

Performance Testing of an Inline Electrocoalescer Device With Medium and Heavy Crudes

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Summary

ExxonMobil Upstream Research Company (EMURC) recently completed a subsea technology development and qualification program that included performance testing of an inline electrocoalescer device supplied by FMC Technologies (FMC). This paper will summarize the results from these performance tests.

Although heavy oil has been processed onshore successfully for many decades, processing heavy oil in deepwater, subsea, or Arctic fields is extremely challenging. One key challenge is oil/water separation, in which physical separation is constrained by the high viscosity of the crude and the narrow density difference between oil and water. Installing conventional electrostatic coalescers or dehydrators is often not economical or is impractical at remote locations. As part of ExxonMobil's subsea program, several different separation technologies have been investigated and tested that could enable development of these fields. One example of such a technology is an inline electrocoalescer device.

An inline electrocoalescer device enhances the coalescence of water droplets dispersed in emulsified oils. This technology has the potential to improve the performance of the downstream oil/water separator considerably. By applying an electrical field to an oil/water mixture, the dispersed water droplets become polarized and reorient themselves in the electrical field. As these water droplets approach one another, attractive forces between the individual water droplets lead to coalescence. Larger water droplets that can be separated faster and more easily in the downstream separation equipment are formed. Such a device can be used to increase the throughput, performance, and reliability of existing oil-processing systems, while reducing the energy consumption and/or use of chemical demulsifiers. In new processing systems, either subsea or topside, deployment of such a device has the potential to significantly reduce the size and weight of the downstream separation equipment, thereby lowering the overall capital expenditure.

The results presented in this paper are from performance tests that have been carried out on an inline electrocoalescer device at FMC's testing facilities in the Netherlands, with EMURC's involvement. Extensive testing was executed with both medium and heavy crude oils. The operating temperatures were varied in a range representative for subsea processing applications, where heating of the process fluids is difficult. Thus, the performance of the inline electrocoalescer device was evaluated over a range of oil viscosities. Water-in-oil concentration, flow velocity, upstream shear, and electrical-field strength were also varied to investigate their effects on the performance of the inline electrocoalescer device. The results demonstrate that the unit is able to deliver high preconditioning performance to medium- and heavy-crude-oil emulsions, provided that the appropriate process conditions and electrical settings are used.

Introduction

Dehydration plays a fundamental role in the production and processing of crude oil. The removal of water from heavy crude is a challenge for many oil-processing facilities, even when only topside applications are considered (Moraes et al. 2013). It can also pose a big challenge for processing medium crudes, and in general for any highly emulsified hydrocarbon liquids, such as those obtained from high-pressure applications and enhanced-oil-recovery (EOR) processes.

Besides using mechanical means to separate water from oil, other common methods of enhanced dehydration include heating, use of chemical demulsifiers, and electrostatic treatment (Silset 2008). Other possible techniques are pH adjustment, filtration, and membrane separation (Eow et al. 2001). Heat treatment can effectively destabilize water-in-oil (WIO) emulsions; however, it is also energy intensive and typically results in a larger system footprint. Capital and operational expenditure can be considerable in conventional applications (Pruneda et al. 2005), and the use of heat treatment is either economically unattractive or impractical in subsea, Arctic, remote, or marginal field applications. Further, the solubility of water in oil increases with temperature. As the oil cools during transportation, free water drops out in the pipeline, which could cause flow-assurance issues. Besides this, heat treatment causes volatile hydrocarbons to flash out of the liquid phase, which can result in appreciable volume shrinkage and API-gravity reduction in the heated crude oil (Manning and Thompson 1995). This means that there is a practical and economical limit in the amount of water that can be removed from crude oil through the use of heat treatment alone. For this reason, a combination of heat treatment and demulsifiers is by far the most-common method of enhanced dehydration because many crude-oil emulsions become unstable when treated with the right type and concentration of demulsifier (Arnold and Stewart 1998; Caird 2008; Kelland 2009) at high temperature. While chemical treatment requires a relatively lower capital investment and less energy than heat treatment, it can bear a considerable operating cost, and ensuring an uninterrupted supply of chemicals to the production site can be challenging. While the supply of chemicals to any production facility can be expensive and sensitive to changes in weather conditions, market availability, or political factors, the supply of chemicals to subsea, Arctic, remote, or marginal field applications is a far greater logistical and economic challenge.

Electrostatic treatment can be effective at breaking WIO emulsions. It is also one of the most energy-efficient methods used for destabilization of WIO emulsions (Eow et al. 2001), and is considered an enabling technology for the subsea separation of produced water from heavy oil in deepwater developments (Euphemio et al. 2007). When it is used in combination with chemical and/or heat treatment, it can improve the economics of the production facility by reducing the overall energy consumption, by reducing the use of chemical demulsifier, or both. The electrical field produced by an electrostatic coalescer affects the morphology of WIO emulsions because of the polarization of dispersed water droplets in the oil

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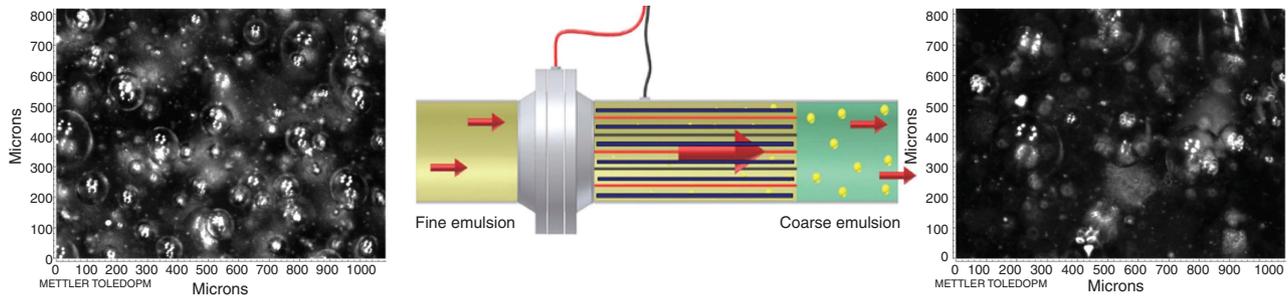


Fig. 1—Schematic of the inline electrocoalescer device that was tested (middle). The emulsion enters the unit from the left. A series of insulated active and grounding electrodes create an electrical field that enhances the coalescence of water droplets dispersed in the crude oil. The emulsion leaves the unit from the right, with substantially enlarged water droplets.

phase. Given the appropriate process conditions and electrical settings, the electrostatic treater will enhance the coalescence of the dispersed water droplets in the emulsion, making the emulsion less stable and, therefore, easier and faster to break (Boschee 2012). As expressed by Stokes's law, the settling velocity of a dispersed droplet has a quadratic dependency upon its diameter; therefore, the separation time is reduced significantly when dispersed droplets coalesce into larger droplets. That said, electrostatic technologies that are commercially available still have room for improvement, at least with respect to operational versatility (e.g., handling higher water cuts, temperatures, and pressures), robustness, and reliability. Furthermore, technologies that are intended for subsea, Arctic, remote, or marginal field applications need to be as compact as possible and versatile with regard to operation and integration into the rest of the system (Akdin 2013). Power consumption must also be minimized. An electrostatic coalescer installed subsea must have the ability to be retrieved and replaced quickly and easily, without major logistics involved and without stopping production. Its mean time between failures must be at least comparable with that of technologies that are already qualified for subsea use, such as subsea rotating equipment. Some applications, with the associated benefits, that need an improved electrocoalescence technology include

- Oil dehydration of medium and heavy crude oil by subsea separation in shallow and deepwater applications
- Oil dehydration of medium and heavy crude oil in Arctic, remote, or marginal fields
- Reduced size and weight of new separation equipment
- Reduced size and weight of offshore platform structures by deploying more-compact production systems
- Increased performance and/or throughput of existing separation equipment (i.e., debottlenecking)
- Reduced demulsifier injection and/or energy consumption by the heating system
- Ability to meet oil-quality specifications when the emulsion stability is high (e.g., medium or heavy oil, high-pressure applications, cold production, oil from EOR processes)
- Reduced energy consumption of the oil-pumping system by means of improved oil dehydration (i.e., viscosity of WIO emulsions is reduced when water cut is reduced)
- Maximizing oil production and minimizing problems related to corrosion and/or hydrate formation in long transportation pipelines

Last year, ExxonMobil Upstream Research Company (EMURC) completed a subsea separation technology development and qualification program that included performance tests on a laboratory-scale inline electrocoalescer supplied by FMC Technologies (FMC). The results from these tests are presented in this paper. The tests were carried out at FMC's Separation Innovation and Research Centre in the Netherlands, with EMURC's involvement. The tests were performed with two crude oils (i.e., medium and heavy) at different operating temperatures, thus covering a range

of oil viscosities. The performance trends are presented as a function of flow velocity, upstream shear, oil viscosity, and electrical-field strength.

Materials and Methods

Tested Equipment. The inline electrocoalescer device that was tested is a compact, pipe-based electrocoalescer technology that uses an electrical field to polarize and rapidly coalesce dispersed water droplets in a continuous oil stream, effectively shifting the droplet-size distribution. This is reflected in a substantial increase in the size of the water droplets in the emulsion leaving the device and, consequently, a substantial reduction in the total amount of water droplets per unit volume. As a result, the oil quality (i.e., degree of oil dehydration) leaving the separator downstream of such a device is improved and/or the residence time required to achieve that quality is reduced.

The compact nature of such a design may further reduce the weight by a factor of two to four, as compared with commercially available compact electrostatic coalescers. This will enable applications in operating environments with space and weight constraints, as well as in deepwater subsea processing systems, allowing hydrate-free export of crude oil through long-distance pipelines to a host facility.

Fig. 1 shows a schematic of the inline electrocoalescer device that was tested, with its main components and an illustrative example of the droplet-growth effects. In this particular design, the active electrodes are encapsulated in a ceramic housing, which is considerably more durable and temperature resistant compared with other insulation materials. The figure also shows images made in previous tests with the laboratory-scale inline electrocoalescer device, showing its ability to coalesce water droplets dispersed in a crude oil. The images were made with a particle vision and measurement technology (i.e., PVM[®] from Mettler-Toledo).

Inside the inline electrocoalescer device, a high-voltage alternating current (AC) is applied to insulated electrodes to form the intense electrical field. Because of the electrical field, water droplets that are dispersed in the oil phase become polarized and collide in a moderately turbulent flow regime. The intense electrical field provides the polarized droplets with a strong short-range-attraction force that enables them to break the interfacial film between them and eventually merge to create a larger droplet (Eow et al. 2001; Mikkelsen et al. 2013). These polarization-induced attractive forces are orders of magnitude larger than the colloidal forces created by the natural surfactants that stabilize the emulsion (Boyson 2007).

In addition to this, as water droplets pass through the electrical field, their molecules are constantly forced to rotate and realign in the direction of the electrical field because of the nature of the AC current. The constant realignment of the water molecules results in continuous deformation of the individual water droplets at a relatively high frequency (Lundgaard and Nilsen 2006). As a result of

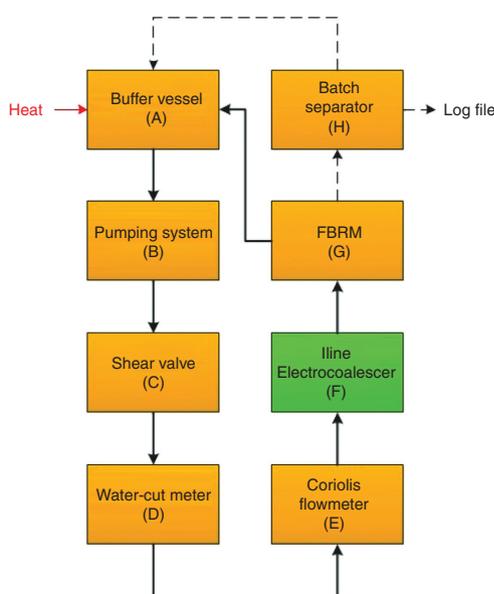
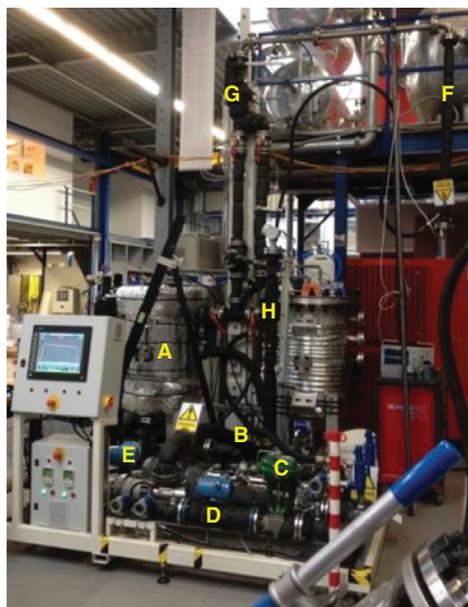


Fig. 2—Detailed picture of the test loop, with the main components indicated (left) and a simplified process-flow diagram of the same loop (right).

that vibration, the mobility of water droplets dispersed in the oil phase is enhanced, which increases the probability that these water droplets will collide as they pass through the unit. Furthermore, during the collision of any two droplets, these high-frequency vibrations increase the magnitude of the dynamic forces acting at the interface between them, increasing the likelihood that the droplets will be able to break the interfacial film that keeps them apart and coalesce. The effectiveness and speed at which the interfacial film between these water droplets breaks are related to the amplitude and frequency of the electrical field (Eow and Ghadiri 2002). Furthermore, the collision rate between droplets depends on the level of turbulence of the fluid as it passes through the electrical field. Flowing conditions that induce a moderate amount of turbulence are required to maximize coalescence efficiency (Less and Vilagines 2012). However, these parameters must be adjusted and optimized for a given emulsion to maximize the coalescence efficiency for that particular application.

During normal operation, the inline electrocoalescer must be fed with an oil-continuous emulsion, preferably containing more than 10% water cut and less than 20% gas volume fraction. Higher water cuts will typically result in improved performance of the unit, and the unit will operate normally as long as oil is the continuous phase. In the event that water suddenly becomes the continuous phase (e.g., following a water slug), the inline electrocoalescer will sense a change in the electrical current and automatically switch into a standby mode. The unit's normal operation will be automatically re-established when the system's phase split is stable, with oil as the continuous phase.

Test Loop. The test system consists of a small, semi-automated closed loop for studying electrocoalescence of water droplets dispersed in crude oil under flowing conditions. As depicted in **Fig. 2**, the main components of the loop are (A) a buffer vessel, (B) a pumping system, (C) a shear valve, (D) a water-cut meter, (E) a Coriolis flowmeter, (F) an inline electrocoalescer device, (G) a Mettler-Toledo focused-beam reflectance measurement (FBRM[®]) probe, and (H) a batch separator. Depending on the test scenario, the volume required to operate the loop varies between 100 and 300 L of water-in-oil (WIO) emulsion. The pumping system is able to move the emulsion at a flow rate of up to 10 m³/h. The dual heating system connected to the buffer vessel ensures that the emulsion is

heated to the desired temperature and that a constant temperature is maintained during the tests. The loop is insulated thermally and can be operated at temperatures up to 75°C and pressures up to 8 barg. **Fig. 3** shows an overview of the test loop and the control-system interface.

Performance Measurements. The Mettler-Toledo FBRM[®] probe (an advanced, in-situ droplet-size monitoring device), which was installed in the main process line immediately downstream of the inline electrocoalescer device, provides an indication of the unit's effect on the water-droplet-size distribution by measuring the chord length of water droplets flowing in the pipe. A change in the measured chord lengths gives a good indication of the rate at which the droplets coalesce as they pass through the inline electrocoalescer device. During a test, the emulsion is constantly being sheared, meaning the number of water droplets counted by the FBRM probe is considerably high. This fact makes it reasonable to assume, with minimal statistical error, that the droplet-chord-length-growth ratio measured by the FBRM probe is directly proportional to the water-droplet-diameter-growth ratio. By use of this rationale, the FBRM probe can provide an online measurement of the rate and degree of change in the droplet-size distribution downstream of the inline electrocoalescer device at various operating conditions. This provides a direct measurement of the coalescence efficiency of the unit, which in turn directly reflects the droplet-settling time and oil-dehydration efficiency in the downstream separator. An example of the water-droplet-chord-length measurements for a WIO emulsion during an experiment before treatment (inline electrocoalescer off) and after treatment (inline electrocoalescer on) is shown in **Fig. 4**, left image. Through comparison, the two curves provide a means to approximate the water-droplet-diameter-growth ratio (i.e., ratio of water-droplet diameter before and after treatment). In this experiment, the mean chord length was approximately 30 μm before treatment (i.e., inline electrocoalescer off) and approximately 300 μm after treatment (i.e., inline electrocoalescer on); therefore, the water-droplet-diameter growth-factor ratio was approximately 10.

To directly compare the increased water-droplet-size distribution to real separation-performance improvement, the test loop includes a bypass line downstream of the inline electrocoalescer device, which is used to isolate and drain a sample volume into a batch separator made of a pipe spool (**Fig. 4**, middle image). The

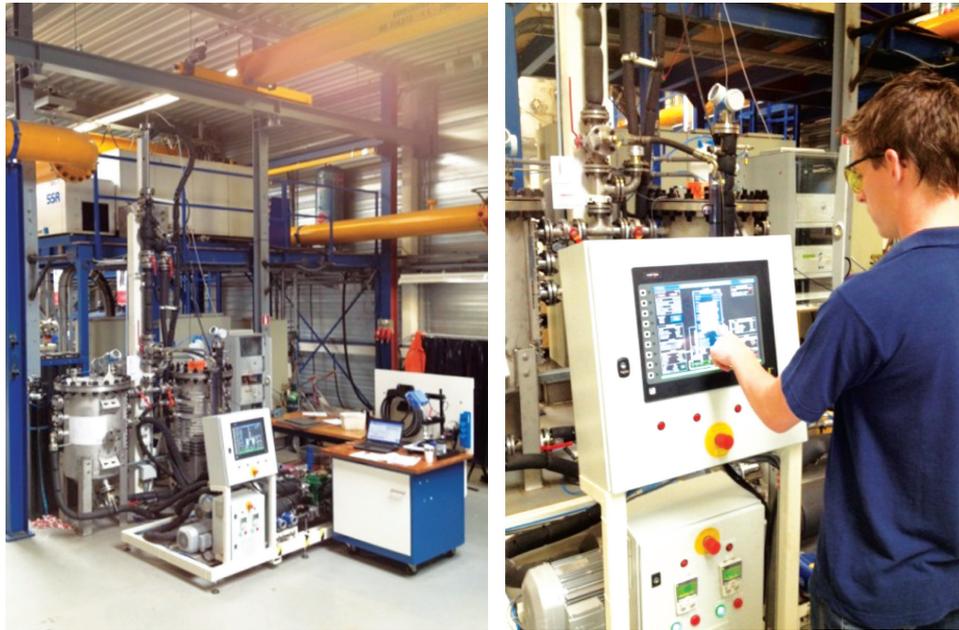


Fig. 3—Overview picture of the test loop in operation (left) and the control-system interface (right).

batch separator is oriented vertically and is sized to accommodate a liquid column of approximately 1.5 m in height. To minimize the probability of modifying the morphology of the emulsion (i.e., coalescence or breakup of water droplets) while transferring it from the device through the spool piece with the FBRM probe and into the batch separator, all of the intermediate piping and components are made of similar pipe diameters.

During sampling, a representative volume of the emulsion is taken from a point downstream of the inline electrocoalescer device, isolated, and drained into the batch separator. A capacitance probe installed in the upper section of the batch separator provides an indication of the change in water concentration in the oil layer vs. time. The sample liquid volume in the separator remains stationary, while the capacitance in the oil layer is being monitored. Sampling can be performed with the device on or off. During a test with sampling, the capacitance in the oil layer of the batch separator is monitored and logged for a certain amount of time. Fig. 4 (right image) shows an example of the way in which this method can be used to determine the degree of separation of water from a crude-oil emulsion as a function of time for a case in which the device was switched on

before the emulsion entered the column, whereas in the other case, the device was switched off. The separation rate is substantially increased when the device is switched on, demonstrating the positive effect that the increased droplet size leaving the inline electrocoalescer device has on the downstream separation.

The separation-efficiency measurements in the separator downstream of the inline electrocoalescer device and the droplet-size increase measured by the FBRM probe are related; therefore, the trends provided by these two methods should be consistent with one another. This validates the use of the FBRM probe for monitoring the coalescence of water droplets dispersed in crude oil. For this reason, sampling was not performed for all tests points, but only for a selection. This allowed more test points to be recorded in a shorter time frame.

Test Conditions. During a test, the emulsion is constantly being formed by passing the crude oil and water through a shear valve. By controlling the pressure drop over the shear valve, the droplet-size distribution of the dispersed water in the emulsion can be adjusted and is continuously measured downstream of the inline electrocoalescer device by use of the FBRM probe. Before the start

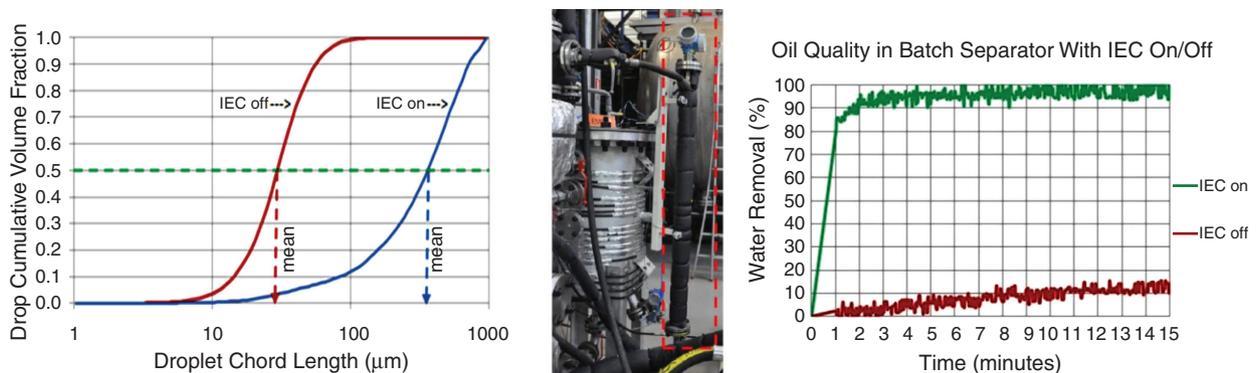


Fig. 4—Example of a cumulative, volumetric droplet-size distribution measured by the FBRM probe with the inline electrocoalescer device (designated as IEC in the image) switched off and switched on (left image). In this example, the inline electrocoalescer device increased the mean droplet size of the emulsion by a factor of 10. Photograph of the batch settling column located downstream of the inline electrocoalescer device (middle image). An example of the rate of water removal from crude oil in the batch settling column is shown, with the device switched off and switched on (right image).

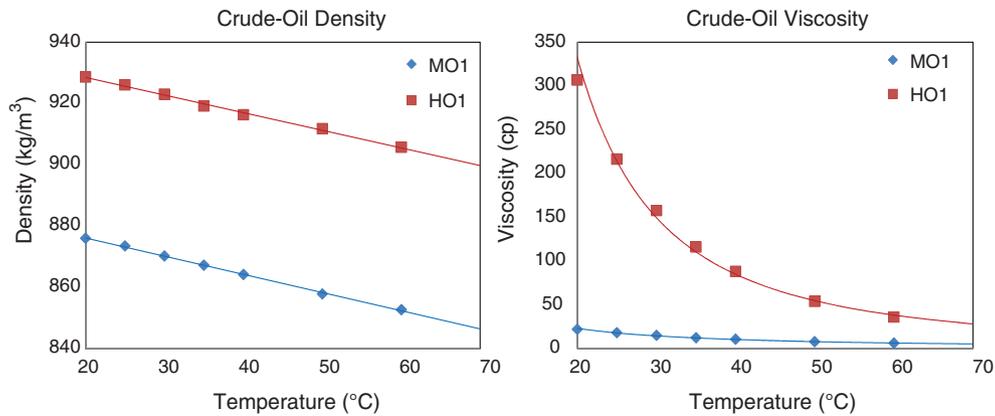


Fig. 5—Density (left) and viscosity (right) of the crude-oil blends used in this test program, as a function of temperature.

of a test, emulsion is circulated through the loop, while the unit is switched off, until the droplet-size distribution is stable. This provides a baseline for the emulsion at a given set of operating parameters and fluid properties. Later, experiments are conducted with the unit switched on at the same operating parameters and fluid properties. When the device is switched on, the intensity of the electric field can be varied by the operator by adjusting the input voltage to the electrocoalescer cell; thus, the performance of the inline electrocoalescer device can also be determined for various electrical-field strengths. For all conditions, the droplet-size distributions are recorded, and as explained earlier, for some conditions, the separation of a sample is recorded with the settling column to validate the data from the FBRM probe. A comparison of the results provides valuable information about the performance of the inline electrocoalescer device and its effect on the downstream separation equipment. During these experiments, the following parameters were studied: flow velocity, upstream shear, oil viscosity, and electrical-field strength.

Fluid Properties. Two different crude-oil blends were supplied for the performance tests: a medium-crude-oil blend and a heavy-crude-oil blend. Both crude-oil blends had been stabilized and were stored in barrels for transportation to the test facility. In this paper, the medium-crude-oil blend will be referred to as MO1, and the heavy-crude-oil blend will be referred to as HO1. Fig. 5 shows the densities and viscosities of these different crude-oil blends at atmospheric pressure in the range of temperatures used during the tests. Certain WIO emulsions were created by adding an amount of brine to the oil that corresponds to the target water cut, as indicated in the predefined

test matrix. The brine was synthesized with tap water and sodium chloride to obtain the desired salinity. The entire test campaign was performed without adding any chemical enhancers, such as chemical demulsifier, corrosion inhibitor, or biocide, to the emulsion.

Test Results

With the exception of the oil-viscosity sensitivity trials, the tests were carried out at constant temperature. In the case of MO1, the temperature setting was 35°C, corresponding to an oil viscosity of 13 cp. In the case of HO1, the temperature setting was 60°C, corresponding to an oil viscosity of 38 cp. The electrical-field strength was varied by changing the voltage applied to the electrodes. During the tests, the supplied voltage was in the range of 0 to 4 kV. The voltage is clearly indicated Figs. 6 through 10. Although the performance of the inline electrocoalescer device was studied for a range of water cuts, only results corresponding to 30% water cut are presented in this paper. In general, the benefit of the inline electrocoalescer device was less pronounced at lower water cuts.

Influence of Flow Velocity and Electrical-Field Strength. The flow velocity was changed to study the influence of flow conditions and residence time on the performance of the inline electrocoalescer device. Generally, the pressure drop over the shear valve upstream of the unit was fixed at 0.25 bar. No tests were carried out for the flow-velocity sensitivity tests with the batch separator; therefore, only the data from the focused-beam reflectance measurement (FBRM) probe are available. The results of these tests are presented in Fig. 6. As expected, increasing the applied voltage (i.e., electrical-field strength) resulted in an increase in

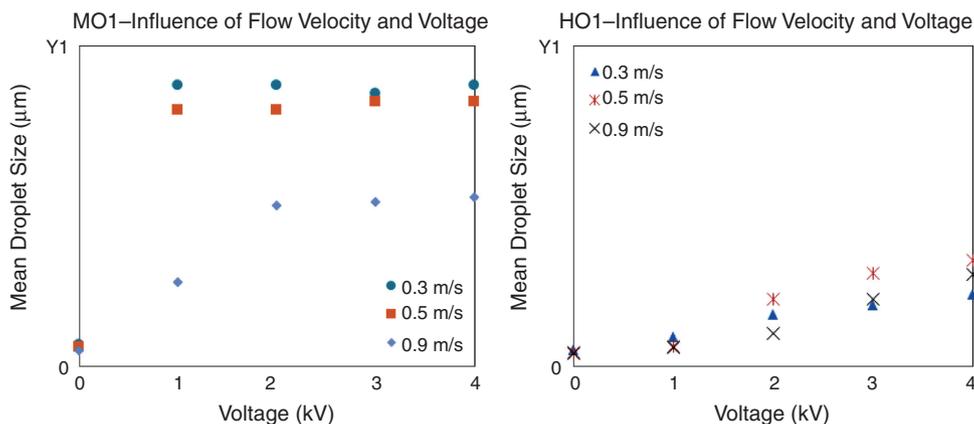


Fig. 6—Influence of flow velocity and electrical-field strength on the volumetric mean droplet chord length for MO1 (left) and for HO1 (right). Inlet water cut is 30% v/v in all cases.

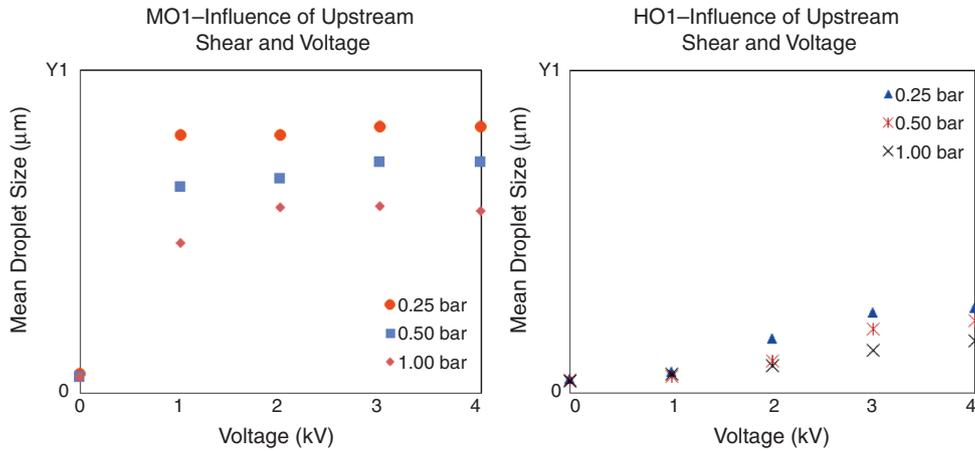


Fig. 7—Influence of upstream shear (i.e., pressure drop over shear valve) and electrical-field strength on the volumetric mean droplet chord length for MO1 (left) and for HO1 (right). Inlet water cut is 30% v/v in all cases.

coalescence until a maximum was reached, as shown by the asymptotic shape of the performance curves. In the case of MO1, such a maximum was reached at relatively low voltage. Operating at higher flow velocity required relatively higher voltage to reach the maximum achievable performance at the same process conditions. In the case of HO1, water droplets continued to coalesce more as the voltage was increased (in the voltage range used) without reaching saturation. However, when operating at lower

flow rates, the effect of the voltage on the rate of coalescence reduced slightly at a voltage greater than 3 kV. This suggests that the maximum coalescence performance for the emulsion formed at those process conditions should not be far beyond the maximum voltage used in the tests. During the tests, it was observed that continuing to increase the voltage after the maximum achievable coalescence performance had been reached resulted in a substantial increase in power consumption.

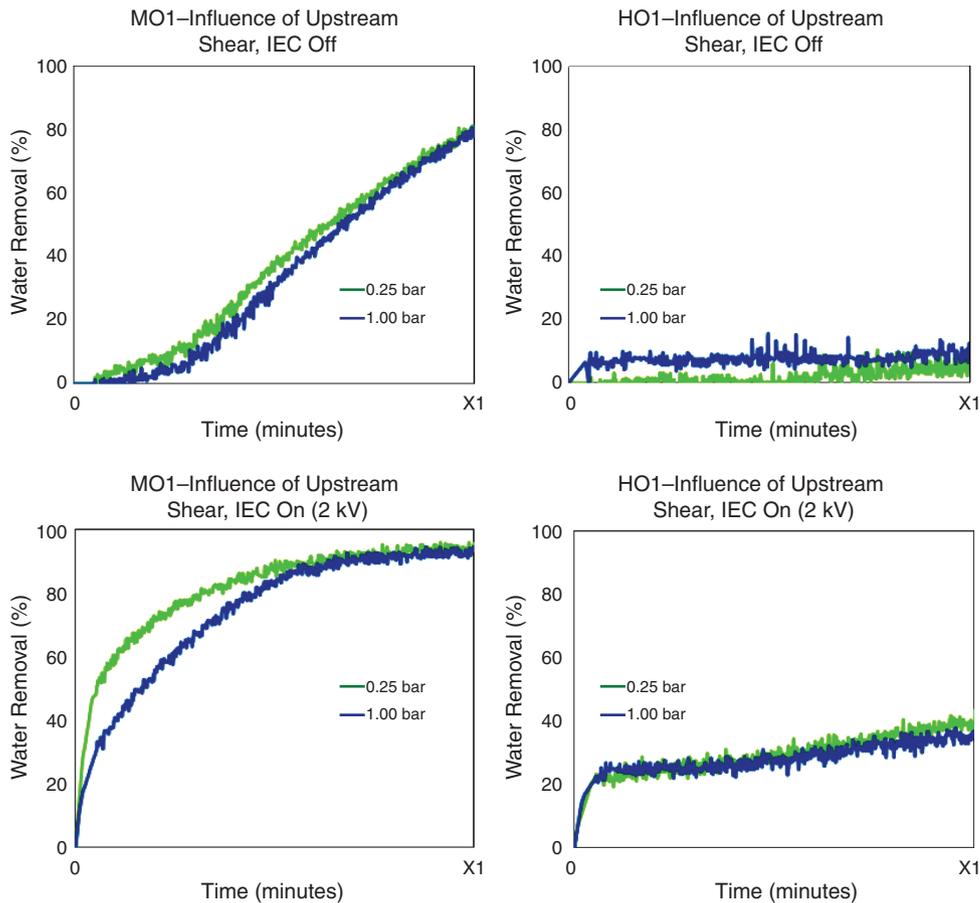


Fig. 8—Influence of upstream shear on water removal from oil in the batch separator downstream of the inline electrocoalescer device (designated as IEC in the image) for MO1, with the unit switched off (top left) and switched on (bottom left), and for HO1, with the unit switched off (top right) and switched on (bottom right). Inlet water cut is 30% v/v in all cases.

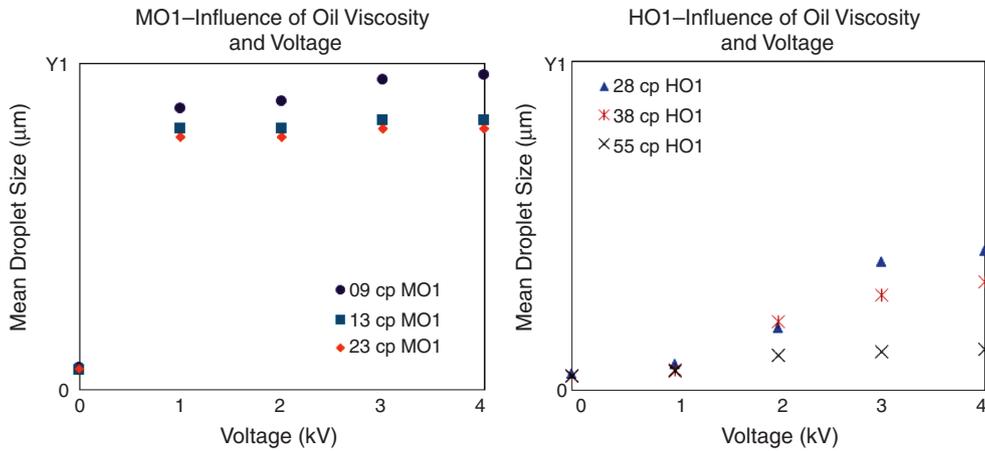


Fig. 9—Influence of oil viscosity and electrical-field strength on the volumetric mean droplet chord length for MO1 (left) and for HO1 (right). Inlet water cut is 30% v/v in all cases.

Flow regime, shear rate, and level of turbulence have a large influence on the formation and breaking of water-droplet chains, and on overall coalescence performance. Thus, these operating parameters have a significant impact on the power consumption of the inline electrocoalescer device. As indicated in Fig. 6, the results from the tests with MO1 show that the coalescence performance of the unit improved (i.e., larger droplets are generated) as flow velocity decreased and residence time increased. For that particular oil blend, the difference in coalescence performance at flow velocities between 0.3 and 0.5 m/s was small; however, at 0.9 m/s, the difference in coalescence performance was relatively large. Tests

with HO1 showed a somewhat unexpected trend because the maximum coalescence performance was achieved at an intermediate flow velocity of 0.5 m/s. In the range tested, the performance was reduced slightly when operating either above or below this setting. This indicates that the optimum flow velocity depends on the emulsion characteristics and the process conditions used.

As indicated in Fig. 6, the droplet-growth factor obtained by subjecting the emulsion to the electrical field inside the inline electrocoalescer device was moderate for HO1 compared with the results for MO1 at the same flow conditions and electrical settings. It is important to mention that the viscosity of HO1 is considerably higher than

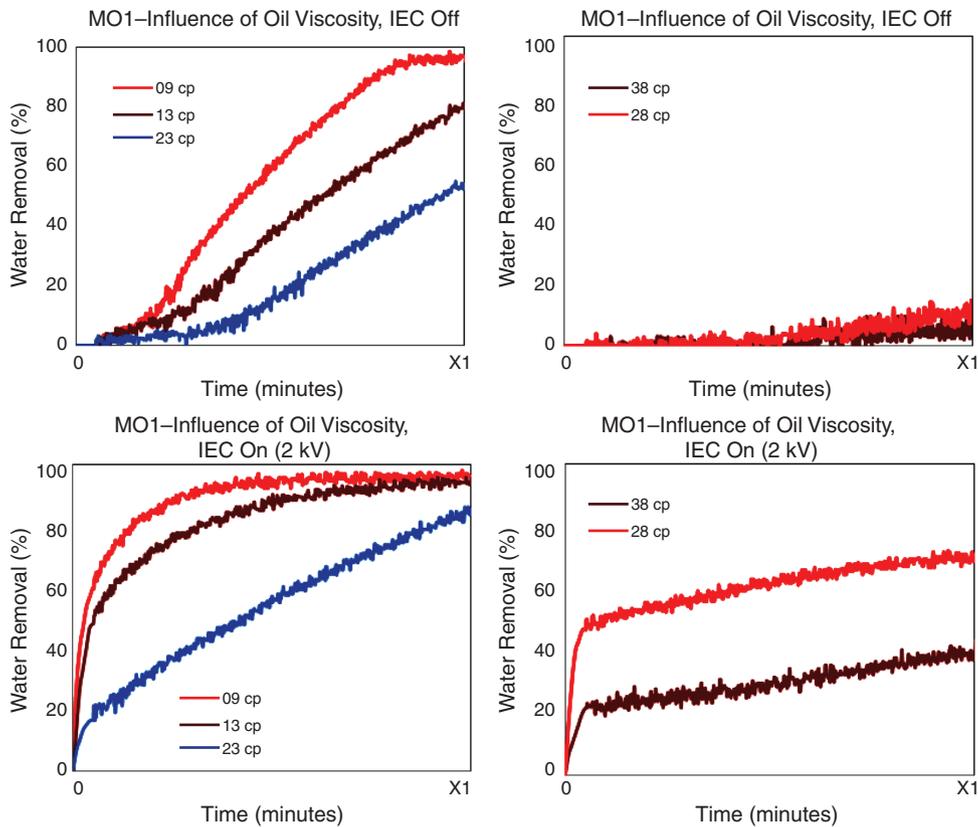


Fig. 10—Influence of oil viscosity on water removal from oil in the batch separator downstream of the inline electrocoalescer device (designated as IEC in the image) for MO1, with the unit switched off (top left) and switched on (bottom left), and for HO1, with the unit switched off (top right) and switched on (bottom right). Inlet water cut is 30% v/v in all cases.

the viscosity of MO1 at the test conditions, which means that the drag force experienced by the water droplets present in HO1 is also considerably higher. It is expected that increasing the electrical-field strength beyond the range applied during the tests would at least partially compensate for the higher drag force; however, the test results show that reducing the oil viscosity by increasing the operating temperature could be a more-effective option, as indicated by the considerable improvement in the performance of the inline electrocoalescer device during the viscosity sensitivity tests. These viscosity sensitivity tests will be discussed in more detail in later subsections.

Influence of Upstream Shear and Electrical-Field Strength. The pressure drop over the upstream shear valve was changed to study the influence of a different inlet water-droplet size distribution. In these sensitivity tests, the flow velocity was constant. The data from the FBRM probe for these tests are presented in Fig. 7. In the absence of an electrical field, the mean droplet size with both MO1 and HO1 was considerably small, regardless of the shear rate applied. For the range of shear rates tested, combined with the instrumentation and the scale used to visualize the test results, the difference in the water-droplet-size mean values can be neglected in the cases in which the unit was switched off. When the unit was switched on, increasing the shear rate upstream of the inline electrocoalescer device resulted in a shift of the mean water-droplet size, which confirms that the water droplets dispersed in the oil phase break up into smaller droplets when the shear rate applied to the emulsion is increased.

In the case of MO1, the size of the water droplets increased significantly when the unit was switched on, and a relatively low electrical-field intensity inside the inline electrocoalescer device was sufficient to increase the water-droplet-size mean value. However, such an effect was at least reduced slightly when the shear rate increased. Similar to the test results from the flow-velocity sensitivity tests, the figure shows that increasing the electrical-field strength resulted in an increased droplet-growth factor until a maximum value was reached.

The water-removal efficiency in the separator downstream of the inline electrocoalescer device is shown in Fig. 8. These graphs correspond to the 0- and 2-kV cases shown in Fig. 7. The relationship between droplet size and separation efficiency is confirmed both in the case of MO1 and in the case of HO1. Increasing the amount of shear applied to the emulsion results in a decrease in the size of water droplets dispersed in the oil phase; this in turn is reflected in a reduced oil-dehydration performance in the downstream separator. That said, the difference in separation efficiency in the downstream separator was considerably more dependent on the presence or absence of the electrical field than on the shear applied to the fluid. The figure shows that the inline electrocoalescer device enables an overall higher level of oil dehydration in the downstream separator at the given set of test conditions.

Influence of Oil Viscosity and Electrical-Field Strength. The oil viscosity was changed to study its influence on the performance of the inline electrocoalescer device. In these tests, the flow velocity in the unit and the shear valve upstream of the inline electrocoalescer device were constant. The oil viscosity was adjusted by changing the temperature of the fluid in the loop. The tests with MO1 were carried out at 9, 13, and 23 cp. The tests with HO1 were carried out at 28, 38, and 55 cp. The data from the FBRM probe are shown in Fig. 9.

From this figure and the water-removal-efficiency results in Fig. 10, it is shown that reducing the oil viscosity by increasing temperature can result in a considerable increase in the measured mean droplet size, the coalescence efficiency of the device, and the water-removal efficiency of the downstream separator. Similar to the velocity and the upstream shear sensitivity tests, the difference in the water-droplet-size mean values can be neglected in the case in which no electrical field is applied. This indicates that a small increase in the droplet size of the nontreated emulsion can result in a relatively large increase in the droplet-growth factor, as achieved

by the inline electrocoalescer device. In the case of HO1, the increase in the growth factor can be substantial when a high electrical-field intensity is combined with a relatively low oil viscosity.

Fig. 10 shows the water-removal efficiency achieved by the downstream separator when the unit is switched off and when the unit is switched on. These graphs correspond to the 0- and 2-kV cases, as shown in Fig. 9. Similar to the upstream shear-sensitivity tests, the relationship between the droplet size and the separation efficiency was also confirmed in the oil-viscosity sensitivity tests for MO1 and HO1. Decreasing the oil viscosity by increasing the temperature results in decreased viscous forces acting on the water droplets, with a higher rate of droplet coalescence and a corresponding increase in their size; this in turn is reflected in an improved oil-dehydration performance in the downstream separator. The figure shows that the electrical field created by the inline electrocoalescer device led to coalescence of dispersed water droplets and made it possible for the downstream separator to achieve an overall higher degree of oil dehydration. When the unit was switched off, the amount of water removed from the water-in-oil (WIO) emulsion in the downstream separator was considerably lower.

From Figs. 9 and 10, one can see that the results for MO1 at 23 cp and HO1 at 28 cp are significantly different. This suggests that viscosity and density are only a small part of a very complex coalescence-settling phenomenon. This phenomenon is not yet fully understood; however, it is known that apart from viscosity and density, there are other key parameters that play an important role in this process, such as interfacial tension between the oil and water phases, crude-oil composition, oil electrical properties, interfacial chemistry, and the presence of surface-active components. These parameters may have had an effect on the results for MO1 and HO1 because they can vary greatly from oil to oil and/or from WIO emulsion to WIO emulsion. This subject is discussed briefly in the conclusions of this paper.

Conclusions

The test results presented in this paper demonstrate that the inline electrocoalescer device that was used in this test program is able to process medium- and heavy-oil blends with high fluid velocities, while achieving high coalescence performance provided that the appropriate process conditions and electrical settings are used. Because of its compact design, this technology has the potential to enable production from subsea, Arctic, remote, or marginal oil-field applications and to improve oil dehydration of medium and heavy crude oils considerably in facilities with space and weight constraints, as compared with conventional electrostatic coalescers or dehydrators.

The tests also show the significant impact that oil viscosity has on the overall dehydration efficiency in heavy-oil-processing systems. When the oil viscosity was high, the amount of water removed from the oil was considerably lower without the unit, and even an increase in residence time did not improve the performance much. On the other hand, the dehydration efficiency of the downstream separator improved significantly when the unit was switched on.

It is important to consider that the coalescence of water droplets dispersed in a crude oil is influenced not only by oil viscosity and/or other physical properties, such as interfacial tension and density difference between water and oil, but also by the oil chemistry. For instance, only a small amount of surface-active molecules can significantly influence the surface chemistry of water droplets in the emulsion, which affects the probability that water droplets will either coalesce or bounce back when they approach each other. The composition of the oil will also influence its electrical permittivity and conductivity, which in turn will have an effect on the electrical field and on the overall performance of any electrocoalescence technology. Every crude oil has a chemical composition that makes it unique. That said, the chemistry of the produced water associated

with different crude oils is also unique. As a consequence of this, every process fluid [i.e., water-in-oil (WIO) emulsion] is different—in its chemical composition, the way it is made (formation history), the amount and type of chemicals added in its production process, the operating conditions at which it is processed, and its emulsion morphology.

The probability and rate of coalescence between water droplets dispersed in a crude oil are largely dependent on the nature of the emulsion being processed. For this reason, the coalescence performance of any electrostatic technology, including the inline electrocoalescer device that was used in this test program, strongly depends on the type of emulsion and the operating conditions that are present in a given application. When comparing different crude oils and emulsions, the performance trends presented in this paper provide an indication of the type of reaction that can be expected from the system; however, in practice, representative performance trends can only be obtained by testing directly with the crude oils in question at realistic operating conditions.

The results shown in this paper are for a prototype of the inline electrocoalescer device, which was a laboratory-scale, monocell design. A scaled-up, multicell design is currently being developed. The plan is to develop a multicell design on the basis of a single, standard cell with fixed dimensions. This way, the main difference between different applications will be the number of cells. Obviously, because each piece of equipment will be custom-made, factors such as the material of construction, pressure rating, and overall dimensions of the pressure-containing parts will change from application to application. The number of cells required for a particular application will be chosen on the basis of the range of flow rates expected over the life of the installation. The scaled-up, multicell design is also being designed such that the velocity and phase split of the fluids passing through each cell are similar across the different cells. Regardless of the size or type of design, the installation of the inline electrocoalescer must be such that the unit remains liquid-filled during operation. It is also important that the piping downstream of the inline electrocoalescer be designed to minimize the breakup of coalesced water droplets between the unit and the settling region of the downstream separator.

To obtain similar performance between the scaled-up, multicell design and the laboratory-scale, monocell design that was used in this test program, factors such as the working frequency, achievable electrical-field intensity, and electrical-field distribution must be comparable between these two designs. The cells of the inline electrocoalescer technology being discussed are powered by a smart, alternating-current resonance circuit that enables this unit to achieve high coalescence performance, while consuming only a fraction of the power consumed by conventional electrostatic coalescers with similar flow capacity.

In general, it can be concluded that an improved electrocoalescence technology, such as the inline electrocoalescer device that was used in this test program, would benefit the oil and gas industry in that it would enhance oil dehydration of medium and heavy crude oil in subsea separation (shallow and deepwater applications) or in Arctic, remote, or marginal fields while reducing the size and weight of new separation equipment and/or offshore platform structures by enabling the use of more-compact production systems. In older facilities, an advanced inline electrocoalescer device could be used to increase the performance and/or throughput of existing separation equipment (i.e., debottlenecking), reduce demulsifier injection, and/or decrease the energy consumption of the heating system. Such a device would also help meet oil-quality specifications when the emulsion stability is high (e.g., medium or heavy oil, high-pressure applications, cold production, oil from enhanced-oil-recovery processes), such that the amount of energy consumed by the oil-pumping system because of the more-viscous, higher-water-cut WIO emulsions decreases and/or the problems related to corrosion and/or hydrate formation in long transportation pipelines are mitigated. Such an improvement in the performance

of the oil-dehydration system would ultimately allow for higher total liquid-handling capacities for a given separation system design and, therefore, help maximize oil production.

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