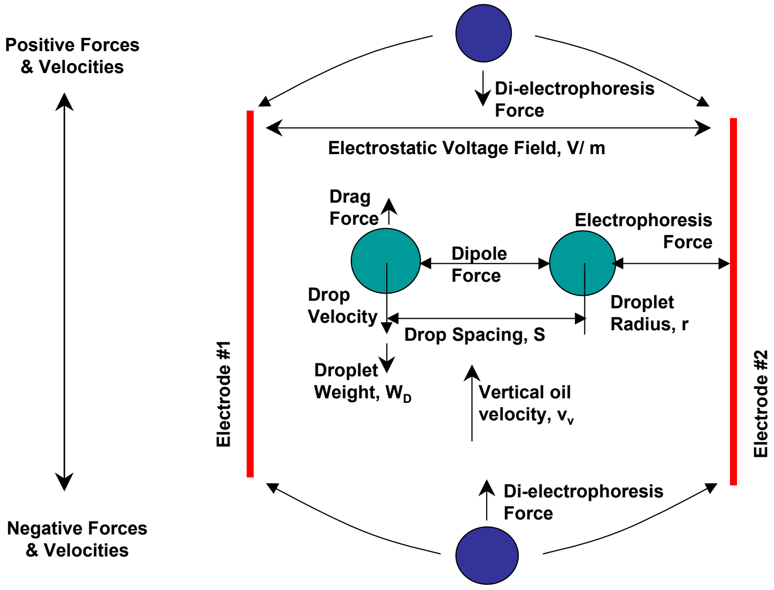

Figure 5: Coalescence Forces

To maximize the desalting process performance, the electrostatic forces must be capable of promoting droplet coalescence to diameters greater than the Stokes' diameter. The three electrostatic forces are dipolar, electrophoretic and di-electrophoretic.

$$d_{Stoke} = \left(\frac{18\, \mu_o\, v_v}{g\,(\rho_w - \rho_o)} \right)^{0.5}$$

Figure 6: Stokes' Droplet Diameter

1) Dipole forces are established by the alignment of the polar water molecules in the droplet and are proportional to the electric field gradient, the water droplet diameter and the spacing between droplets as shown in Figure 7.

$$F_d = \frac{6\, K\, E^2\, r^6}{s^4}$$

Figure 7: Dipole Force

2) Electrophoretic forces are both attractive and repulsive forces established in a uniform voltage field between charged droplets and the electrodes. They are proportional to the field strength, droplet diameter and oil conductivity as shown in Figure 8.

$$F_e = C\pi^3 \mu\, \varepsilon_c\, r^2\, E^2\, e^{(-\sigma_c t/\varepsilon_c)}$$

Figure 8: Electrophoretic Force

3) Di-electrophoretic forces are attractive forces established in a non-uniform field. These forces pull the droplet toward the highest voltage gradient and are proportional to the droplet diameter and the oil conductivity as shown in Figure 9.

$$F_{diel} = 2\pi r^3\, \varepsilon_c \left(\frac{\varepsilon_d^{*} - \varepsilon_c^{*}}{\varepsilon_d^{*} + 2\varepsilon_c^{*}} \right) \nabla E^2$$

Figure 9: Di-electrophoretic Force

These three electrostatic forces are present in all desalters but they can be manipulated to achieve enhanced coalescence and separation by altering the electrostatic voltage fields.

As Figure 7 shows the dipole force is dependent on the water droplet size and the spacing between them. Assuming the water droplets are uniformly sized and homogeneously distributed it is easy to see the spacing is inversely proportional to the dispersed water volume as shown in Figure 10. Therefore, as the dispersed water is coalesced and separated from the oil, the spacing between droplets increases and the dipole forces decline rapidly. Figure 10 also shows that when the droplet radius increases the spacing increases. Therefore, the dipole force weakens rapidly as droplets are coalesced and separated from the oil.

$$s = r\left(\frac{1.333\pi}{X}\right)^{0.333}$$

Figure 10: Uniform Droplet Spacing

As Figure 8 shows the electrophoretic force is independent of the droplet spacing, but is dependent on both the oil viscosity and conductivity. The electrophoretic force has a time constant equal to the ratio of the oil's dielectric constant and conductivity. As the equation in Figure 8 shows the electrophoretic force will decay most rapidly in highly conductive oil. Therefore, the force can only be sustained by replenishing the droplet charge frequently.

As Figure 9 shows the di-electrophoretic force is independent of the droplet spacing, but is dependent on the change in field strength which pulls the largest droplets into the highest field gradient. This force acts to accumulate water in areas of the electrostatic field where its divergence is greatest.

Dipolar and di-electrophoretic forces are predominating in these AC desalting processes. The drop to drop dipolar forces are greatest in the bottom of the desalter where the water content is highest and the droplets are closely spaced. The di-electrophoretic forces will pull droplets to the rods used to construct the electrode arrays and thereby increase the droplet population and the dipolar forces. Since the electrical polarity on the AC electrodes reverses every few milliseconds, the electrophoretic force also reverses direction and has little influence in the coalescence process.

The uniform DC field established between the electrodes relies on the electrophoretic force to push and pull droplets in a horizontal plane between electrodes. Once a water droplet approaches one energized electrode it is charged to the same polarity. Once the droplet is charged, the electrophoretic force then pushes the droplet toward the adjacent and oppositely charged electrode. (Urdahl, Williams, Bailey, and Thew, 1996) As the droplet approaches this electrode, the electrophoretic force pulls the droplet toward it until the droplet charge is reversed. Therefore, the electrophoretic forces provide a motive force to move the water droplet population in opposite directions between electrodes. The resulting collisions achieve efficient coalescence, large droplet sizes and rapid separation. These actions are shown schematically in Figure 11.

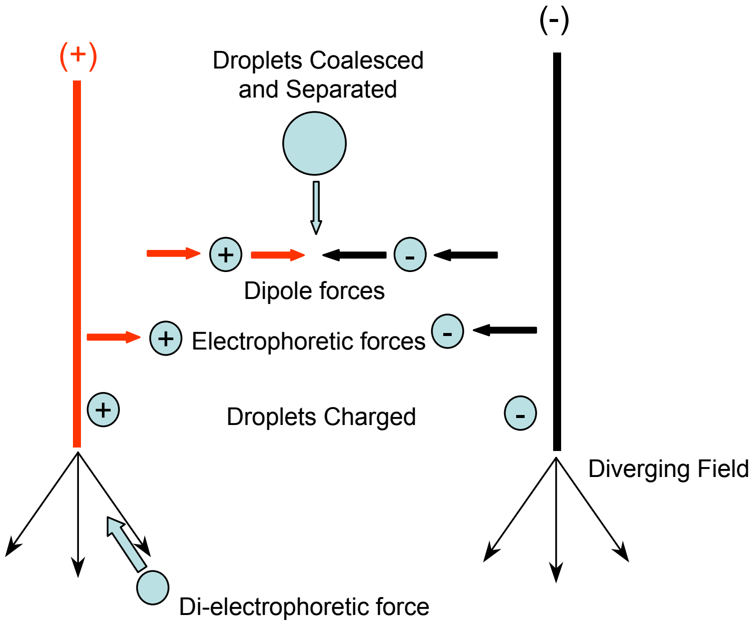

Figure 11: Combined AC/DC Droplet Forces

Oil Properties:

When determining the proper size of a desalter, the most important physical properties include the oil viscosity, oil density and water density. When these properties are used in Stokes' law along with the vertical oil velocity as shown in Figure 2, the neutrally buoyant droplet (Stokes') diameter can be calculated. All larger water droplets will have sufficient weight to overcome the viscous drag force and will settle to the interface. Smaller droplets will continue to be lifted by the flowing oil to the desalter outlet.

Certain design parameters can be adjusted to achieve the desired outlet BS&W and salt content. The oil velocity or flux is directly proportional to the desalter size and the oil flowrate. The oil viscosity is inversely proportional to the process temperature. Increasing the temperature will reduce the oil viscosity permitting smaller water droplets to settle. However, increasing the temperature will also change the density difference and affect the droplet separation rate. As Figure 12 shows the maximum density differential is around 90 to 100ºC and decreases if the process temperature is increased or decreased.

A proper balance of the oil viscosity, density difference and oil flowrate is essential to ensure proper performance of a desalter. While these design parameters are certainly the primary variables that influence the desalter behavior, two other parameters play a key role in the efficiency of the electrostatic process, namely interfacial tension and oil conductivity.

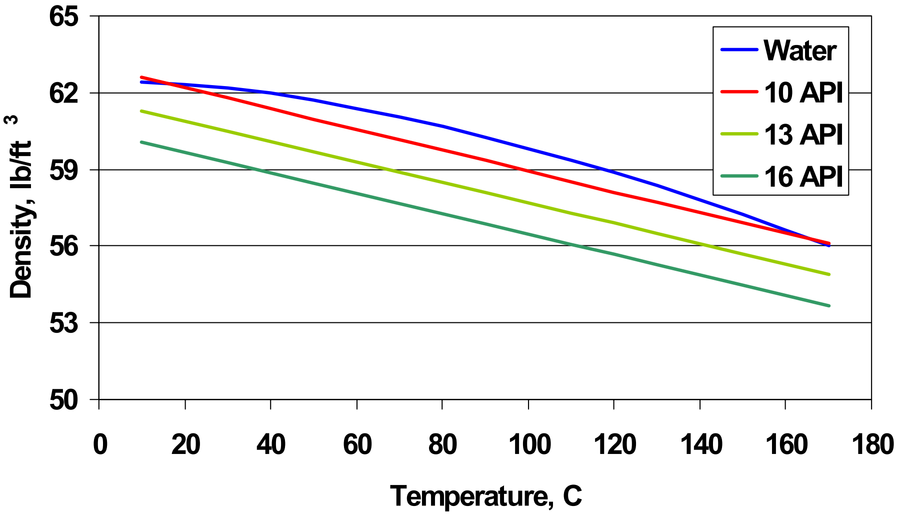

Figure 12: Oil / Water Density

Interfacial tension is usually measured in dynes/cm and ranges from 15 to 25 dynes/cm for typical oils. High interfacial tensions make it difficult for droplets to coalesce by requiring higher coalescence forces to rupture the droplet interface. Low interfacial tension makes droplet coalescence easy, but makes the coalesced droplets very unstable and easy to re-disperse. Demulsifying chemicals and electrostatic fields lower the interfacial tension to promote coalescence. (Byers and Amarnath, 1995) Excessive electrostatic droplet charge or excessive chemical treatment will reduce the interfacial tension and may promote droplet breakup and dispersion.

Oil conductivity, usually measured in nanoSiemens/meter, ranges from 40 to 80 nS/m for typical crude oils. However, for blended oils such as bitumen and SAGD (steam assisted gravity drainage) oils, conductivity of 250 nS/m has been measured. The oil conductivity is a result of excessive water in the electrode zone, polar organic and inorganic compounds and the presence of conductive solids in the oil. High oil conductivity adversely affects the electrostatic process in three ways. First, increasing oil conductivity results in an increase in resistive heating, which is not contributory to the electrostatic coalescence process. This may require the manufacturer to use a larger power unit in order to maintain the efficiency of the electrostatic process. Second, high oil conductivity will reduce the electrophoretic forces which reduces droplet mobility in the combined AC/DC electrostatic desalter. Finally, the di-electrophoretic forces also decrease to further reduce the coalescence efficiency in both the AC and combined AC/DC processes.

Understanding the roles played by oil conductivity and interfacial tension it is possible to establish an electrostatic field that aggressively promotes droplet coalescence and achieves deeper dehydration. (Eow and Ghadiri, 2003)

Electrostatic Voltages:

The combined AC/DC field utilizes these electrostatic forces in such a fashion that manipulation of the electrostatic voltage can benefit from the oil conductivity and interfacial tension. For clarity, the remainder of the paper will consider the combined AC/DC electrostatic field only.

In nearly all desalter applications a single voltage level is applied to the electrodes to achieve a beneficial level of dehydration and desalting. However, as the force equations show the smaller droplets require higher voltages to develop sufficient force to overcome the interfacial tension and promote coalescence. However, if the voltage is too high, the electrostatic forces may exceed the interfacial forces resulting in droplet breakup and dispersion.

Two voltages define the limits of an efficient dehydration process. The first voltage can be thought of as a 'threshold' voltage. Figure 13 shows the results of a lab experiment conducted with a combined AC/DC field. This experiment was used to determine the threshold voltage for a 20ºAPI oil containing 10% water flowing through a pilot treater. The applied voltage was increased slowly starting at a low voltage and while measuring the secondary current. At 12.5 the secondary current increased sharply suggesting the dispersed water was being electrically charged. Once the water was energized the current began to decrease rapidly indicating the water was coalescing. A second experiment was conducted with 'dry' oil. As Figure 13 shows the secondary current failed to spike but continued to increase linearly with the voltage. The placement and slope of the 'dry' oil line is consistent with the oil conductivity.

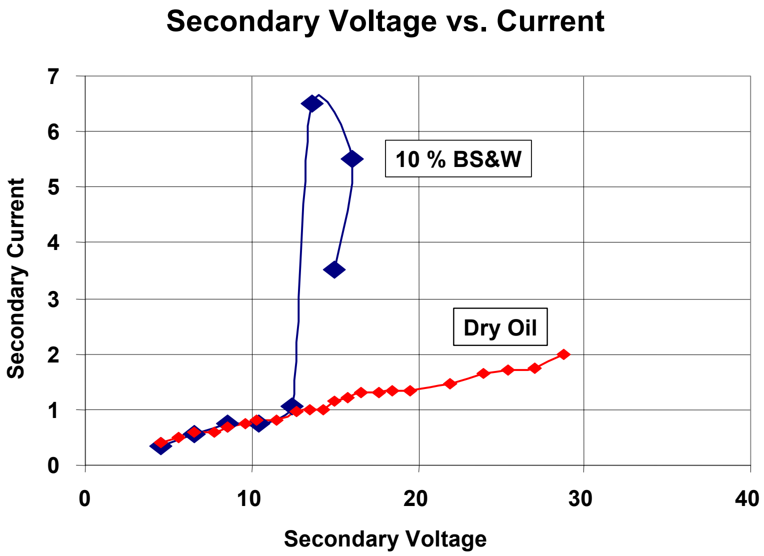

Figure 13: Threshold Voltage

As the experiment clearly indicates operating below the threshold voltage fails to provide sufficient electrostatic energy to initiate coalescence. There is a process benefit in operating at a voltage level near the threshold voltage because it maximizes the droplet diameters. However, it can be shown that operating at such a low voltage fails to reach the smallest water droplets necessary to achieve the effluent water and salt specifications.

For perfect dehydration, all of the entrained water would be coalesced to a droplet diameter larger than the Stokes' diameter so they will separate from the rising oil. Coalescing the smallest water droplets requires an increased voltage capable of developing significant electrostatic forces. However, increasing the voltage also increases the electrostatic forces on the larger droplets which may cause them to fracture. Therefore, the applied voltage should not be increased above a level than would fracture water droplets of the Stokes' diameter. This voltage level can be considered the 'critical' process voltage. Sustained operation above this 'critical' voltage results in a reduction in the water droplet diameter and a significant decline in dehydration performance.

Electrostatic Frequency:

Just as there are two voltage limits that define the boundaries for efficient dehydration there are also two frequencies. These two frequencies are dependent on the rate of droplet charge and discharge and the fundamental oscillation frequency of a water droplet of Stokes' diameter.

As Figure 14 shows, when using 50 or 60 Hz power, the rate of voltage decay on the electrodes increases as the oil conductivity increases which permits the charge on the water droplets to decrease. Furthermore, as the oil conductivity increases the electrode voltage is below the threshold level for a significant part of the voltage cycle. Therefore, to sustain the droplet charge and maintain the electrostatic forces for coalescence, the frequency of the applied voltage must be increased. For oil with

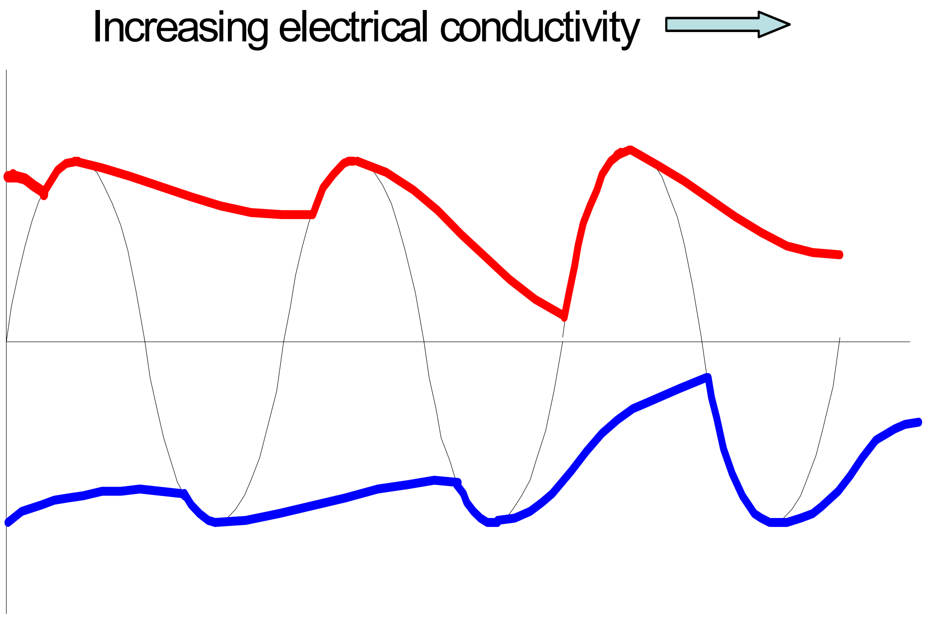

Figure 14: Applied Voltage vs. Oil Conductivity

a conductivity of 100 nS/m, the frequency must be near 1600 Hz. Operating above this ‘base’ frequency ensures the highest level of electrostatic forces.

The fundamental oscillation frequency of a water droplet can be determined using a simple mass-spring analogy. (Ivanitskii, 1998) For a Stokes’ droplet diameter of 750 microns with an interfacial tension of 15 dynes/cm the fundamental frequency is 20 Hz. Therefore, when operating with a 60 Hz power unit, the Stokes’ droplet is oscillating at its third harmonic. The increased droplet oscillation amplitude may result in droplet shatter due to increased electrostatic forces. However, by operating at a ‘modulation’ frequency below 20 Hz the destruction due to harmonic droplet oscillation can be avoided and maximum droplet growth can be promoted. (Bailes, Freestone and Sams, 1997)

Modulated Electrostatic Results:

Combining the ‘base’ and ‘modulation’ frequencies with the ‘threshold’ and ‘critical’ voltages it is possible to construct an electrostatic field that can derive a significant dehydration benefit from the oil conductivity and interfacial tension.

The dehydration benefits of these electrostatic fields have been confirmed in numerous laboratory tests conducted over the past 4 years. The results from one test are presented here showing the efficiency improvements that can be achieved by this enhanced dehydration method.

Since field data was available to confirm then lab results, Venezuelan oil was used for these comparison tests. The physical properties were determined to be:

- Oil Density @ 60ºF = 0.9370 g/cc
- API Gravity = 25.1ºAPI
- Viscosity @ 35ºC = 37.31 cp
- Viscosity @ 50ºC = 20.15 cp
- Interfacial Tension @ 85ºF = 22.5 dyne/cm
- Conductivity @ 77ºF = 42 nS/m

Lab tests were conducted in a pilot dehydrator consisting of a vertical 5 inch ID x 8 foot high column. The oil and water was premixed in a 70 gallon charge tank and held at 90ºF and 5 psig pressure for the duration of the testing. The oil / water mixture was initially recycled for 45 minutes across a 50 psi pressure drop to create a tight emulsion. The oil had been previously treated with a demulsifier chemical so no additional chemical was added. To avoid additional shear, the mixture was pumped with a progressive cavity pump to a pressure of 40 psig. A shell and tube heat exchanger increased the mixture temperature to 140ºF prior to entering the dehydration vessel. The vertical column has the same geometry as an 8 foot diameter dehydrator vessel and achieves results that are consistent with field results. The electrostatic configuration uses a combined AC/DC field with a single pair of oppositely charged electrodes.

For comparison, a series of tests were conducted at several oil rates and a constant temperature of 140ºF using both combined AC/DC and modulated, high frequency power supplies. The AC/DC power supply was operated at a steady voltage of 23 kV (rms). The voltage limits and frequencies for a modulated, high frequency electrostatic power supply were optimized for these tests.

The commercial AC/DC vessels operated at 90 bopd/ sq.ft. and averaged 0.38% BS&W over a 6 week test period. The effluent BS&W results from the lab tests are shown in Table 1 below.

Table 1: Outlet BS&W Comparison

Oil Flowrate, Bopd/Sq. Ft.	Combined AC/DC	Modulated, High Frequency
90	0.4 %	- - -
135	0.4 %	0.1%
180	0.5 %	0.2 %
250	0.6 %	0.4 %
300	- - -	0.5 %

As these results clearly show the modulated, high frequency power supply consistently achieved improved dehydration results and was capable of achieving the same performance as the commercial units at nearly twice the oil flow rate. Even more dramatic results would have been achieved if the parameters of the modulated, high frequency power unit were optimized for the increased flows.

Figures 15 and 16 show the benefits of shifting the base and modulation frequencies on 30ºAPI oil tested at 125ºF. As the base frequency increases the electrostatic forces also increase and the dehydration performance improves significantly. However, high base frequencies can develop an excessive charge

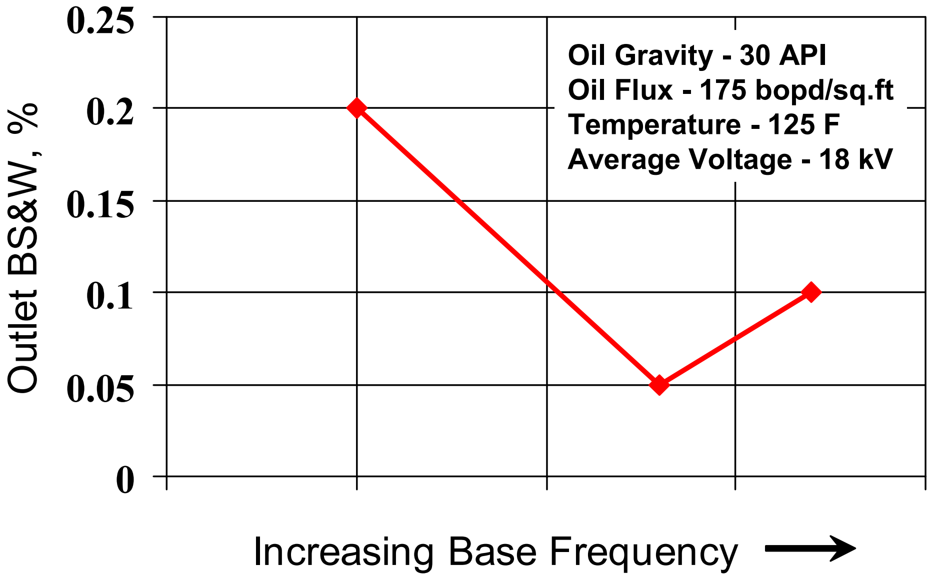

Figure 15: Base Frequency Performance

on the droplets which decreases the interfacial tension resulting in a loss of performance as shown for this oil.

Figure 16 shows the benefits obtained by varying the modulation frequency. Slow droplet oscillation stretches the droplet surface destabilizing the film to promote coalescence. It also sweeps the voltage to the maximum voltage level to energize the smallest water droplets and promote their coalescence. It then slowly sweeps to the minimum voltage level where the droplet size is maximized.

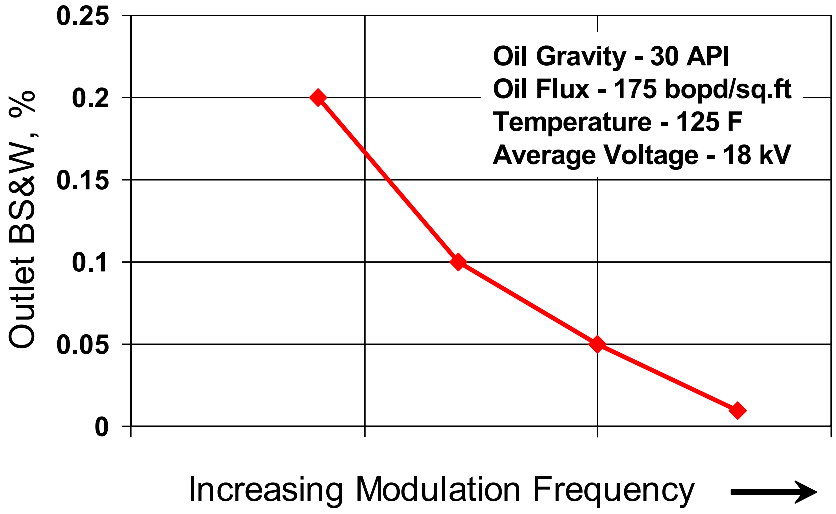

Figure 16: Modulation Frequency Performance

Dehydration tests conducted on a SAGD oil further demonstrated the benefit of the modulated, high frequency power unit. All three power unit configurations were used on a pilot dehydration designed to dehydrate a 6.5ºAPI oil at a temperature of 430ºF. The 'dry' oil conductivity was determined to be around 400 nS/m at the process temperature. An AC power unit failed to develop sufficient voltage to initiate and sustain dehydration. A combined AC/DC power unit permitted the applied voltage to be increased but also failed to promote coalescence. Only the modulated, high frequency power unit was able to achieve and maintain sufficient voltage for dehydration.

Conclusions:

As more difficult oils are produced and used by refiners to increase production and maximize profits, the electrostatic desalter must be capable of handling these highly conductive oils and maintain the desalter specifications. Understanding the role of oil conductivity and interfacial tension in the development of electrostatic forces makes it possible to design a customizable electrostatic field to handle these oils.

The technology is available to produce an electrostatic power unit capable of operating at a 'base' frequency and cycling at the 'modulation' frequency between the 'threshold' and 'critical' voltages. Experimental results have clearly demonstrated the process benefits that can be achieved by this technology. Field trials are currently underway to demonstrate the benefits on a commercial installation for a field dehydrator. (Sams and Wallace, 2003)

Nomenclature:

C = constant
X = BS&W, Inlet or Outlet
V_v = Vertical Oil Velocity
ρ_c = Continuous phase density
ρ_d = Dispersed phase density
w_d = Weight dispersed droplet
μ_c = Continuous phase viscosity
μ_d = Dispersed phase viscosity
σ_c = Continuous phase conductivity
σ_d = Dispersed phase conductivity
ω = frequency
ε_c = Continuous phase permittivity
ε_d = Dispersed phase permittivity
ε_c^* = Complex Continuous phase permittivity
$= \varepsilon_c - j\,\sigma_c / \omega$
ε_d^* = Complex Dispersed phase permittivity
$= \varepsilon_d - j\,\sigma_d / \omega$
F_d = Dipole Force
F_e = Electrophoretic Force
F_{diel} = Di-Electrophoretic Force
∇E = Voltage field gradient
E = Voltage
r = droplet radius
γ = Interfacial tension
d_{Stoke} = Stokes' droplet diameter

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