Case History of Dehydration-Technology Improvement for HCPF Production in the Daqing Oil Field

Zhihua Wang and **Xinyu Lin,** Northeast Petroleum University; **Tianyu Yu,** University of Western Australia; **Zhiwei Hu,** Daqing Oilfield Company Limited; and **Mengmeng Xu** and **Hongtao Yu,** Northeast Petroleum University

Summary

High-concentration polymer flooding (HCPF) is an enhanced-oil-recovery (EOR) method that has been used since conventional polymer flooding was applied in the main reservoirs of the Daqing oil field because its higher viscoelasticity can improve the oil-displacement efficiency. However, as a result of more produced hydrolyzed polyacrylamide (HPAM), the oil/water mixture is emulsified easily and separated with more difficulty.

In this work, a case history of dehydration technology for HCPF production in the Daqing oil field is reviewed, and a laboratory investigation to assess the emulsification behaviors of HCPF-produced emulsions is conducted. Besides the dehydration-mechanism description of a high-voltage pulsed electrical field, electrostatic-demulsification performance for produced liquid from HCPF production is improved, and the operation parameters are optimized. Recent actual acceptance of the optimization recommendations is presented, and the field-application results are also discussed. The results indicate that dehydration technology for the Daqing oil field has been innovated with the industrialization of the EOR process. Traditional methods of gravity or centrifugal settling are replaced; this upgraded freewater knockout (FWKO) has the functions of adsorption, wetting, collision, and coalescence, and oil pretreating for HCPF production. Because it is dominated by periodic vibration as its main mechanism, the pulsed-direct-current (DC) electrostatic-demulsification technique has some advantages in overcoming the obstacles encountered by regular types of electrical-field dehydration processes at strong emulsification stability. Compared with previous dehydration processes having complex alternating-current (AC)/DC electrical fields, the process with a pulsed-DC electrical field shows a unique advantage in terms of emulsified water-separation efficiency, energy conservation, environmental protection, lower labor intensity, and more-stable operation, and the dehydration performance meets the oil-treating standards.

As the surface-matching technology of EOR, this improvement in dehydration technology is significant for promoting the construction of an HCPF demonstration project and accelerating petroleum development and production efficiently.

Introduction

Polymer flooding is the most-common chemically enhanced process for improving oil-recovery factor in oil fields when compared with waterflooding (Thomas 2008; Wang et al. 2016). Polymer basically increases the viscosity of injection water and reduces the permeability of porous media, then improves the vertical and areal sweep efficiency. A higher viscoelasticity in the water phase will cause a greater residual-resistance coefficient (the coefficient is usually defined as a permanent permeability reduction after the HPAM solution flows through the porous media), a water-phase velocity, and a lower mobility ratio between the water and oil phases (Wu et al. 2012; Zhang et al. 2015). All these allow higher oil recovery from the larger reservoir volume swept and higher oil-displacement efficiency with polymer fluids. Evidence from pilot tests in the Daqing oil field clearly demonstrates the feasibility and superiority of the HCPF method, which is worth pursuing (Yang et al. 2006b; Denney 2009; Zhu et al. 2013). Yang et al. (2006a) also used high-concentration HPAM solution to conduct flooding studies for a Canadian oil field and illustrated the promising effect of HPAM, showing that it can increase the recovery factor to 21% of original oil in place (OOIP), even though, during the process of HCPF, the oil/water mixture is more easily emulsified and is separated with more difficulty because more HPAM is produced with the liquid.

Emulsifications are ubiquitous in oil-production operations, and they are often responsible for oil-productivity impairment and increased production costs associated with transportation and separation, which are more serious in the HCPF process. Emulsions formed without addition of particles or chemicals might be stabilized by polar components in the crude oil such as resins and asphaltenes. Numerous publications have reported that a number of factors could impact the emulsion stability. McLean and Kilpatrick (1997) studied the role of asphaltenes and their interactions with the resins and surrounding crude media in forming interfacial films leading to emulsion stability. Grutters et al. (2007) observed that polar resins, such as naphthenic acids, play an important role in stabilizing the emulsions. Liu et al. (2002) used zeta-potential measurements to study the interaction between bitumen and clay in aqueous solutions. Yang et al. (2007) studied the stability of paraffin/water emulsions, and they argued that the adsorption of particles at interfaces may be controlled by adjusting the electrostatic interaction between particles and the interface without changing hydrophobicity, which is thought to be a main controlling factor of emulsion type and stability. Wang and Alvarado (2008) sampled aqueous phase and oil from a Wyoming reservoir and studied the effect of salinity and pH on emulsion stability. The role of polymer is to further provide stabilization conditions for emulsions, leading to more-complex emulsification behavior. Rigidity of the water/oil interface has been attributed to significant contributions to the suppression of films, hence limiting coalescence. In other words, the rigidity of the surface that is reflected by the rheology is not controlled by interfacial tension in these stable emulsions. At the same time, significant effort has been dedicated to designing protocols to break up harmful emulsions in oil production (Kokal 2005; Nasiri et al. 2013; Liu et al. 2014).

Many dehydration methods, such as gravity sedimentation, centrifugation, vacuum heating, adsorption, and electro-demulsification, are available for emulsified oil in the petroleum industry (Mohammed et al. 1994; Sun et al. 1999; Eow and Ghadiri 2002; Jin and Wojtanowicz 2013). Electro-demulsification technology has been applied extensively to separate oil and water in emulsified oil because it is regarded as the best method in terms of high

This paper (SPE 172768) was accepted for presentation at the SPE Middle East Oil & Gas Show and Conference, Manama, Bahrain, 8–11 March 2015, and revised for publication. Original manuscript received for review 24 March 2015. Revised manuscript received for review 10 July 2016. Paper peer approved 19 August 2016.

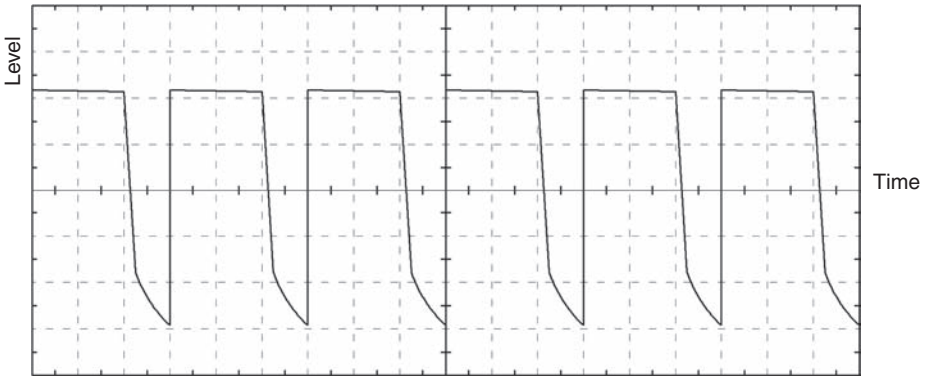


Fig. 1—Square pulsed-wave forms.

efficiency and energy conservation (Chiesa 2008). However, stable deformation of droplets is the premise of highly efficient electrodemulsification, and the deformation is closely associated with the conditions of the electrical field and the interface of the droplet and oil. A high-voltage pulsed electrical field can effectively avoid excessive deformation of the drops, and it is commonly used for the dehydration of crude oil (Lee et al. 2001).

This study focuses on the emulsification behavior and separation technology of HCPF-produced liquid. Some HCPF-produced liquids with different polymer-containing concentrations and water cuts were sampled from the Daqing oil field to investigate the various properties related to sample emulsification stability. As the main task in this work, a case history of dehydration technology for Daqing oilfield HCPF production is reviewed, and the oil/water separation technology is optimized, which has some advantages in overcoming the obstacles encountered in regular types of electrical-field (AC, DC, and AC/DC) dehydration processes at strong emulsification stability. Additionally, this work will present actual acceptance of the optimization recommendations. Furthermore, results and potentialities of the field application are also discussed, and it should be mentioned that the optimized operating parameters reflect the conditions in the Daqing oil field and may not be representative for other fields.

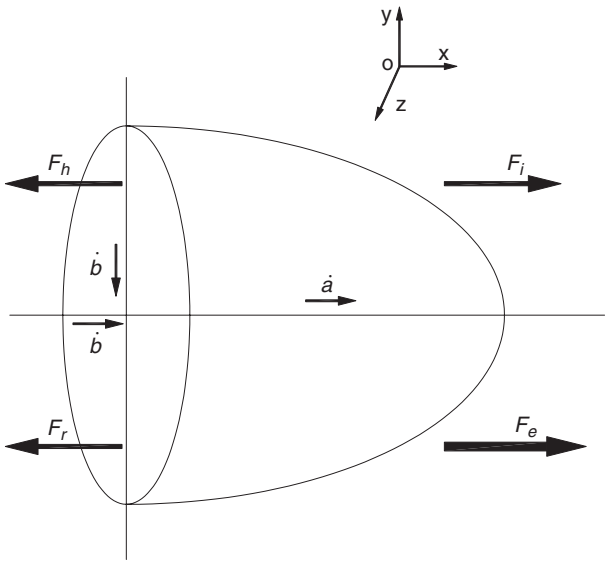


Fig. 2—Illustration of forces acting on the right hemisphere of a prolate spherical drop during its vibration.

Mechanism Description

A water drop is polarized in a high-voltage pulsed electrical field and vibrates periodically; then, the strong electrostatic force among multiple drops appears and results in collision and coalescence of many drops (Eow and Ghadiri 2003). If a single water drop is placed between parallel-plate electrodes and high-voltage pulses (shown in **Fig. 1**) are applied to the electrodes, the drop will be polarized by the high-level pulse, and then stretched and deformed by the dipole force. The drop takes on a nearly prolate spheroid shape during the stretching. When the pulse falls to a low level, the drop recovers its initial spherical shape by the action of an interfacial force. It is then stretched again when the next high-level pulse is released. Thus, the drop undergoes periodic stretching vibration in the pulsed electrical field. The pulsed electrical field can be expressed as

$$E(t)=E\left[\frac{1}{2}+\frac{2}{\pi}\left(\sin\omega t+\frac{1}{3}\sin 3\omega t+\frac{1}{5}\sin 5\omega t+\cdots\right)\right]. \quad \text{.....(1)}$$

According to previous studies and relevant assumptions (Zhang et al. 2007; Gong et al. 2015), four types of force act on a vibrating drop: inertial force (F_i), vibration resistance (F_r), interfacial force of the vibration (F_h), and the excitation force of the electrical field (F_e). Assuming that the major and minor semiaxes of the drop are a and b during a transient vibration, the deformation velocities are denoted by $\dot{a}$ and $\dot{b}$, respectively. The Cartesian coordinate system can be illustrated as shown in **Fig. 2.**

The mechanistic model describes the vibration phenomena.

- Inertial force (Zhang et al. 2007):

$$F_i=\frac{1}{4}\pi\rho R^4\frac{\mathrm{d}^2\chi}{\mathrm{d}t^2}. \quad \text{.....(2)}$$

- Vibration resistance (Gong et al. 2009):

$$F_r=\pi\mu(1+\chi)^{-1/2}R^2K\cdot\frac{\mathrm{d}\chi}{\mathrm{d}t}. \quad \text{.....(3)}$$

- Interfacial force (Zhang et al. 2007):

$$F_h=2\pi\gamma R\frac{\chi}{\left[(1+\chi)^{1/2}+1\right](1+\chi)}. \quad \text{.....(4)}$$

- Excitation force (Gong and Peng 2013):

$$F_e=\pi\varepsilon_0\varepsilon_2R^2E^2(t)\frac{\lambda^{-2/3}}{1-\lambda^2}\left(1+\frac{2\ln\lambda}{\lambda^{-2}-1}\right)\frac{1}{N(\lambda)}. \quad \text{.....(5)}$$

Polymer-Containing Concentration (mg/L)	Water Cut (%)	Oil Property										Temperature (°C)	
		Viscosity (mPa·s)			Density (g/cm^3)			Freezing Point (°C)	Wax Content (%)	Asphaltene Content (%)	Homogenization	Bottle Test Time	Phase Inversion Test	Bottle Test
		25°C	35°C	65°C	25°C	35°C	65°C							
315 503 708 920 1053	40 ≈ 80*	558.9	61.2	12.5	0.8522	0.8450	0.8242	26.5	24.6	9.10	6,000 rev/min, 35°C, 2 minutes	30 min.; 1, 2, 3, 5, 8, and 10 hours	30; 35	40

*Water-cut percentage range includes 40, 50, 55, 60, 65, 70, 75, and 80%.

Table 1—Experimental matrix.

- Kinetic model of the vibration can be written as

$$F_e - F_i = F_r + F_h \cdot \quad \text{.....(6)}$$

By combining Eqs. 2 through 6, we obtain the equation of the vibration of a single drop of water subjected to a pulsed electric field:

$$\frac{d^2\chi}{dt^2} + A\phi(\chi)\frac{d\chi}{dt} + Bf(\chi) - GE^2(t)e(\chi) = 0 \cdot \quad \text{.....(7)}$$

The low-Reynolds-number fluid theory can be used to describe the vibration behavior because the diameters of the dispersed water drops are small and the vibration velocities are relatively low in a high-voltage pulsed electrical field without electro-dispersion created. Unlike the interfacial force and the excitation force, the inertial force and the vibration resistance of the drops mentioned in the preceding can be ignored because of the small diameter, low vibration velocity, and the surrounding oil that is in a low-viscosity range. The interfacial force and the excitation force, which are in competition with each other potentially, are the strongest and most-important forces of the drops in a pulsed electrical field. The interfacial force overcomes the periodically changed excitation force as much as possible. Two competing processes of coalescence and noncoalescence are distinguished as a result of excitation force and interfacial force, respectively, which determines whether dispersed water drops separate or not.

Experimental Material and Procedure

To explain the emulsification behavior and draw a comparison, the conventional method of preparing simulated emulsion was replaced by sampling actual produced liquid (mixture of oil, water, and chemicals of wells), which was taken from 20 production wells with different performances in the same HCPF area of the Daqing oil field. Water cuts and polymer-containing concentrations were analyzed by means of the centrifuging/distillation combination method and the starch/cadmium iodide method, respectively (Figueroa-Johnson et al. 2007; Taylor et al. 1998). Phase-inversion measurement experiments were conducted in accordance with *ASTM D4440-15* (2015) and *ISO 6721-10* (2015). On the basis of the evaluation of electronegativity, oil/water interfacial tension, and oil-droplet-size distribution, emulsion stability was assessed by simple bottle tests, and it was also measured by the quantification of basic sediment and water (BS&W). The data from a series of tests that covered a wide range of polymer-containing concentrations and water cuts for different produced-liquid samples are shown in **Table 1.**

The general purpose of the experimental study was to seek and verify safe, efficient, and stable oil/water-separation technologies; relate the chemical concentrations and destabilization of emulsions; and optimize the operation parameters for the HCPF-produced-liquid dehydration. A dehydration experimental setup with pulse power supply was established, as illustrated in **Fig. 3.** It is composed of a high-frequency pulse power supply, high-frequency pulse electrode plate, high-frequency pulse electric dehydration tank, heating system, pressure-control unit, and an operation con-

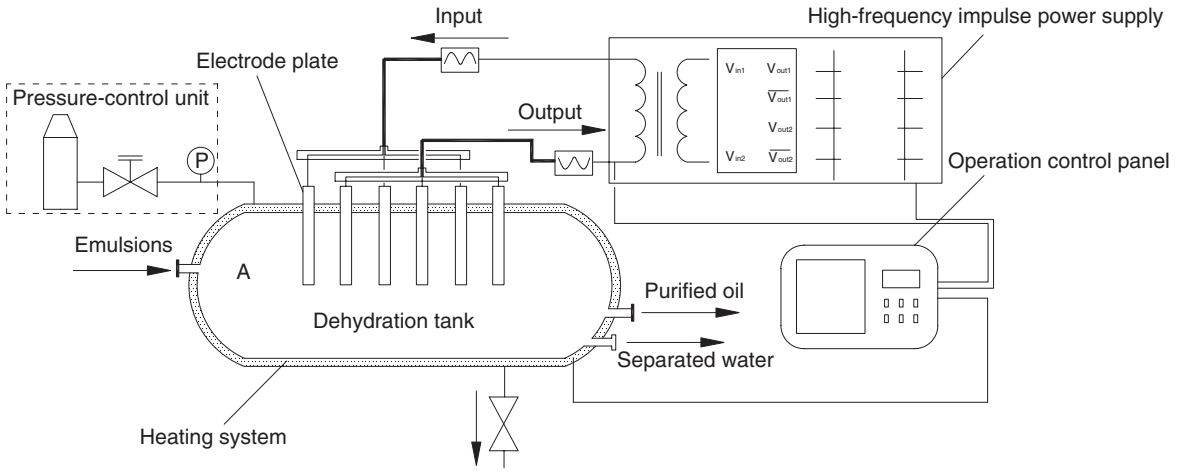


Fig. 3—Schematic of the dehydration experimental setup with pulse power supply.

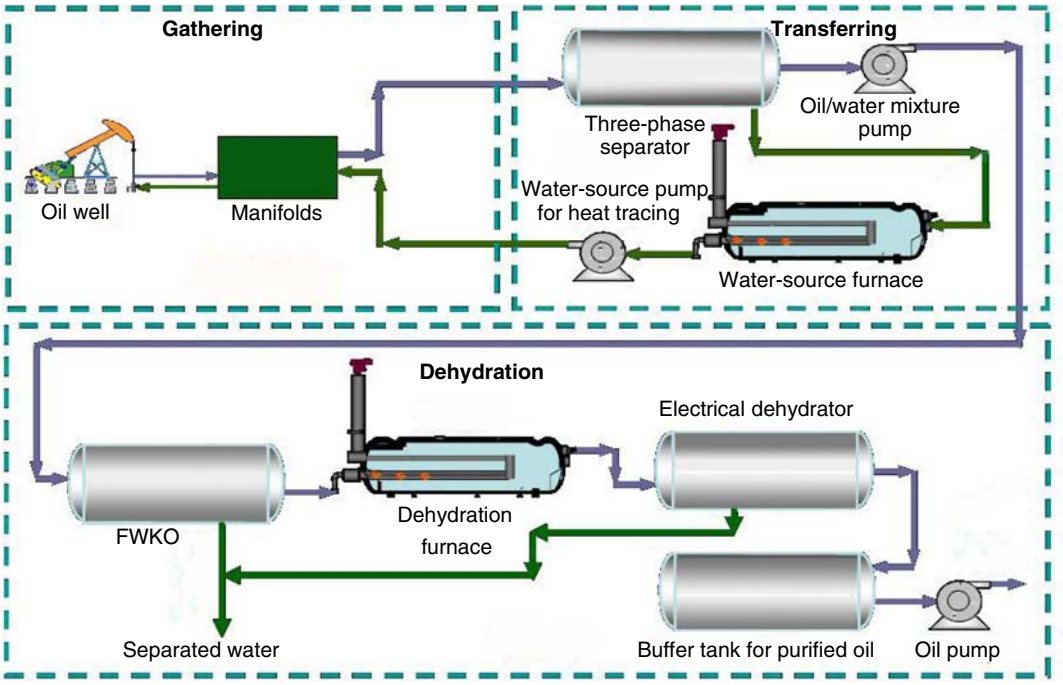


Fig. 4—Schematic of nonoptimized general surface production process for oil treating in the field.

trol panel. In the experiment, the emulsion, which has been separated out of free water by means of sedimentation with demulsifier, travels continuously into the high-frequency pulse electrical-dehydration tank. The operation control panel is started at a set temperature condition for heating or maintaining desired temperature of the emulsion, and the pressure in the tank is adjusted by the pressure-control unit. At the same time, the desired pulse frequency and electrical-field strength are set, and the high-frequency pulse power supply is started to form a high-voltage electrical field for the dehydration experiment. The dehydration currents with different time intervals are recorded during the experiment. The purified oil and separated water are drained out after a suitable separation time. The water content in purified oil and oil content in separated water are determined by the distillation method and spectrophotometry, respectively. In addition, an electrical-field dehydration-performance analyzer with AC/DC power supply is used to conduct a comparison experiment.

Field Tests

To review the case history of oil treating in the Daqing oil field, a typical HCPF industrial pilot area was surveyed, and the general surface-production process is shown in **Fig. 4.** Information on how to deal with the phase separation in the development stage of water and chemical flooding in this area is presented. Because the optimization in the case study is the pulse power supply, the main purposes of the field tests are still to practice optimized dehydration technology for HCPF production (as shown in **Fig. 5**), present actual acceptance of the optimization recommendations, and further demonstrate the influence of produced liquid with strong emulsion stability on dehydration efficiency. The effects of field application are discussed as well.

Results and Discussion

Emulsification Behavior of HCPF-Produced Emulsions. As shown in **Fig. 6,** the measured zeta potential for oil droplets is approximately –20 to –35 mV, and the absolute value is highest at water cuts ranging from approximately 55 to 65%, which indicates that the HCPF-produced liquid would show an obvious emulsification tendency. This can be attributed to the particles not having enough energy to overcome the barriers created by the double-electrode-layer repulsive force, and then coalescing when the absolute value of the zeta potential on particle surfaces is more than 25 mV. This undoubtedly proves that the zeta potential, even at this level, is a significant contributor to the emulsion stability. Although the observed electronegativity variation is relatively small, its absolute value increased, with the polymer-containing concentration increasing because of the thickening of the HPAM adsorption layer, which relies on the function of hydrogen bonds on

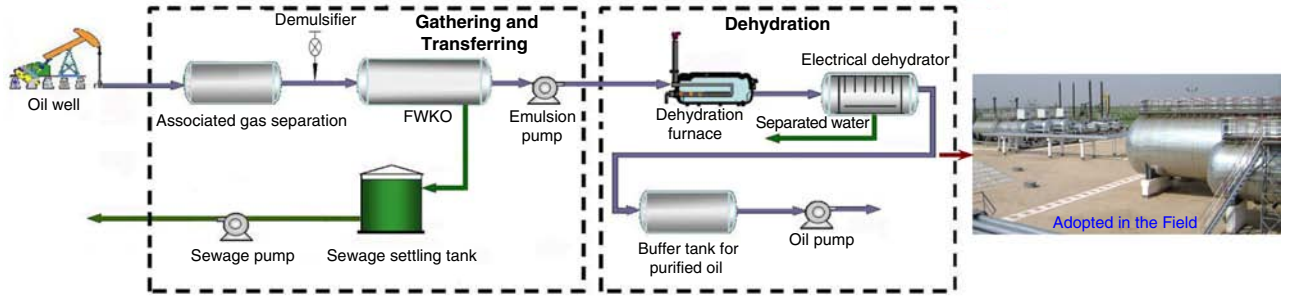


Fig. 5—Schematic of the optimized separation process of HCPF-produced liquid.

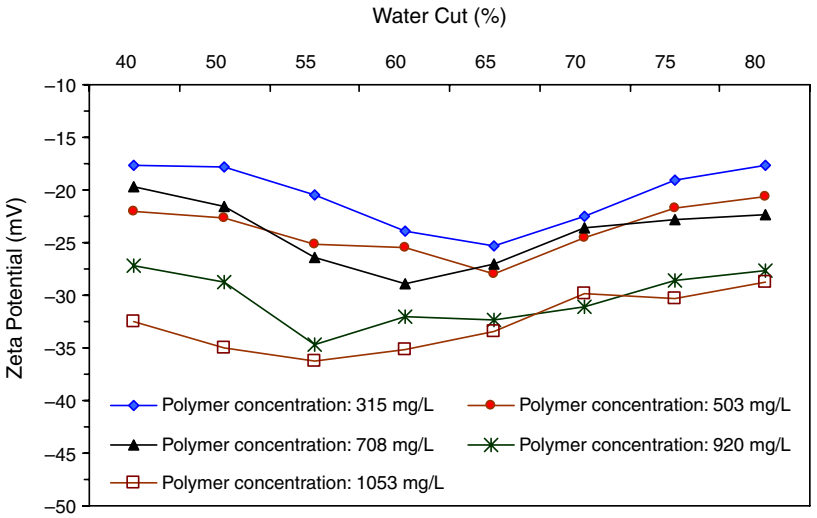


Fig. 6—Zeta-potential measurements of HCPF-produced emulsions.

oil droplets. As mentioned previously, the actual produced emulsions were sampled from production wells with different performances in the same HCPF area of the Daqing oil field; that is to say, the water source used for each polymer-containing concentration played an equivalent role, and is thereby most likely caused by a critical micellar concentration for the HPAM, which could contribute to this effect. The equilibrium and dynamic interfacial tensions of HCPF-produced emulsions with different oil/water ratios and polymer-containing concentrations are both approximately 20 to 30 mN/m. This indicates that there are not many surface-active substances adsorbed on the surface of oil droplets in the produced liquid, and the interfacial activity is not enhanced by the polymer-containing concentration increase. This is also in agreement with the existing knowledge that increasing interfacial tension would not be expected to stabilize an emulsion. However, an obvious tight emulsion layer was observed in bottle tests, as shown in **Fig. 7.** This is mainly attributed to the formation of a viscous and elastic film caused by a large amount of HPAM in produced liquids, and this hypostable aggregate of oil droplets would result directly in an increase of the emulsification stability. In addition, emulsification tendency is also related to the viscosity of the oil, but it can be seen from Table 1 that the crude oil in the target oil field is not heavy oil, so the current treating difficulties and challenges mainly belong to the emulsification behavior caused by chemical flooding.

As shown in **Fig. 8,** the change of BS&W specification is related to test time and the original water cut of the emulsions. The highest separation degree of BS&W is less than 75% of the original water content of the emulsion. Furthermore, combined with the aforementioned quantitative analysis of produced-emulsion electronegativity, which is related to the negative-charge density, the change of separation degree in various HCPF-produced emulsions reveals that the excessive negative-charge density on the oil-droplet surfaces of HCPF-produced emulsions is relatively high and the electrostatic repulsive force between oil droplets is comparatively strong. However, it is observed in tests that the bulk of emulsion becomes obviously larger with the original water cut decreasing, and there appears to be a nonlinear relationship between the dehydration efficiency and dehydration time. Therefore, we can conclude that extending dehydration time to improve the demulsification effect of HCPF-produced emulsions is not an advisable method.

For the sake of completeness of this case study, it should be noted that addressing the separation of free water from HCPF-produced liquid is also very necessary. Besides characterizing the tightness of emulsions, the produced-emulsified-oil-droplet size can directly affect the oil/water separation efficiency in the stage of free-water removal, especially the water quality of separated water. As shown in **Fig. 9,** the emulsified-oil-droplet-size distribution of HCPF-produced liquid obeys the normal principle: The average size of oil droplets is approximately 30 μm, and 80% of these

Fig. 7—HCPF produced emulsions after centrifuging during one group of bottle tests. (The water cuts are 80, 65, 55 and 40%, in order from left to right, and the polymer-containing concentration is 920 mg/L.)

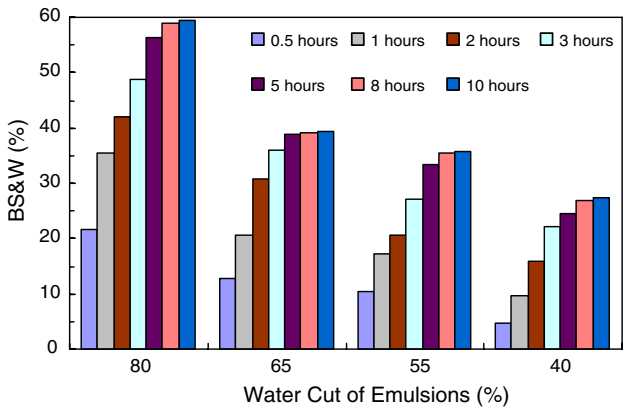


Fig. 8—Change of BS&W in various HCPF produced emulsions in bottle tests. (Polymer-containing concentration is 920 mg/L.)

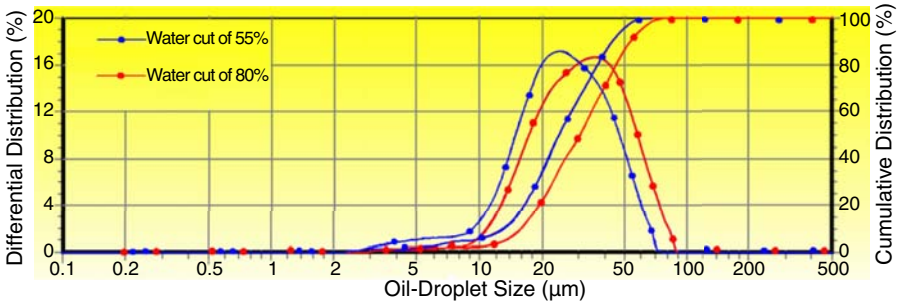


Fig. 9—Emulsified oil-droplet size distribution of the HCPF-produced liquid. (Polymer-containing concentration is 920 mg/L.)

are approximately 10 to 50 μm, which reflects that the tendency of oil droplets to coalesce into larger droplets to float up is weak and difficult, and the removal efficiency of free water from produced liquid could fluctuate. Water quality of separated water would be deteriorated, which will bring more challenges to the subsequent sewage disposal.

Generally, the peaking point of the curve between water cut and apparent viscosity of emulsion is defined as the phase-inversion point (Plasencia et al. 2013). From **Fig. 10,** we can see that the emulsification effect of low-water-cut emulsion is more obvious as the polymer-containing concentration increases, which leads to the phase-inversion point decreasing in different degrees. For example, the phase-inversion points of five emulsions with polymer-containing concentrations of 315, 503, 708, 920, and 1053 mg/L are 65, 65, 60, 55, and 50%, respectively. Typically, the micromorphologies of the emulsions are as shown in **Fig. 11.** We can clearly observe the superior dispersion stabilities of the oil and water phases in HCPF-produced liquid. The oil and water droplets keep separate from each other, and the emulsified particle size is directly influenced by the polymer-containing concentration. The higher the polymer-containing concentration is, the stronger the independence will become and the smaller the size of the emulsified particle will be. Therefore, the coalescence and phase separation of the particles will be more difficult.

The emulsification behavior of HCPF-produced liquid is complicated and the water cut, polymer, suffered shearing action, and some mineral particles (such as clay) may be the dominating influential factors. The water cut can transform the emulsification type of the produced liquid. The polymer can adsorb on the oil/water interface to increase the shearing viscosity, strengthen the electronegativity, and form a viscous and elastic film around the dispersion phase. These actions make the coalescence of oil and water

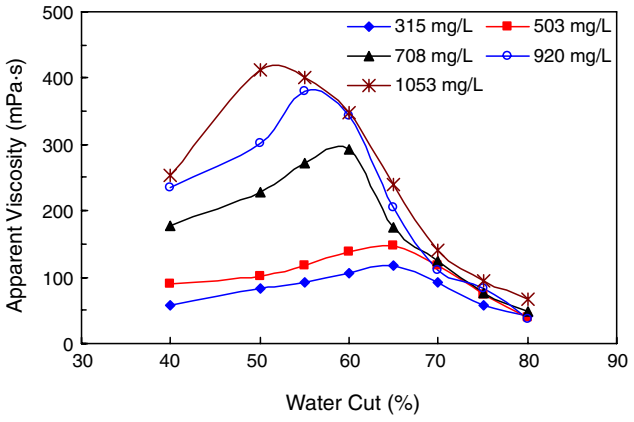
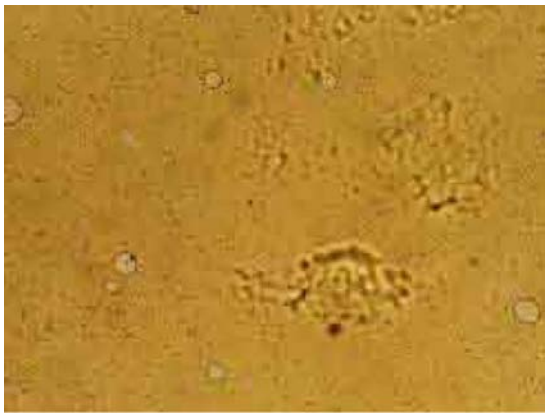


Fig. 10—The phase-inversion characteristics of HCPF-produced emulsions with different polymer-containing concentrations. (The shearing rate is 50 s^{-1}, and the temperature is 35°C.)

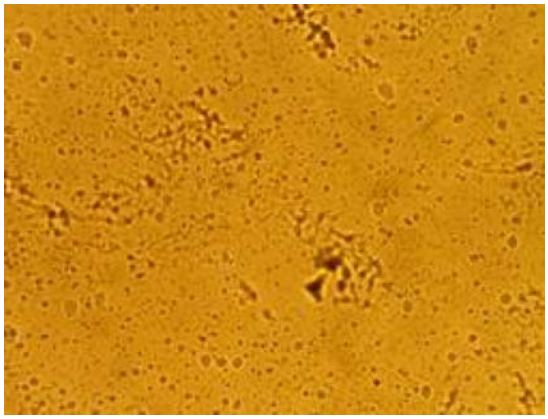
droplets in the produced liquid difficult. Furthermore, the mineral and impurity particles in the produced liquid can also adsorb on the oil/water interface and cooperate with the polymer to form a screen, which can restrict the coalescence of oil and water droplets, further strengthening the emulsification stability.

Case-History Information on Oil Treating in the Pilot Area. In facing the challenge of reducing investment and energy consumption in the oil industry, optimization and simplification of the surface process have been explored and practiced in the Daqing oil field. With water cut of wells increasing in HCPF production, the improvement of produced-liquid rheological properties provides the advantage of no-heat-tracing gathering and transferring. Thus, the water-source furnace, pipeline, and pump used for heat tracing in the surface-production process shown in Fig. 4 are eliminated, and the separated water from the three-phase separator is directly discharged into the sedimentation unit of the downstream sewage-disposal station. The traditional method of gravity-settling separation is controlled by Stoke's law, and the oil is allowed to rise upward because of the density differences with produced water. Additionally, the centrifugal-settling separation mechanism is also governed by Stoke's law, and is seen in the difference between centrifugal force generated by the spinning fluids and the drag force on the moving droplets (Ogunsina and Wiggins 2005). To ensure the quality and efficiency of oil treating, it is essential to improve the removal efficiency of free water to the maximum degree; however, the difficulty of oil/water separation increases because of the existence of viscous HPAM in produced liquid in the polymer-flooding EOR process, which can lead to the decrease of the floating velocity of emulsified oil droplets. Therefore, the regular gravity or centrifugal-settling technology has been replaced gradually, and FWKO is developed instead in the HCPF pilot area. As shown in **Fig. 12,** one of the major factors affecting free-water-removal efficiency is the coalescing element. Oil droplets will float up to the surface, which could result in adsorption, wetting, collision, and coalescence behaviors, and oil/water separation will be achieved under gravity and flow conditions. A steel rectifier plate makes liquid flow toward uniformity and plays a role in buffering and releasing energy. The coalescing element is made of corrugated-plate packing, and the staggered-setting method promotes the collision and coalescence of dispersed particles. After experiencing the development stage from conventional ceramics to metal products, packing is now replaced by polypropylene in the HCPF pilot area. Waste heat of produced liquid is used for oil treating in this upgraded equipment, and treating time is determined to be 15 to 20 minutes from years of operating practice in the HCPF pilot area. Under the conditions that original historical water cut of wells in production is in the range of approximately 45 to 85%, the water cut in oil is lower than 20% and the oil concentration in water is less than 3000 mg/L after treating.

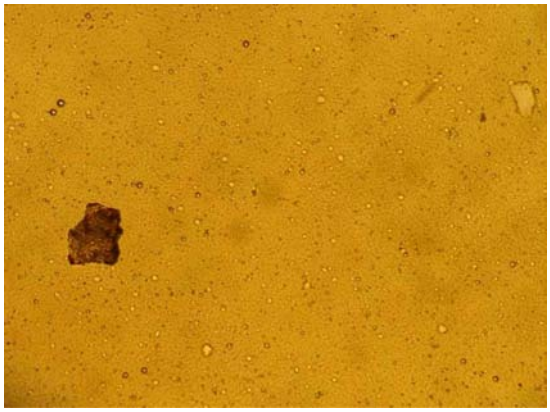
The destabilization of emulsified water in oil treating is crucial, and the electrostatic-demulsification technique has been used to enhance the separation of water in crude-oil emulsions in the Daqing



(a) Water cut is 65% and polymer-containing concentration is 315 mg/L.



(b) Water cut is 65% and polymer-containing concentration is 708 mg/L.



(c) Water cut is 80% and polymer-containing concentration is 708 mg/L.

(d) Water cut is 55% and polymer-containing concentration is 1053 mg/L.

Fig. 11—Micro-morphologies of HCPF-produced emulsions with different components.

oil field. Admittedly, the electrical parameters, such as type of electrical field, frequency, and electrical field strength, have been optimized and practiced constantly. The DC electrical field has been less common compared with the AC electrical field, and the major electrical-field type is still the AC electrical field with main frequency (50 Hz). Together with the AC electrical field, a complex AC/DC electrical field has been used extensively since chemical-flooding industrialization was achieved in the Daqing oil field. However, besides affecting the electrical dehydration efficiency, the complicated physical and chemical properties of the emulsions in HCPF production are also threats to the operating stability of the dehydrator, such as serious deposition on the electrode plate, frequent current leakage, and deteriorating separated-water quality. Therefore, the electrostatic-demulsification

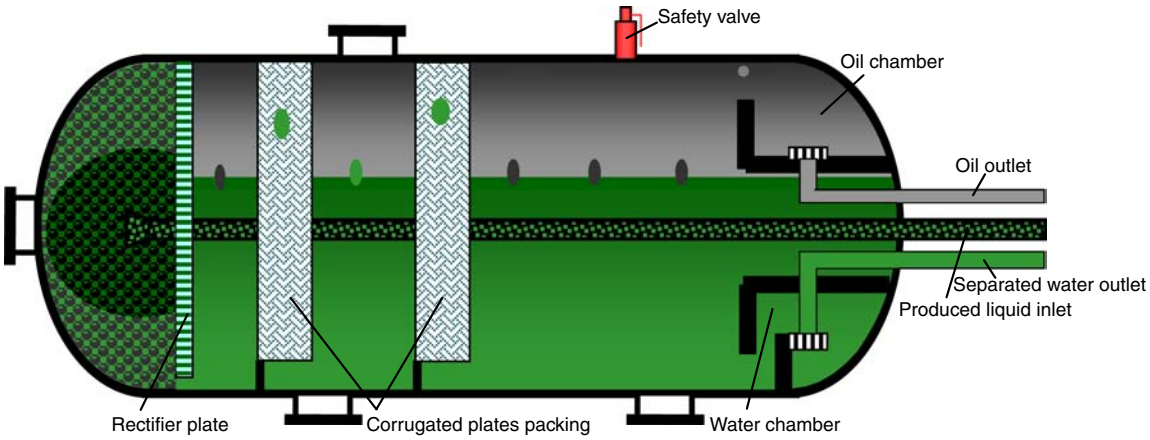


Fig. 12—Options for equipment upgrading to improve the separation performance of free water in late HCPF production.

Electrical Parameters	Demulsifier (mg/L)	Dehydration Time (minutes)	Water Content in Purified Oil (%)	Oil Content in the Separated Water (mg/L)	Oil/Water Interface
Blank	20	120	3.75	1546	Irregular with tight emulsion layer
Blank	30	120	3.06	1503	Irregular with tight emulsion layer
AC/DC Power Supply					
E = 0.258 kV·mm^{-1}	20	90	1.18	1217	Irregular with current leakage
	30	90	1.02	1140	Irregular with current leakage
	50	90	0.71	1108	Irregular
Pulsed DC Power Supply					
E = 0.258 kV·mm^{-1};	15	70	0.46	1120	Irregular
n = 0.5; f = 0.98kHz	20	70	0.35	1006	Relatively clear
E = 0.258 kV·mm^{-1};	15	65	0.25	954	Relatively clear
n = 0.5; f = 2.03 kHz	20	65	0.19	893	Clean and clear
E = 0.258 kV·mm^{-1};	15	65	0.15	708	Clean and clear
n = 0.5; f = 2.95kHz	20	65	0.14	646	Clean and clear
E = 0.258 kV·mm^{-1};	15	60	0.21	673	Clean and clear
n = 0.5; f = 4.10kHz	20	60	0.19	659	Clean and clear
E = 0.258 kV·mm^{-1};	15	65	0.24	626	Clean and clear
n = 0.5; f = 5.07kHz	20	65	0.25	610	Clean and clear

Table 2—Result of chemical and electrical-field method on HCPF-produced-emulsions dehydration (50°C).

technique is being further optimized in the pilot area, and as the focus of this paper, the pulsed-DC electrical-field dehydration draws much attention.

Dehydration Adaptability of HCPF-Produced Emulsions in Pulsed-DC Electrical Field. After the removal of free water, different dehydration methods of HCPF-produced emulsions, containing approximately 20% emulsified water and approximately 600 mg/L of polymer-containing concentration, are investigated in the labratory. Meanwhile, dehydration time in laboratory testing was maximized to 60 to 90 minutes in experiments to reliably reflect the dehydration efficiency, especially the operation stability of the electrical field. As in the preceding discussion of emulsification behavior, the complicated physical and chemical properties of the emulsions in HCPF production would make the electrostatic field unstable. As shown in **Table 2,** at the temperature of 50°C, application of the combined electro-chemical method, in contrast to a single chemical method, on HCPF-produced emulsions can improve the separation effect. However, there are still some problems when dehydration occurs in an AC/DC electrical field, such as frequent current leakage, unstable operation, and especially high oil content in separated water. When the emulsions are exposed to a pulsed-DC electrical field, the electrical-field strength and duty ratio are 0.258 kV·mm^{-1} and 0.5, respectively. At these conditions, the separation effect is much better and the problem of unstable operation no longer appears when pulse frequency is adjusted; but, sometimes, the water content in purified oil after dehydration fluctuates. This can be attributed to the electro-dispersion under some electrical parameters. As Sun et al. (2012) observed, the interaction of pulsed electrical-field parameters on polarization deformation of water droplets is complicated and not to be ignored. The deformation and coalescence degree of water droplets are related to the pulse frequency (f), electrical-field strength (E), and duty ratio (n).

The curves in **Fig. 13** depict the condition at Point A in Fig. 3. Compared with the AC/DC power-supply dehydration, the time length of high dehydration current could be shortened greatly when a pulsed-DC electrical field is used. The results reveal that high-frequency pulsed-DC power supply can build a high-voltage electrical field without electro-dispersion by square-wave pulse and the oil/water-emulsion film in the HCPF-produced emulsions with strong

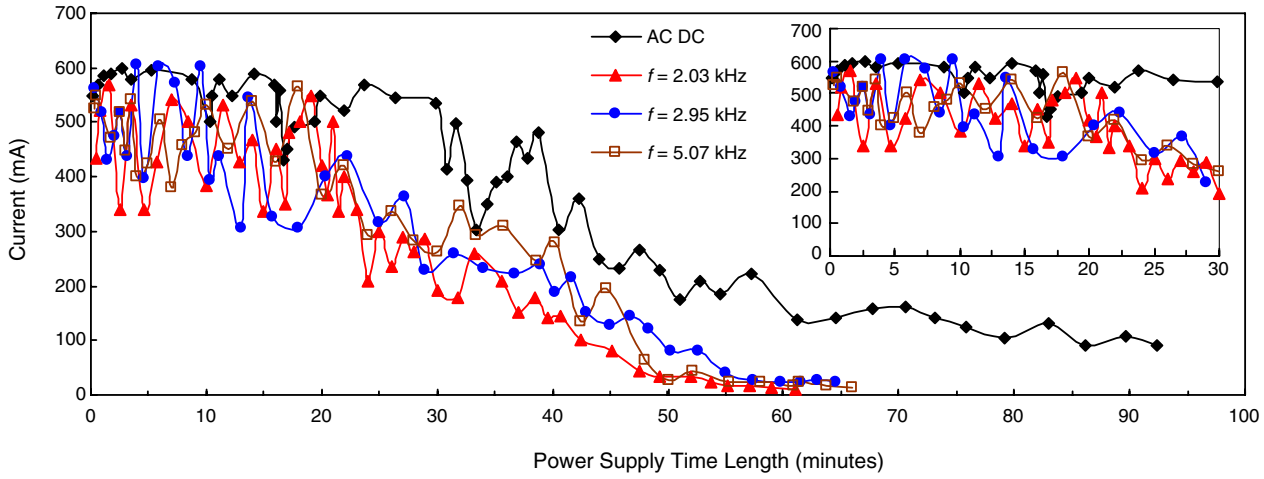


Fig. 13—Dehydration current curves of HCPF-produced emulsions.

conductivity can be broken by the impact of instantaneous high-power electrical pulse. Then, the emulsified water droplets in the emulsion can absorb enough energy, the vibration amplitude and coalescence probability are increased, and the oil/water interface is remarkably changed over to a clean and clear state. To avoid leakage from the electric dehydrator, the amount of demulsifier is reduced and the HCPF-produced emulsions are separated effectively. The results indicate that stable-droplets deformation is the premise of highly efficient electro-demulsification, and the frequency of the electrical field can directly affect the vibration of the emulsified drop and the dehydration efficiency. Overall, dehydration adaptability of HCPF-produced emulsions in a pulsed-DC electrical field is positive.

Field Application Effects of the Optimized Dehydration Technology. Because this is a case study, there is no need to add tables and graphs to show the application results, and the field data, including treating volume, specifications of dehydrators, treating temperature, electrical-field parameters, treating time, demulsifier consumption, dehydration current, water cut of purified oil after treatment, oil concentration in water, and operation stability, are all contained in the following text description. This optimized dehydration technology was recommended to an oil-treating station in the HCPF pilot area in the Daqing oil field. Treating volume of produced emulsions after free-water removal in this station is approximately 1500 m^3/d, three electric dehydrators are in parallel operation, the specifications are all Φ4000×16 000 mm, and the distance between electrodes is 100 mm, including one electric dehydrator with complex AC/DC electrical field (50 Hz). As compared with the optimized recommendation shown in Fig. 5, the other two electric dehydrators are equipped with a high pulsed-DC electrical field instead, and high-voltage output is 0 to 40 kV, pulse frequency is 1 to 5 kHz, and duty ratio is 0.4 to 0.5. Produced emulsions are exposed to the electrical field for approximately 20 minutes at approximately 55 to 60°C. Several months of operation practice in HCPF production indicates that the dehydration current in a high pulsed-DC electrical field is lower than that in a complex AC/DC electrical field for 5 to 10 A, and current leakage is avoided, impact resistance capability of dehydration facilities is improved, and the stable operation of the dehydration process is realized. Compared with previous dehydration processes with a complex AC/DC electrical field, the demulsifier consumption is reduced from 30 mg/L to approximately 15 to 20 mg/L with this optimized technology, and water cut of purified oil is continuously lower than 0.15% in HCPF production. Furthermore, the oil concentration in water is less than 1000 mg/L with slight fluctuations, especially when electrical-field strength is 3.00 kV·cm^{-1} and pulse frequency is approximately 3 kHz. This illustrates that the use of pulsed-DC electrical fields with these parameters is clearly advantageous, and provides the potential to obtain a further stable operation in comparison with any other electrical parameters without concern of unfavorable formation of secondary droplets. In addition, the dredging period of this optimized dehydrator is doubled, labor intensity decreases significantly, and facilities pollution and health and environmental threats are reduced compared with the previous dehydration process. The operation practice reveals that this dehydration-technology optimization is worth pursuing in HCPF production.

Conclusions

This paper presents dehydration-technology optimization for HCPF production in the Daqing oil field. In view of the fact that the treatment of continuous emulsion of water and oil in oilfield production is an integrated process, the emulsification stability of HCPF-produced liquid with different properties, the adaptability of oil continuous emulsion in pulsed-DC electrical field, and the separation of free water are involved in this case study. The following conclusions can be drawn from the emulsification-behavior assessment, process simulation, mechanism analysis, and field application conducted in this study:

- Gravity settling and electrostatic demulsification are the widely used dehydration technologies in the Daqing oil field. The emulsification behavior of HCPF-produced emulsions is complicated and dominated by water cut, polymer-containing concentration, effect of shearing action, and some mineral particles. The tight emulsion layer is easy to form, and the capability of phase separation with this conventional dehydration technology is limited.
- After the effective removal of free water in upgraded equipment for HCPF production, the destabilization of HCPF-produced emulsions in a pulsed-DC electrical field is stable and highly efficient, and parameters through simulation experiments, which are optimized and recommended, are as follows: maximum electrical field strength is approximately 0.25 to 0.30 kV·mm^{-1}, pulse frequency is 3 kHz, duty ratio is approximately 0.5, dehydration temperature is approximately 50 to 60°C, and demulsifier consumption is approximately 15 to 20 mg/L.
- Compared with the previous dehydration process with a complex AC/DC electrical field, the process with a pulsed-DC electrical field shows a unique advantage in high dehydration efficiency of emulsified water, energy conservation, environmental protection, lower labor intensity, and especially the enhancement of operation stability. The water content in purified oil after treating is less than 0.15%, and oil content in separated water is less than 1000 mg/L, making the oil/water interface clean and clear in this process. It demonstrates that this dehydration-technology optimization is worth pursuing and has a potential for treating emulsions with complicated properties.

Nomenclature

a = major semiaxis of water-drop deformation, m
$\dot{a}$ = deformation velocity along major semiaxis, m/s
A = constant of resistance
b = minor semiaxis of water-drop deformation, m
$\dot{b}$ = deformation velocity along minor semiaxis, m/s
B = constant of interfacial force
$e(\chi)$ = expression of excitation term
E = amplitude of pulsed electric field, kV/m
$E(t)$ = expression of pulsed electrical field
f = frequency
$f(\chi)$ = expression of interfacial force
F_e = excitation force, N
F_h = interfacial force, N
F_i = inertial force, N
F_r = vibration resistance, N
G = constant of excitation force, N
K = resistance coefficient
n = duty ratio
N = polarization deformation of water drop;

$$N(\lambda) = -\frac{1}{\lambda^2} - 1\left\{1 - \left(\frac{\lambda^2}{\lambda^2 - 1}\right)^{1/2} \ln[\lambda + (\lambda^2 - 1)^{1/2}]\right\}$$

R = radius of water drop, mm
t = time, seconds
γ = interfacial tension, mN/m
ε_0 = permittivity of vacuum
ε_2 = relative permittivity of oil
λ = drawing ratio of water drop, a/b
μ = viscosity, Pa·s
ρ = density, kg/m^3
$\varphi(\chi)$ = expression of resistance
Φ = diameter, mm
χ = deformation ratio of water drop, $(a - R)/R$
ω = angular frequency of pulsed electric field, rad/s

Acknowledgments

This work was financially supported by the National Natural Science Funds for Young Scholars of China (Grant No. 51404068),

the University Nursing Program for Young Scholars with Creative Talents in Heilongjiang Province of China (Grant No. UNPYSCT-2015074), and the State Key Program of National Natural Science Foundation of China (Grant No. 51534004). This support is gratefully acknowledged.

References

ASTM D4440-15, Standard Test Method for Plastics: Dynamic Mechanical Properties Melt Rheology. 2015. West Conshohocken, Pennsylvania: ASTM International. http://dx.doi.org/10.1520/D4440-15.

Chiesa, M. 2008. Toward Compact Separation of Crude Oil. *World Oil* **229** (4): 38.

Denney, D. 2009. Effect of Elasticity on Displacement Efficiency: High-Concentration-Polymer Flooding. *J Pet Technol* **61** (1): 50–51. SPE-0109-0050-JPT. http://dx.doi.org/10.2118/0109-0050-JPT.

Eow, J. S. and Ghadiri, M. 2002. Electrostatic Enhancement of Coalescence of Water Droplets in Oil: A Review of the Technology. *Chemical Engineering Journal* **85** (2–3): 357–368. http://dx.doi.org/10.1016/S1385-8947(01)00250-9.

Eow, J. S. and Ghadiri, M. 2003. Motion, Deformation and Break-up of Aqueous Drops in Oils Under High Electric Field Strengths. *Chemical Engineering and Processing: Process Intensification* **42** (4): 259–272. http://dx.doi.org/10.1016/S0255-2701(02)00036-3.

Figueroa-Johnson, M. A., Tindall, J. A., and Friedel, M. 2007. A Comparison of $^{18}O\delta$ Composition of Water Extracted From Suction Lysimeters, Centrifugation, and Azeotropic Distillation. *Water, Air, and Soil Pollution* **184** (1): 63–75. http://dx.doi.org/10.1007/s11270-007-9399-8.

Gong, H. F. and Peng, Y. 2013. Effect of Oil Viscidity on Optimal Demulsion Frequency in Pulse Electric Field. *Acta Petrolei Sinica (Petroleum Processing Section)* **29** (1): 168–173. http://www.syxbsyjg.com/EN/10.3969/j.issn.1001-8719.2013.01.027.

Gong, H. F., Peng, Y., Shang, H .H. et al. 2015. Non-Linear Vibration of A Water Drop Subjected to High-Voltage Pulsed Electric Field in Oil: Estimation of Stretching Deformation and Resonance Frequency. *Chemical Engineering Science* **128:** 21–27. http://dx.doi.org/10.1016/j.ces.2015.01.063.

Gong, H. F., Tu, Y. Q., Shi, Y. G. et al. 2009. Calculation of Force Acting on Flexing and Deforming Latex Particle in Oil. *Journal of Chemical Industry and Engineering Society of China* **60** (9): 2191–2196.

Grutters, M., van Dijk, M., Dubey, S. et al. 2007. Asphaltene Induced W/O Emusilon: False or True? *Journal of Dispersion Science and Technology* **28** (3): 357–360. http://dx.doi.org/10.1080/01932690601107658.

ISO 6721-10, Plastics—Determination of Dynamic Mechanical Properties, Part 10: Complex Shear Viscosity Using a Parallel-Plate Oscillatory Rheometer. 2015. Geneva, Switzerland: Internation Organization for Standardization.

Jin, L. and Wojtanowicz, A. K. 2013. Experimental and Theoretical Study of Counter-Current Oil–Water Separationin in Wells With In-Situ Water Injection. *Journal of Petroleum Science and Engineering* **109:** 250–259. http://dx.doi.org/10.1016/j.petrol.2013.08.037.

Kokal, S. L. 2005. Crude-Oil Emulsions: A State-of-the-Art Review. *SPE Prod & Fac* **20** (1): 5–13. SPE-77497-PA. http://dx.doi.org/10.2118/77497-PA.

Lee, C. -M., Sams, G. W., and Wagner, J. P. 2001. Power Consumption Measurements for AC and Pulsed DC for Electrostatic Coalescence of Water-in-Oil Emulsions. *Journal of Electrostatics* **53** (1): 1–24. http://dx.doi.org/10.1016/S0304-3886(01)00029-8.

Liu, J., Zhou, Z., Xu, Z. et al. 2002. Bitumen-Clay Interactions in Aqueous Media Studied by Zeta Potential Distribution Measurement. *J Colloid Interface Sci* **252** (2): 409–418. http://dx.doi.org/10.1006/jcis.2002.8471.

Liu, Y., Wang, Z. H., Li, X. L. et al. 2014. ASP Flooding Produced Water Management: Evaluation, Disposal and Reuse. Presented at the SPE Middle East Health, Safety, Environment and Sustainable Development Conference and Exhibition, Doha, Qatar, 22–24 September. SPE-170396-MS. http://dx.doi.org/10.2118/170396-MS.

McLean, J. D. and Kilpatrick, P. K. 1997. Effects of Asphaltene Solvency on Stability of Water-in-Crude-Oil Emulsions. *Journal of Colloid and Interfaces Science* **189** (2): 242–253. http://dx.doi.org/10.1016/jcis.1997.4807.

Mohammed, R. A., Bailey, A. I., Luckham, P. F. et al. 1994. Dewatering of Crude Oil Emulsions 3. Emulsion Resolution by Chemical Means. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **83** (3): 261–271. http://dx.doi.org/10.1016/0927-7757(93)02706-K.

Nasiri, H. G., Mosavian, M. T. H., and Kadkhodaee, R. 2013. Demulsification of Gas Oil/Water Emulsion via High-Intensity Ultrasonic Standing Wave. *Journal of Dispersion Science and Technology* **34** (4): 483–489. http://dx.doi.org/10.1080/01932691.2012.681990.

Ogunsina, O. O. and Wiggins, M. L. 2005. A Review of Downhole Separation Technology. Presented at the SPE Production Operations Symposium, Oklahoma City, Oklahoma, USA, 16–19 April. SPE-94276-MS. http://dx.doi.org/10.2118/94276-MS.

Plasencia, J., Pettersen, B., and Nydal, O. J. 2013. Pipe Flow of Water-in-Crude Oil Emulsions: Effective Viscosity, Inversion Point and Droplet Size Distribution. *Journal of Petroleum Science and Engineering* **101**: 35–43. http://dx.oi.org/10.1016/j.petrol.2012.11.009.

Sun, D., Jong, S. C., Duan, X. D. et al. 1999. Demulsification of Water-in-Oil Emulsion by Wetting Coalescence Materials in Stirred- and Packed-Columns. *Colloids and Surfaces A: Physicochemical & Engineering Aspects* **150** (1–3): 69–75. http://dx.doi.org/10.1016/S0927-7757(98)00590-1.

Sun, Z. Q., Jin, Y. H., Wang, L. et al. 2012. Impact of High-Frequency Pulse Electric Field Parameters on Polarization and Deformation of Water Droplet. *Journal of Chemical Industry and Engineering (China)* **63** (10): 3112–3118.

Taylor, K. C., Burke, R. A., Nasr-El-Din, H. A. et al. 1998. Development of a Flow Injection Analysis Method for the Determination of Acrylamide Copolymers in Brines. *Journal of Petroleum Science and Engineering* **21** (1–2): 129–139. http://dx.doi.org/10.1016/S0920-4105(98)00042-4.

Thomas, S. 2008. Enhanced Oil Recovery - An Overview. *Oil and Gas Science and Technology* **63** (1): 9–19. http://dx.doi.org/10.2516/ogst:2007060.

Wang, X. and Alvarado, V. 2008. Effect of Salinity and pH on Pickering Emulsion Stability. Presented at the SPE Annual Technical Conference and Exhibition, Denver, 21–24 September. SPE-115941-MS. http://dx.doi.org/10.2118/115941-MS.

Wang, Z., Yu, T., Lin, X. et al. 2016. Chemicals Loss and the Effect on Formation Damage in Reservoirs With ASP Flooding Enhanced Oil Recovery. *Journal of Natural Gas Science and Engineering* **33:** 1381–1389. http://dx.doi.org/10.1016/j.jngse.2016.06.048.

Wu, Y., Mahmoudkhani, A., Watson, P. et al. 2012. Development of New Polymers with Better Performance Under Conditions of High Temperature and High Salinity. Presented at the SPE EOR Conference at Oil and Gas West Asia, Muscat, Oman, 16–18 April. SPE-155653-MS. http://dx.doi.org/10.2118/155653-MS.

Yang, F., Niu, Q., Lan, Q. et al. 2007. Effect of Dispersion pH on the Formation and Stability of Pickering Emulsions Stabilized by Layered Double Hydroxides Particles. *Journal of Colloid and Interface Science* **306** (2): 285–295. http://dx.doi.org/10.1016/j.jcis.2006.10.062.

Yang, F., Wang, D., Wang, G. et al. 2006a. Study on High-Concentration Polymer Flooding To Further Enhance Oil Recovery. Presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 24–27 September. SPE-101202-MS. http://dx.doi.org/10.2118/101202-MS.

Yang, F., Yang, X., and Li, J. 2006b. Daqing Pilot Shows Effectiveness of High-Concentration Polymer Flooding. *Oil & Gas Journal* **104** (9): 49–53.

Zhang, J., Dong, S., and Gan, Q. 2007. Dynamic Model of Liquid Droplets of Water-in-Oil Emulsions With High-Frequency Pulsating Electrical Field. *Journal of Chemical Industry and Engineering (China)* **58** (4): 875–880.

Zhang, R., Winterfeld, P. H., Yin, X. et al. 2015. Sequentially Coupled THMC Model for CO_2 Geological Sequestration Into a 2D Heterogeneous Saline Aquifer. *Journal of Natural Gas Science and Engineering* **27** (2): 579–615. http://dx.oi.org/10.1016/j.jngse.2015.09.013.

Zhu, Y., Hou, Q., Jian, G. et al. 2013. Current Development and Application of Chemical Combination Flooding Technique. *Petroleum Exploration and Development* **40** (1): 96–103. http://dx.doi.org/10.1016/S1876-3804(13)60009-9.

Zhihua Wang is an associate professor of petroleum engineering at Northeast Petroleum University, Daqing, China. He has been with the university for nearly 13 years. During the past 5 years, Wang was involved in many large-scale projects at the National Natural Science Foundation of China, China National Petroleum Corporation, and China National Offshore Oil Corporation. His current interests include flow assurance, emulsification and demulsification, produced-water treatment, and facility design and optimization. Wang has authored more than 50 technical papers, including a number of SPE papers, and holds 10 patents. He holds a BS degree in petroleum engineering, an MS degree in oil and gas storage and transportation engineering, and a PhD degree in petroleum and natural gas engineering, all from Northeast Petroleum University.

Xinyu Lin is an MS-degree candidate at Northeast Petroleum University. His research interests include fluid mechanics and numerical simulations. Lin has coauthored two papers in international journals or conference proceedings. He holds a BS degree in oil and gas storage and transportation engineering from Northeast Petroleum University.

Tianyu Yu is an MS-degree candidate in the School of Civil, Environmental, and Mining Engineering at the University of Western Australia, Perth. His research interests include flow assurance, structural dynamics, and waste management. Yu has authored or coauthored four technical papers, one of which was published in an SPE proceedings. He holds a BS degree in oil and gas storage and transportation engineering from Northeast Petroleum University.

Zhiwei Hu is an engineering specialist at Daqing Oilfield Company Limited. He has been with the company for 10 years. Hu has more than 6 years of experience dedicated to oilfield surface engineering, ranging from conceptual design to detailed design, installation, and production management. He holds a BS degree in oil and gas storage and transportation engineering from Northeast Petroleum University.

Mengmeng Xu is a BS-degree candidate at Northeast Petroleum University. Her research interests include flow assurance and numerical simulations. Xu has authored or coauthored five papers in international journals or conference proceedings and holds one patent.

Hongtao Yu is a BS-degree candidate at Northeast Petroleum University. Her research interests include fluid mechanics, produced-water treatment, and numerical simulations.