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Advanced Electrostatic Technologies for Dehydration of Heavy Oils

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Abstract

Effective oil/water separation continues to be a major challenge in heavy oil (HO) production operations and often involves high capital costs (large, heated vessels) and high operation costs (heat, fouling, upsets, chemicals). Application of new electrostatic dehydration technologies has the potential to have a major impact in reducing these costs. A systematic evaluation of four electrostatic dehydration technologies was performed using lab, bench scale, and pilot scale (40 gallons) testing. Four heavy oils ranging from 8 to 21 API were used. Performance criteria measured were effective emulsion separation rate (vessel throughput), separated oil and brine quality, water droplet size distribution for inlet and outlet emulsions, and comparison with field data (as available) for older electrostatic technologies. Traditional bottle tests were performed for reference. A 2 to 4 fold increase in emulsion treating rate was observed for some of the heavy oils using the newer electrostatic technologies relative to the traditional Alternating Current (AC) method with the same output quality of crude and brine. Relative cost data per barrel of emulsion processed were developed from system cost estimates and throughput data developed in the pilot tests. Treatment with acid to bring the separated brine into a 6 to 6.5 pH range had a very beneficial effect on the oil/water separation for some of the heavy oils with high TAN.

Introduction

Effective water removal from heavy oils (HO) often involves high capital costs (large, heated vessels) and high operation costs (heat, fouling, upsets, chemicals) that impacts both upstream and downstream (desalting) operations. New electrostatic dehydrator technologies offer the potential to have a major impact in reducing these costs[1, 2]. An evaluation of some of these new technologies using four different heavy oils was performed to compare the relative performance and costs of four electrostatic dehydrator technologies in dehydration of these four heavy oils.

Why is water separation (dehydration) an increased challenge for Heavy Oils? The two major reasons for the more challenging dehydration of HO are their **high viscosity** and the **small density difference between the HO and the brine**. The high viscosity slows the mechanical separation process and also slows the transport of emulsion breaker chemical to the water droplet interfaces. The small density difference also slows the mechanical (gravity) separation process. Although not unique to HO, heavy oils also commonly contain surface-active molecules (such as asphaltenes, naphthenic acids and fatty acids) and particles (such as silica, clay, iron oxide, iron sulfide) that aid in the formation of very stable emulsions. The viscosity and density issues are well illustrated by Stokes' Law which gives the rate of fall for a small sphere in a viscous fluid which is:

$$\text{Falling Velocity of Water Droplet} = \frac{\text{gravity constant}*(\rho_{wd}-\rho_{oil})*D^2_{wd}}{18*\text{viscosity of dehydrated oil phase}}$$

where D_{wd} = diameter of water droplet
ρ_{wd} = density of water droplet
ρ_{oil} = density of oil phase

Thus the time required for effective dehydration is reduced by lower viscosity, increased density difference, and larger droplet size. Special issues in heavy oil dehydration have been discussed previously.[3] Common methods used to aid oil/water separation are:

- Use a long residence time for separation by using a large separator vessel.
- Heat the emulsion to reduce viscosity and increase density difference between crude and water at temperatures less than ~100°C as illustrated in Figures 1a and 1b. It may sometimes cause loss of lighter components.
- Add chemicals that enhance coalescence of emulsified water droplets.
- Add a hydrocarbon diluent to reduce viscosity and increase density difference.
- Subject emulsion to electrostatic field to enhance and accelerate coalescence of emulsified water droplets.

Figure 1a.

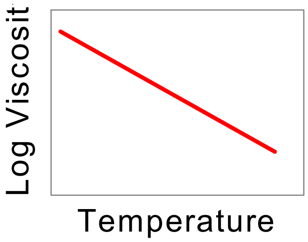
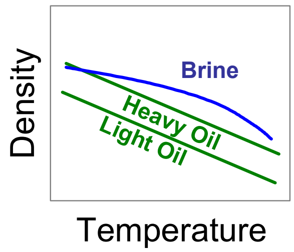


Figure 1b.



For very heavy crude oils a combination of all of the above methods may be needed to achieve effective oil/water separation. Of course heat, diluent, large vessels, emulsion treating chemicals, and electrostatic systems all increase costs. A universal goal is to select the optimum combination of methods that will minimize the costs, meet crude sales specifications, produce oil-free water, and maximize the crude value.

Advances in oil/water separation have been reported in recent years for the use of new electrostatic technologies[1]. A study was performed to systematically evaluate four electrostatic dehydration (ED) technologies using lab, bench scale, and pilot scale (40 gallons) testing. The lab studies were performed at ConocoPhillips' Bartlesville Facility and the bench and pilot scale tests at NATCO's Tulsa Facility. A brief description and history of the ED technologies evaluated are presented in the section below. Note that some of the newer ED technologies are patented and are not yet in commercial service. Four heavy oils ranging from 8 to 21 API were used in the tests and some of the oil and brine characteristics are presented in Table 1. Based on the test results, relative costs and performance data were also developed.

Table 1. Characteristics of Crudes and Brines.

	Heavy Crude			
Property	Crude A	Crude B	Crude C	Crude D
API (Neat)	21	20	8	8-10
API (Test Blend)	21	20	17	16.4
Diluent Addition	None	None	~ 35 v%	~50 v%
TAN	4	0.7	2	1
Blend Conductivity	78,000 pS/m @ 80°C	63,000 pS/m @ 80°C	112,000 pS/m @ 135°C	146,000 pS/m @ 135°C
Brine Conductivity	19.2 mS/m @ 23°C	17.6 mS/m @ 23°C	6 mS/m @ 23°C	7.6 mS/m @ 23°C

Description of Electrostatic Technologies Evaluated

Alternating (AC). Alternating Current (AC) is 60-70 year old standard ED technology and is by far the most widely used. The AC ED process applies an alternating electric field at 50 to 60 Hz to the emulsion which causes the water droplets to deform and accelerates their coalescence. See Figure 2.

High Voltage DC Field with AC (HVDC/AC). HVDC/AC ED has been widely used for 30+ years with improved results over AC. HVDC/AC with composite electrodes is about 15 years old. The HVDC/AC ED uses a different electrode configuration and transformer system than the AC systems as illustrated in Figure 3.

Figure 2.

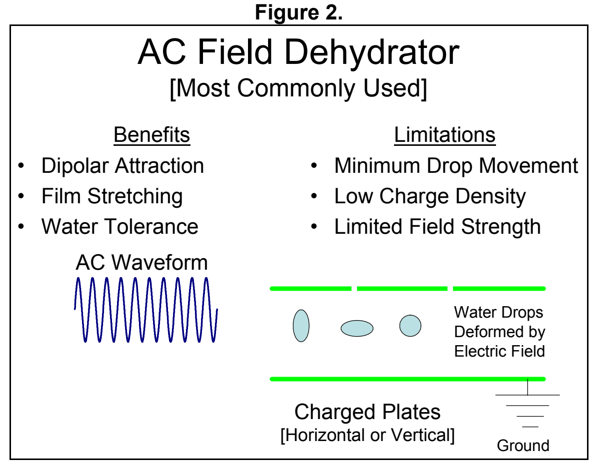
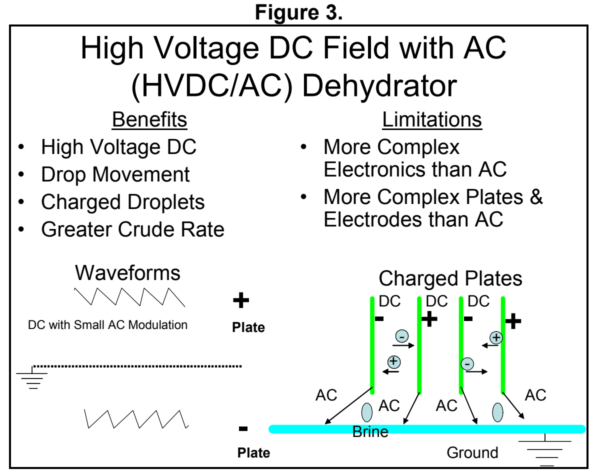


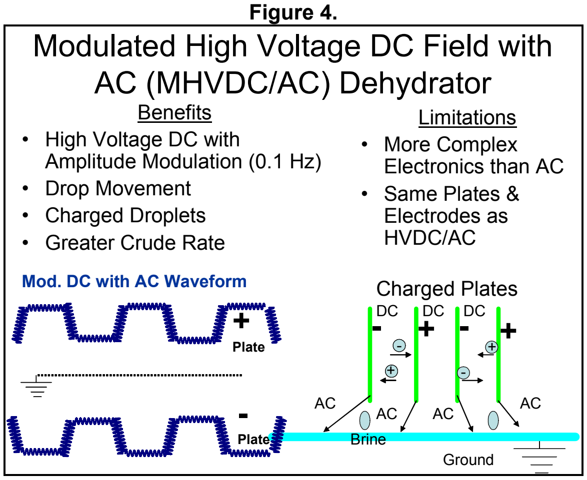
Figure 3.



HVDC/AC ED subjects the emulsion to both a high voltage direct current (DC) field and an alternating field (50 to 60 Hz). In the DC field the water droplets acquire a charge and are accelerated to the DC electrode of opposite polarity. Upon approaching the opposite polarity electrode, the droplet acquires the charge of that polarity and is then accelerated to the opposite electrode. As the droplets move in the DC field, deform due to the AC field, and collide, they become larger and eventually fall out of the DC field and enter the separated brine phase.

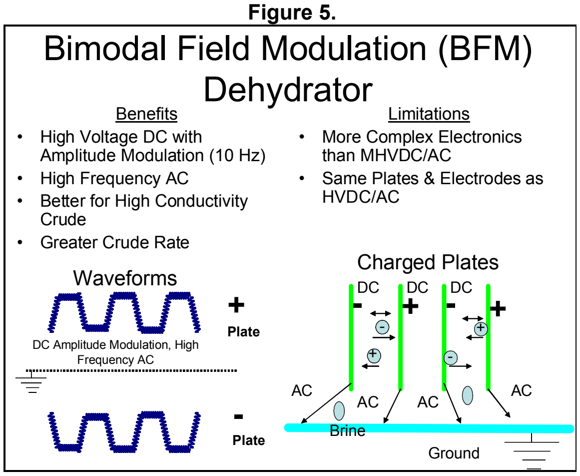
Modulated High Voltage DC Field with AC (MHVDC/AC). Modulated HVDC/AC (MHVDC/AC) is a new ED technology and has achieved improved separation performance over the HVDC/AC technology[1]. It is not yet widely used in field applications. Modulated HVDC/AC uses the same electrode configuration as the HVDC/AC ED technology. The modulated HVDC/AC is different from the HVDC/AC technology in that it modulates the amplitude (~50%) of the DC field at a frequency on the order of 0.1 Hz. This additional modulation supposedly aids drop coalescence. The electronics are similar to the HVDC/AC system, but uses an additional unit that induces the amplitude modulation. See Figure 4.

Figure 4.



Bimodal Field Modulation (BFM). Bimodal field modulation (BFM) is a new ED technology that looks very attractive in trials and is not yet widely used in field applications. BFM uses the same electrode configuration as the HVDC/AC ED technology. The BFM ED technology also modulates the amplitude of the DC field but at much higher frequency (~10 Hz) than used by the modulated HVDC/AC technology. The BFM technology also increases the base AC frequency to 800 to 1600 Hz. This high frequency decreases the charge bleed off for high conductivity crudes. This enables handling of high conductivity crudes and higher throughput. The electronics are more complex than the MHVDC/AC system. See Figure 5.

Figure 5.



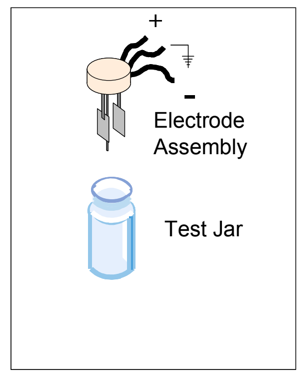
A secondary issue in these ED technologies is the type of electrodes (or grids) used. The traditional AC system uses carbon steel electrodes and the advanced systems can use either carbon steel or composite electrodes. Although it is not a part of this test program ~50% improvement in performance has been reported for the composite electrodes[1]. The carbon steel electrode will have an equal charge over its whole surface that creates very large electric field gradients at the edges. These large field gradients at the edge are prone to break up droplets and to arc when the water cut is high. Composite electrodes have a peak charge at the center of the electrode and lower charge at the edges due to their high electrical resistance. Thus they are less prone to arc and break up droplets. Also composite electrodes will be charged only on one side which permits better electrostatic field control.

Test Program

The laboratory characterizations tests included bottle tests, crude characterization (API, viscosity versus temperature, interfacial tension, conductivity) and testing for water droplet size for inlet and outlet emulsions used for the pilot scale tests. A goal of the viscosity testing was to identify what temperature was needed to reduce the emulsion viscosity to 10 cP. Experience was that a viscosity of 10 cP or lower was needed to achieve good separation.

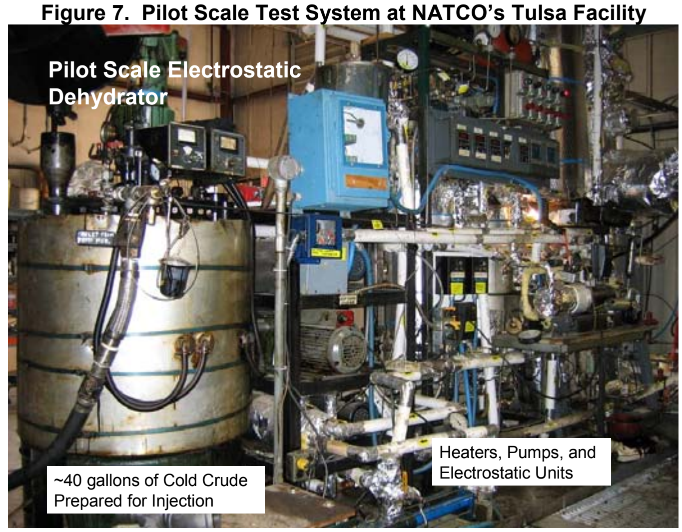
The bench scale screening tests identified electrostatic voltage and frequency requirements and screened chemicals. Some components of the electrostatic susceptibility tester are shown in Figure 6.

Figure 6.



The pilot scale (40 gal) tests simulated the various ED technologies at field type conditions. The pilot test system (Figure 7) has been described previously[1] and included a charge tank with mixing pump, a heat exchanger, a pressure regulator tank, an AC dehydrator with steel electrodes and a second dehydrator with composite electrodes configured for the other three ED technologies. To simulate field operation, the pilot scale system introduces the treated emulsion into the separator at a constant rate and produces dehydrated crude and brine. Samples of dehydrated crude and brine are collected for further analysis. Measurement of the water droplet size for inlet and outlet emulsions was performed.

Figure 7. Pilot Scale Test System at NATCO's Tulsa Facility



Separation performance criteria measured were emulsion separation rate (vessel throughput), separated oil and brine quality, and comparison with field data (when available). These data were used to compare the relative throughput for a given separator vessel using the four ED technologies and the capital costs per barrel of crude dehydration capacity. Note that for all of the ED test results reported for each crude, the same chemical treatment was used. There was no attempt to optimize chemical doseage. Also the only results that are reported achieved "successful" separation as defined by BS&W less than 0.6% in the separated crude and clear separated brine.

Test Results Showed a Significant Increase in Throughput for the Advanced ED Technologies

The test results for the tested crudes are reported below. The results are presented as the barrels of oil per day throughput per square foot of electrode (grid) cross-section that is achieved with a dehydrated oil quality of a given percent BS&W. When higher throughputs are used the oil quality is reduced (BS&W increases). For a given separator vessel, the grid cross-section can be determined and these data used to estimate the overall vessel performance. In all of these tests, emulsion breaking chemicals were used at about a 50% excess rate to compensate for the aged crude. Again the purpose of the tests was to determine the relative performance of the different ED technologies. In actual field applications tuning of the voltage levels and modulation frequencies will be required to optimize performance.

Crude A (API 21). Figure 8 presents Crude A separation performance data for the field AC unit and the pilot tests with an inlet of 10% emulsified brine. The pilot scale performance observed for Crude A was about 30% better than predicted by the ED model as shown by the solid lines. In the bottle tests and the pilot scale tests, it was found that in addition to the emulsion breaker treatment, acid addition to bring the separated brine into a 6 to 6.5 pH range had a very beneficial effect on the oil/water separation. The acid treatment is used in the field and helps to keep the naphthenic acids in the oil phase. The key result is that in the pilot tests the advanced ED technology provided a significant (2 fold for BFM) increase in emulsion treatment throughput for the Crude A emulsion relative to the AC system. An AC system is effectively used for handling field production and its performance is presented in Figure 8. In the bottle tests good separation occurred in 15 minutes with the use of demulsifier chemical and acid treatment.

Crude B (API 20). The Crude B emulsion used for testing was an as-was-produced emulsion with a 38% water cut. Note that no separation occurred in the shipping containers over several months. In Figure 9, the solid lines are the pilot scale performance predicted by the ED model for the Crude B oil normalized to the measured data. A solid line representing an estimate of the performance of a mechanical treater (no electrostatics) was also added based on experience with heavy oils. This datum will be used in the cost analysis. {Note that ED performance can vary widely for oils that may seem similar in most properties and the relative performance of the mechanical only system may be much better for lighter oils.} Corrosion inhibitor was added to better simulate the field conditions when this treatment will be used. Treatment with acetic acid was also used for the Crude B emulsion, but it was not as critical as for the Crude A emulsion treatment. The circles on the 0.5% BS&W line are used to identify what throughput may be expected (with some judgment) to achieve a dehydrated crude quality of 0.5% BS&W. These values will be used later to compare costs of the different ED technologies.

The key result is that the advanced ED technologies provided a significant (almost 4 fold for BFM) increase in emulsion treatment throughput for the Crude B emulsion relative to an AC system. There was no field data available for Crude B alone. The bottle test results achieved good separation in 20 minutes with demulsifier treatment.

Figure 8.

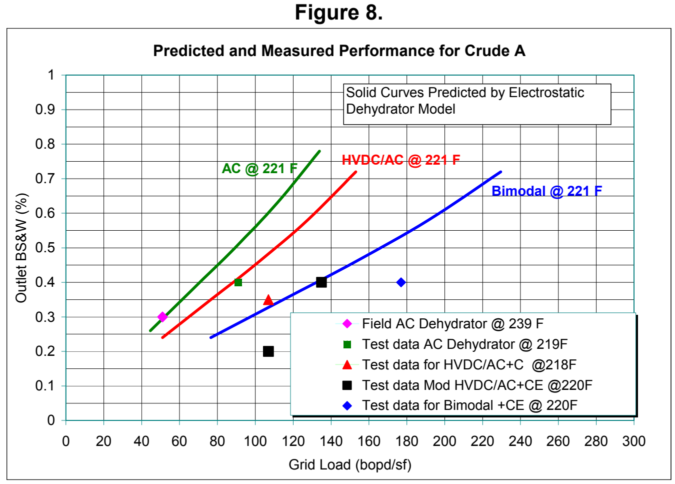
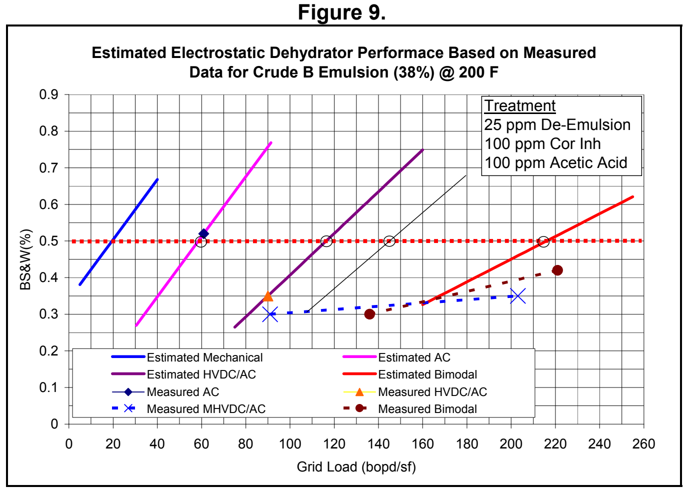


Figure 9.



For each pilot scale test with Crudes A and B, we measured the water droplet size distribution in the emulsion being treated and in the dehydrated crude using a Malvern Particle Size Analyzer. Water droplet size distribution correlates well with emulsion stability[4]. Smaller droplets are generally more difficult to separate and distributions skewed to smaller droplet sizes indicate more stable emulsions. Figure 10 presents an example of the results for the Crude B tests. Figure 10 presents the percent efficiency of water removal from the inlet emulsion for each water droplet size for several ED technologies and throughput rates. Note that the efficiencies for all tests were better than 99% for droplets larger than 10 microns and greater than 98% for droplet sizes 1 to 10 microns. Lower efficiency was achieved for droplets in the 0.1 to 1 micron size but the lower values were for high throughput rates. These results indicate very desirable performance that is difficult to achieve with other separation methods.

The data presented in Figure 10 were further analyzed to illustrate trends in separation efficiency due to throughput rate and ED technology. Figure 11 presents the average separation efficiency for three ranges of water droplet sizes as a function of throughput rate and ED technology. Note that good separation efficiency is achieved for water droplets larger than 1 micron even at the high throughput rates. The broken line was added to illustrate the separation efficiency for the 0.1 to 1 micron droplet sizes. At low to moderate throughput rates the separation efficiency improves for these small droplets as more advanced ED technologies are employed. As the throughput rates are increased, a significant decline in separation efficiency occurs for the 0.1 to 1 micron droplet sizes. It is speculated that the AC ED will have a more rapid decline in efficiency. These droplet size results are consistent with other studies.[4]

Crude C (API 8). Effective oil/water separation for Crude C is achieved with a mechanical separator in field operations using very long resident times and large volume separators. Good oil water separation was not achieved for Crude C in lab bottle tests with blends of ~20% diluent. The as-received crude blend emulsion had been in storage for several weeks prior to testing. Good separation (lab and bench scale) was achieved for the ~35% diluent blend (with ~4% brine) using a non-conventional emulsion breaker and this chemical was used for the pilot scale testing. The results of the pilot scale tests for Crude C are presented in Figure 12. The dashed lines in Figure 12 illustrate the extrapolation of the data to the throughput rate that is anticipated to produce a 0.5% BS&W dehydrated crude.

Several results in the Crude C pilot tests were not expected. First, the throughput rates that achieved low BS&W were higher than anticipated for this class of heavy crude blend. Second, the MHVDC/AC technology did not perform well relative to the other ED technologies. In later review it was determined that the modulation waveforms used for the Crude C pilot tests were not good choices for that class of crude. Thus the MHVDC/AC method was less effective. With more time to determine the optimum modulation waveforms, it should be possible to improve the performance of the MHVDC/AC ED technology for Crude C.

Figure 10.

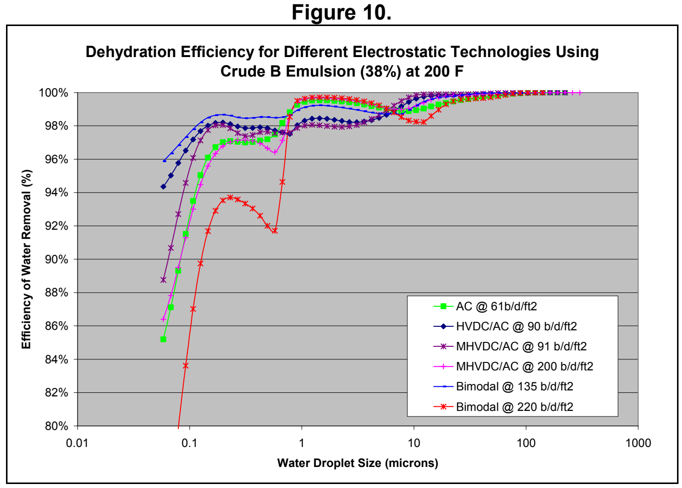


Figure 11.

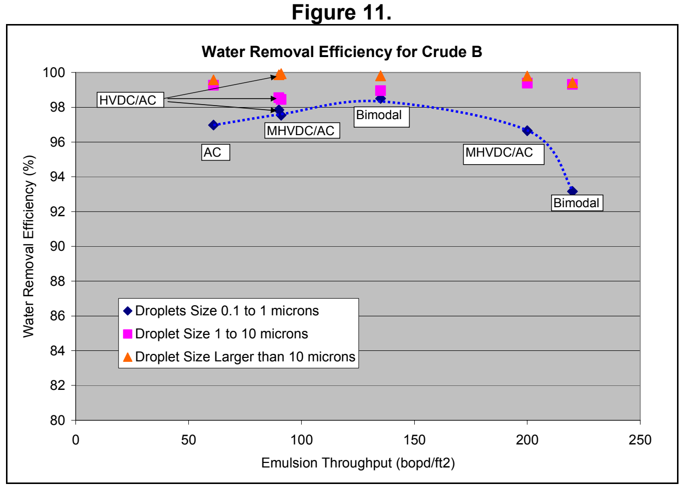
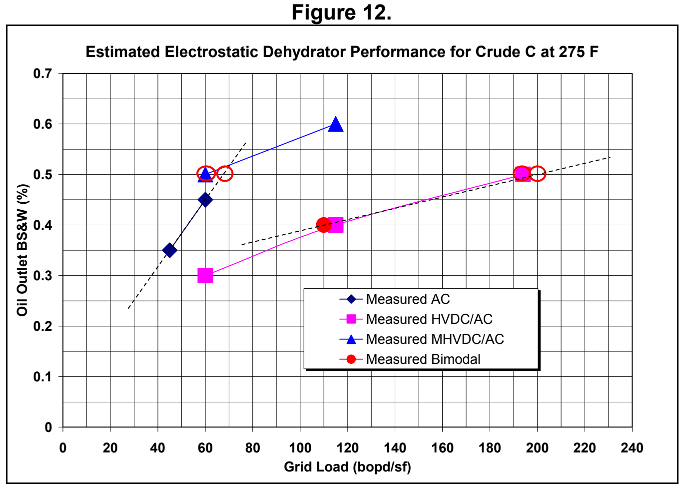


Figure 12.



Crude D (API 8-10). In field operations, Crude D production has had low brine content. A field AC unit was not effective in removing water when levels were less than 1.5% BS&W. In our bottle tests we generated emulsions with 30% brine content and only about 80% of this brine was separated after 60 minutes with demulsifier treatment. Emulsions with 5.5% brine content were developed for the bench and pilot scale tests. The pilot scale results for Crude D are presented in Figure 13 and extrapolations to 0.5% BS&W are included.

Relative Cost of the Electrostatic Technologies

A major goal of this study was to develop data to enable comparison of the water separation costs achieved for the different ED technologies. The pilot scale test data developed throughput rates for the ED technologies. In consultation with the manufacturer, anticipated cost data for mechanical and ED technologies were developed for a 14' x 80' horizontal separator vessel rated for 200 psig service. Since these data change with time and location, they are presented in Figure 14 as cost relative to the cost of an AC ED system with uncertainity error bars. As expected and shown by the $ symbols, the costs of the dehydration systems increase as the electrodes and electronics for the more advanced ED technologies are included. The other curves show the relative performance of the ED technologies with reference to the AC ED technology for emulsion throughput that achieves a 0.5% BS&W. Note that the relative change in throughput increases significantly faster than the cost for the more advanced ED technologies. Also note that the relative throughput performance of Crudes A and D are similar. The throughput data for the mechanical systems were not measured and are presented only for general reference. Some were estimated and some are based on field system design with different chemical treatments.

Figure 15 presents the estimated capital costs per barrel of oil per day for dehydration of the Crude A –D emulsions. These costs were developed by dividing the capital costs of the ED system by the throughput estimated from the pilot tests and the effective cross-section of the 14' x 80' treating vessel.

For the purpose of this study only capital costs were considered. The same heating and chemical usage was assumed. In practice dehydration optimization would also include heat requirements, chemical usage, separated water quality, and crude value.[2]

Figure 13.

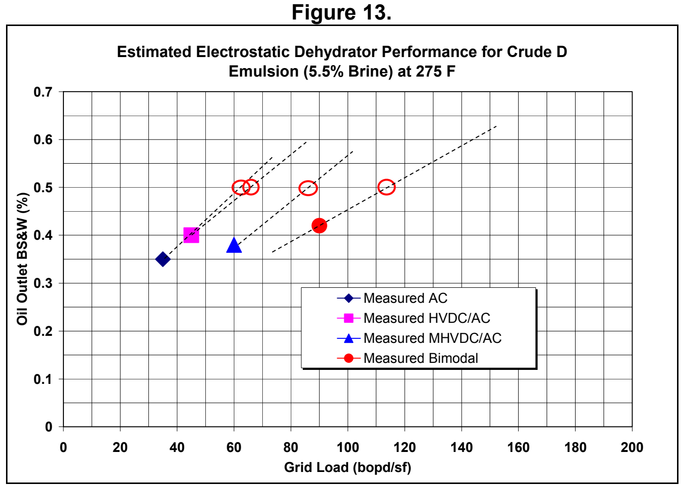


Figure 14.

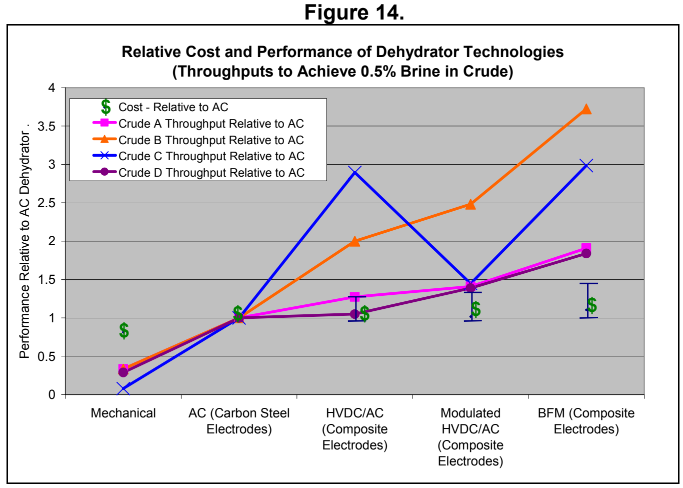
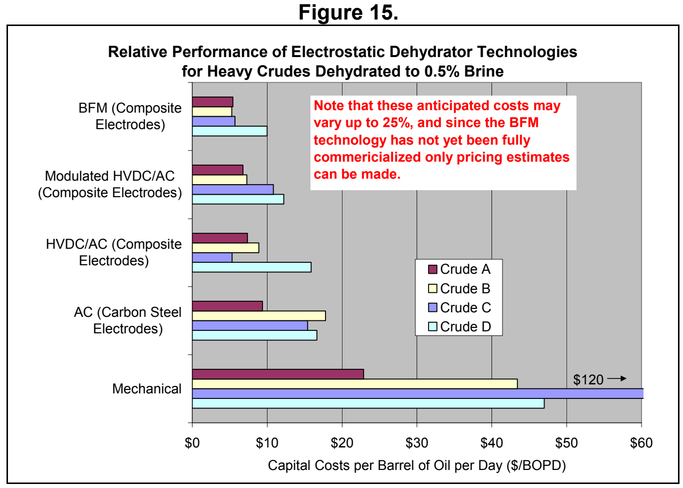


Figure 15.



Conclusions

- Pilot scale tests achieved 2 to 4 times the separator throughput (with same oil quality output) with advanced ED technology relative to conventional AC ED technology for emulsions of Crudes A and Crude B that have APIs of 21 and 20.
- Pilot scale tests achieved 2 to 3 times the separator throughput (with same oil quality output) with advanced ED technologies relative to conventional AC ED technology for emulsions of Crudes C and Crude D that have APIs less than 10. These two crudes offer a greater dehydration challenge.
- pH control can significantly aid brine separation for many heavy oils.
- The advanced ED technologies should be considered in designing dehydration systems for heavy oils.

Acknowledgements

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Nomenclature

D_{wd} = diameter of water droplet
ρ_{wd} = density of water droplet
ρ_{oil} = density of oil phase
API = 141.5/specific gravity (@ 15.5°C) + 131.5
cP = centipoise
BS&W = Basic sediment and water
pS/m = pico-Siemens per meter
mS/m = milli-Siemens per meter

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[4] Kokal Sunil: "Crude-Oil Emulsions: A-State-of-the-Art Review," SPE 77497, SPE Production & Facilities, Vol 20 (1), February, 2005.