Abstract
Polymer flood using partially hydrolyzed polyacrylamide (HPAM) has been proven to be an effective method to increase oil recovery. However, when HPAM breaks through the reservoir and shows up in the produced fluids, it brings unique emulsion characteristics and challenges to the separation processes. Operators have experienced frequent equipment failures on heat exchangers and heating elements. Traditional oil dehydration uses mechanical heater treaters which rely on elevated temperature to improve the settling of the dispersed water phase. In HPAM flood, the fire tubes in these mechanical heater treaters have become problematic and experienced repetitive failures. Electrostatic technology uses the response to the electrostatic field by the polar dispersed water phase to enhance the water settling. Electrostatic technology has been a proven technology for oil dehydration and desalting for water flood and other recovery methods such as Steam Assisted Gravity Drainage (SAGD), but not widely used in HPAM flood. A joint study was conducted between Cameron and Cenovus to evaluate the electrostatic dehydration of the heavy oil from HPAM flood. The results of the study indicate that, due to the presence of HPAM in water, the electrostatic dehydration of the wet oil from HPAM flood demonstrates some unique characteristics. Electrostatic dehydrators can achieve about 300% of the capacity of mechanical heater treaters. Proper equipment and process designs are important to reduce the equipment failures. The results of the study offer a more effective oil dehydration technology to the HPAM flood producers. The benefits of electrostatic dehydration can be especially valuable for the offshore implementation of HPAM flood due to the space and weight savings.

Introduction
Polymer flood using partially hydrolyzed polyacrylamide (HPAM) has been proven to be an effective method to increase oil recovery. However, when HPAM breaks through the reservoir and shows up in the produced fluids, it brings unique emulsion characteristics and challenges to the separation processes. One of the difficulties is the severe deposition on the fire tubes in the heater treaters and separators. The traditional technology of mechanical heater treaters is widely used in the crude oil dehydration and is the most common dehydration equipment used in HPAM flood as of today. The deposition causes excessively high temperature on the fire tubes which leads to fire tube damages. Electrostatic dehydration is a more advanced technology for crude oil dehydration. Electrostatic dehydration is a proven technology in oilfield applications, and has consistently demonstrated performance advantages over mechanical heater treaters in operations such as water flood and Steam Assisted Gravity Drainage (SAGD).

This study was to evaluate the application of electrostatic dehydration on heavy oil from HPAM flooding, explore the potential unique characteristic of the wet oil from HPAM flood, and determine the best electrostatic dehydration technology to be used for HPAM flood.

Typical Oil Field Separation Process
A typical separation process in oil fields is illustrated in Figure 1.
Figure 1. A Typical Oil Field Production Fluids Separation Process.

The produced fluids enter a high pressure separator to perform a preliminary separation. Following the high pressure separator is a low pressure separator in which further separation takes place. The final step in the process is to obtain the oil product that meets the specification. This is achieved in the oil dehydrators also known as treaters. During the separation process, produced water and gas are generated. Depending on the type of the dehydrator, gas may or may not be generated in the dehydrator itself.

Oil Dehydration

Oil dehydration is to remove the dispersed water phase from the continuous oil phase. Water is present in oil phase in the form of small droplets. The separation of droplets is achieved through gravity settling which is governed by Stoke’s law as follows:

\[ V_s = \frac{d^2(\rho_w - \rho_o)}{18 \mu} g \]

Where:
- \( V_s \): Settling velocity of the dispersed water droplets (m/s)
- \( d \): Diameter of the dispersed water droplets (m)
- \( \rho_w \): Density of the dispersed water (kg/m^3)
- \( \rho_o \): Density of the continuous oil (kg/m^3)
- \( \mu \): Viscosity of the continuous oil (N.s/m^2)
- \( g \): Standard gravity (9.81 m/s^2)

Stoke’s law indicates that bigger diameter of the dispersed water droplets, lower viscosity of the continuous oil phase, and greater density difference between the water and oil lead to faster settling of the dispersed water droplets. While not a lot can be done on density difference between oil and water, the viscosity of the continuous oil phase can be effectively reduced by raising the oil temperature, and the diameter of the droplets can be increased by the coalescence of the dispersed water.

The dehydration equipment can be categorized into mechanical dehydrators and electrostatic dehydrators. In both cases, the wet oil is heated to a higher temperature to reduce the viscosity of the continuous oil phase. The heating can be accomplished by fire tubes ahead of the separation section in a same vessel (aka. heater treaters) or external heating mechanisms outside of the dehydration vessel.

A mechanical heater treater is a dehydrator with a fire tube heater in the front section of the vessel and a mechanical gravity separator in the rear section of the vessel. Internals can be included in the separation section to improve the fluid distribution and encourage the coalescence of water droplets. Due to the duty limitation of fire tubes, a mechanical dehydrator can also use an external heater if extensive heating is required. In this case, the dehydrator is basically a mechanical gravity separator operated at higher temperature. Figure 2 illustrates a mechanical heater treater and a mechanical dehydrator with an external heater.
An electrostatic dehydrator uses electrostatic fields to actively mobilize the dispersed water droplets to enhance their coalescence. Same as the mechanical dehydrators, an electrostatic dehydrator can combine the fire tube heating section together with the electrostatic dehydration section in a same vessel (aka. electrostatic heater treaters) or use external heaters to raise the fluid temperature. The electrostatic dehydration is based on the fundamental principle that oil is almost nonpolar and almost nonconductive, and water is polar and conductive. When high voltage is applied to an oil continuous emulsion with dispersed water droplets, the water droplets will respond to the electrostatic fields and being mobilized. Properly applied electrostatic fields will generate the right amount of motion of the dispersed water droplets to enhance their coalescence and separation. Due to the negative impact of gas in the high voltage electrostatic fields, gas needs to be separated before the electrostatic dehydrator. Figure 3 illustrates an electrostatic heater treater and an electrostatic dehydrator with an external heater.

Electrostatic dehydrators selectively mobilize the dispersed water droplets without mobilizing the continuous oil; thus, they are more effective than mechanical dehydrators. Figure 4 illustrates the response of a water droplet to an electrostatic field. The polar water droplets may deform due to the electrostatic field, and the deformation can constantly change by a changing electrostatic field. The water droplets may physically move around in the space driven by the electrostatic fields. The movements of the droplets lead to collision among them causing coalescence.

Electrostatic dehydration includes AC (Alternating Current) and AC/DC (Direct current) technologies. In general, AC/DC
technology offers significant performance advantages over the AC technology. The Dual Frequency technology, which is an advance AC/DC technology, can double the capacity of a traditional AC dehydrator. Even the most basic electrostatic technology, the AC dehydration, offers a significant performance advantage over mechanical dehydrators. Figure 5 is a normalized performance comparison of different dehydration technologies on an API 21° crude oil.

![Figure 5. Comparison of the Performance of Different Dehydration Technologies.](image)

Electrostatic dehydration has been commonly used oil field separation process for water flood and SAGD operations. Its reliability, effectiveness, and performance advantages are well proven. However its application in HPAM flood is still not widely spread. Currently, the most common dehydrators in the HPAM flood separation process are mechanical dehydrators, especially the mechanical heater treaters.

**Challenges in Heavy Oil Dehydration from HPAM Flood Using Mechanical Dehydrators.**

HPAM in the produced fluids causes difficulties to the separation process (Zheng et al 2011; Wylde et al 2013). This issue has brought more attentions in recent years. One of the most troublesome problems is the largely increased fire tube failures in the mechanical heater treaters which lead to production interruptions. Tracing the fire tube temperature revealed the trend of continuous temperature increase at the skin of the fire tube (Wylde et al 2013). Observations on the failed fire tubes indicated severe solid depositions have occurred on the fire tubes causing excessively high temperature which eventually led to damage. Analysis of the deposit material showed evidences of HPAM, its dissociated products, together with typical production solids and etc. (Wylde et al 2013).

Mechanical dehydrators with external heat exchangers have also been used. These heat exchangers tend to foul rapidly and have to be cleaned very frequently. Due to the fouling, the temperature of the wet oil entering the dehydrators continuously decline causing performance concerns. The severe fouling also causes corrosion which leads to early failures of the heat exchangers.

**Electrostatic Heavy Oil Dehydration from HPAM Flood**

Electrostatic dehydration has clear performance advantage over mechanical dehydration for water flooding and SAGD operations (Sellman et al 2012; Thomason et al 2005). A systematic study was conducted to determine whether or not electrostatic dehydration offers similar benefit for HPAM flood. The study used the real fluids produced from a HPAM flood field. The dehydration is handled by mechanical heater treaters in this field. Troubles in fire tubes and heat exchangers have been a constant problem since the large scale HPAM break through occurred in the field. Table 1 summarizes of the properties of the fluids.

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<th>Table 1. The Properties of the Fluids to be Tested from a Real HPAM Flood Field.</th>
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<tr>
<td>Oil API Gravity</td>
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<tr>
<td>Total Dissolved Solids in Produced Water</td>
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<tr>
<td>Produced Water Viscosity</td>
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Same as mechanical dehydration, electrostatic dehydration requires effective treatment chemicals. In typical operations for water flood and SAGD, electrostatic dehydration requires different chemicals from mechanical dehydration. Therefore, the electrostatic treatment chemical has to be purposely screened. This chemical screening is conducted in the bench top Electrostatic Susceptibility Tester (EST) which is essentially a demulsification chemical bottle testing device with electrostatic capability in it. Figure 6 shows a picture of an EST.

Several demulsification chemicals were screened in this study including the one that was used in the field mechanical heater treaters. The results confirmed that, under electrostatic field, the demulsifier for the mechanical dehydrator did not perform well. With the presence of HPAM, most other typical dehydration chemicals did not work well either for electrostatic dehydration. The chemical that performed the best during the EST chemical screening was a water treatment chemical. This is a unique observation for the wet oil from HPAM flood.

The actual performance testing of electrostatic dehydration was conducted in the Cameron’s electrostatic dehydration / desalting pilot plant (HTU). Figure 7 shows a picture of the HTU pilot plant.

Three different AC/DC electrostatic dehydration technologies were compared based on the BS&W in the outlet of the dehydrator, including Dual Polarity which is an AC/DC technology, Modulated Dual Polarity which is an improvement on the Dual Polarity, and Dual Frequency which is an advanced AC/DC technology. AC technology was not tested due to its proven lower performance compared to AC/DC technologies for this type of oil. The results of the comparison are plotted in Figure 8.
The dehydration equipment treatment capacities were also studied. Figure 9 shows the comparison on the dehydration capacity between the existing mechanical heater treaters and modulated dual polarity to achieve the same BS&W under the same temperature. Based on Figure 9, electrostatic dehydration demonstrates a clear benefit. According to Figure 5, the AC/DC electrostatic technology could offer at least about 600% capacity benefit comparing to mechanical dehydration. However, with HPAM, Figure 9 shows that capacity advantage was reduced to about 300%. This observation indicates the impact of HPAM on electrostatic dehydration. Nevertheless, 300% is still a significant improvement. The increase in treatment capacity leads to smaller dehydration equipment which is critical for any producers who consider implementing offshore HPAM flood.

Figures 8 and 9 illustrate the benefits of electrostatic dehydration. A unique characteristic for HAPM flood oil was also identified during the testing and shown on Figure 8. Among the three different AC/DC dehydration technologies tested, the Dual Frequency technology was no longer the best performer as it is in typical water flood or SAGD operations. This was most likely caused by the HPAM in the water. The current Dual Frequency technology has been optimized for regular water droplets. When the water carries HPAM which alters viscoelasticity of the water, it is very likely to cause the dispersed water droplets to have a different response to electrostatic field. The Dual Frequency technology probably can be adjusted for HPAM laden water to achieve further performance benefit.

**Dehydration Equipment Design and Process Considerations for HPAM Flood**

In order to achieve effective dehydration and maintain reliable and robust operation, the dehydration equipment has to be properly engineered and designed, and the process needs to be properly put together.

The benefits of electrostatic technology can be only realized if the wet oil passes through electrostatic field. The fluid dynamics inside the dehydrator dictates whether the fluids truly pass through the electrodes or simply circulates around them. Studies have shown that proper fluid distribution can achieve about 35% higher flux rate from better vessel utilization (Sellman *et al* 2012).
Because the HPAM laden water tends also contain solids and other substances which make the separated water to be prone to stay at the interface forming emulsion layer, the dehydrators should be designed to handle that.

Heating the wet oil to reduce its viscosity is important for the dehydration as indicated in the Stoke’s law. For heavy oil, proper heating is especially critical. Due to the fire tube damages caused by the HPAM together with other solids, any form of direct fired heater is not recommended. The heating of the wet oil should be accomplished through external heat exchangers using heating medium such as glycol or thermal oil with reasonable temperature differences to avoid excessively high temperature. Heat changers should be suitable for fouling services.

**Conclusion**

The dehydration of wet oil from HPAM flood presents unique difficulties due to the presence of HPAM in the water. Electrostatic dehydration offers performance and capacity advantages over mechanical dehydration for HPAM flood. Among the current electrostatic dehydration technologies, the modulated dual polarity technology appears to be the best for HPAM flood. The current dual frequency technology optimized for water flood and SAGD operation does not perform as good as it could be for HPAM flood. This is mostly likely caused by the altered viscoelasticity of the water by the HPAM. A dual frequency dehydrator tailored for HPAM flood has the potential to offer further improvement opportunities. In order to fully achieve the benefit of electrostatic dehydration, the equipment has to be properly engineered, and the process should be properly designed. The advantages of electrostatic dehydration enable smaller equipment leading to space and weight savings which are critical for offshore implementation of HPAM flood.

**References**


