

Pretreatment of Crude Oil by Ultrasonic-electric United Desalting and Dewatering

YE Guoxiang (叶国祥), LÜ Xiaoping (吕效平)*, PENG Fei (彭飞), HAN Pingfang (韩萍芳) and SHEN Xuan (沈旋)

Institute of Sonochemical Engineering, Nanjing University of Technology, Nanjing 210009, China

Abstract A technology of ultrasonic-electric united desalting and dewatering of crude oil is studied. The ultrasonic setup is designed to form a standing-wave field, which is more efficient for agglomeration of water particles. The desalting and dewatering results of the ultrasonic-electric united process are compared with those of the electric process. For high salt-containing crude oil ($40\text{--}70\text{ mg}\cdot\text{L}^{-1}$), the salt content is still above $10.0\text{ mg}\cdot\text{L}^{-1}$ after crude oil has been treated by two-stage electric desalting process in refinery, which cannot meet the need of refinery. Ultrasonic-electric united process is a novel technology for treating the high salt-containing oil. On the optimal operating conditions of the ultrasonic-electric united process, the salt content of crude oil can be reduced from $67.5\text{ mg}\cdot\text{L}^{-1}$ to $3.97\text{ mg}\cdot\text{L}^{-1}$ by one-stage ultrasonic-electric united process, and the water content falls below 0.3% (by volume). The results show that the ultrasonic-electric united process is more effective than the electric process in high salt-containing oil desalting. This technology should be useful in the refinery process.

Keywords crude oil, ultrasonic-electric united process, desalting, dewatering

1 INTRODUCTION

Crude oil is a kind of complicated mixture and commonly contains water and a large quantity of salts [1–3]. Water in crude oil makes the pipeline and the refining processes to be costly and even may cause oil refining process unsteady. Salts, such as sodium, magnesium, and calcium chlorides, in crude oil may corrode the downstream equipments, obstruct the pipes and make the catalysts poison. The main purpose of desalting in the refinery is to avoid the harms mentioned above. Some of the oil fields around the world have already got into the stage of secondary or tertiary oil recovery. The crude oil recovered in this way tends to become ropier and heavier, containing more salts. Current methods as electric desalting and dewatering processes for these oils may be hard to meet the need of the refinery.

Researches [4–7] had shown that the crude oil pretreatment by ultrasound can agglomerate the tiny water particles scattered in the oil, demulsify the oil, and enhance the dewatering and the desalting process. All the researches that have been reported are batch and discontinuous processes [8–10]. The aim of this present research is to study the continuous ultrasonic-electric united process for crude oil desalting and dewatering. The results in our research can be compared with those of the refinery process. The study presented in this article is based on our lab works.

2 INSTRUMENTS AND MATERIALS

2.1 Ultrasonic-electric united device

A novel set of device combined the ultrasonic setup with the electric desalting, and dewatering tank was made. The set of device was designed according

to the process of the refinery. An ultrasonic setup was merged in the position before the oil enters the desalting tank. The ultrasonic setup was designed with a standing-wave tube for obtaining the standing-wave field.

The ultrasonic-electric united process is shown in Fig. 1, containing one ultrasonic setup and one electric dewatering and desalting tank.

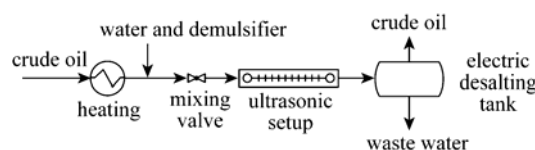


Figure 1 Ultrasonic-electric united process of crude oil desalting and dewatering

The sizes of the ultrasonic-electric united device were calculated and designed carefully to match the ultrasound setup to the electric desalting devices. The frequencies of the ultrasonic setup were 10 kHz or 20 kHz. The ultrasonic setup was designed in the type of standing-wave tube. In the experiments, it was selectable to treat crude oil with or without ultrasound irradiation.

2.2 Design of the standing-wave tube

2.2.1 Achievement of the plane wave

To get a standing-wave field, a tube was used. The relationship of the cut-off frequency and the diameter of the tube can be indicated as $f_c = 1.84c_0 / \pi d$, where f_c is the cut-off frequency, c_0 is the sound velocity in the oil, and d is the diameter of the tube. For the 10-kHz device, to obtain a plane wave in the tube, the inner diameter (d) of the tube must be equal to or less than 8.8 cm. For the 20-kHz device, it should be equal to or less than 4.4 cm.

Table 1 Designed size of the standing-wave tube

Cut-off frequency f_c/kHz	Radius a/cm	Sectional area S/cm^2	Oil fluid $V/L\cdot\text{h}^{-1}$	Residence time of oil t/s	Velocity of oil $u/\text{mm}\cdot\text{s}^{-1}$	Min. tube length L/cm	Designed tube length L/cm
20	2.2	15.2	30	300	5.5	165	165
10	4.4	60.8	30	300	1.4	41.5	45

The relationship of f_c and d can be described as $f_c = 3.832c_0 / \pi d$ if the ultrasonic device can provide an axial symmetric vibration. Commonly, this formula is used to calculate the diameter of the standing-wave tube. Hence, the diameters of the standing-wave tube are confirmed according to the frequencies.

2.2.2 Sound pressure in the tube

Sound pressure of the injection wave in the tube is determined as $p_i = p_{ia} e^{j(\sigma t - kx)}$. That of the reflection wave is calculated as $p_r = p_{ra} e^{j(\sigma t - kx)}$.

The amplitude reflection coefficient can be calculated as $r_p = p_{ra} / p_{ia} = |r_p| e^{j\sigma\pi}$, where $|r_p|$ is the value of the amplitude, $\sigma\pi$ is the phase difference of the two waves. The total sound pressure in the tube is confirmed as $p = p_i + p_r = |p_A| e^{j(\sigma t + \psi)}$, where $|p_A| = p_{ia} \sqrt{1 + r_p^2 + 2r_p \cos 2k(x + \sigma \cdot \lambda / 4)}$.

2.2.3 Standing-wave field

As we know, the acoustic impedance Z_s in the medium can be calculated as $Z_s = \rho_0 c_0 [(\rho c)_{\text{air}} \ll (\rho c)_{\text{oil}} \ll (\rho c)_{\text{steel}}]$. Thus, when the tube is filled with oil and a sound wave incidence from the empty end, the wave can all transmit from the oil to the steel. Because Z_{steel} is larger than Z_{oil} and the thickness of the steel end (0.2 cm) is much smaller than the ultrasound wave length in steel (30.5 cm of 20 kHz, 61.0 cm of 10 kHz). But on the surface of steel and air, the sound wave can be totally reflected, because Z_{air} is far smaller than Z_{steel} . Thus, the injection wave and the reflection wave are gained.

The descriptions of standing-wave field in formula are as below. Standing-wave ratio $G = p_{\text{max}} / p_{\text{min}} = (1 + |r_p|) / (1 - |r_p|)$, position of the wave node is determined as $\cos 2k(x + \sigma \cdot \lambda / 4) = -1$. Thus, the distance of the sound source surface and the reflection surface can be determined.

2.2.4 Size of the standing-wave tube designed in the instrument

The frequency of the ultrasound determines the largest inner diameter of the standing-wave tube. We made two tubes to fit for the 10 kHz and 20 kHz devices, whose inner diameter were 8.8 cm and 4.4 cm, respectively.

The designed value of oil processing rate V was $30 \text{ L}\cdot\text{h}^{-1}$, the sectional area S of the tube (20 kHz) was

$1.5 \times 10^{-3} \text{ m}^2$. Thus, the oil velocity should be $u = V / S = 5.5 \times 10^{-3} \text{ m}\cdot\text{s}^{-1}$. The designed residence time of crude oil in the tube was 5 min. Thus, the working length L of the tube should be $L \geq ut = 1.65 \text{ m}$. On other hand, the length of the tube was also integral times of the half-wave length. The length of the tube in the instrument was able to be adjusted in a range.

To provide a laminar flow in the tube, the Reynolds number of the fluent must be less than 2000. The tube must be able to bear 1.0 MPa. The designed sizes of the standing wave tubes are shown in Table 1.

2.3 Other instruments

Other instruments used in the experiment were ZWC-2001 salt content measuring instrument (with microcomputer workstation, the salt analyzer) and GB/T8299-1998 water content measuring apparatus (water content analyzer).

2.4 Materials and agents

The crude oil used in this study was provided by Yangzi Petrochemical Company (YPC), SINOPEC. The original salt content and typical properties of the oil are listed in Table 2. The original salt content of the crude oil was as high as $40\text{--}70 \text{ mg}\cdot\text{L}^{-1}$, which was very difficult to be desalted. Other agents used in the experiments were fresh water and NP-1 demulsifier.

Table 2 Typical properties of the crude oil

Typical properties	Specifications
API degree	22
density (20°C)/ $\text{g}\cdot\text{cm}^{-3}$	0.9199
kinetic viscosity (50°C)/ $\text{mm}^2\cdot\text{s}^{-1}$	108.0
pour point/°C	19
acid value/ $\text{mg KOH}\cdot\text{g}^{-1}$	1.92
salt content/ $\text{mg NaCl}\cdot\text{L}^{-1}$	40–70
water content/% (by volume)	0.25
carbon residue/% (by mass)	6.41
ash/% (by volume)	0.015
characteristic factor K	11.75

Note: The data are provided by Institute of Yangzi Petrochemical Company, SINOPEC.

3 EXPERIMENTS

According to the plant refining process, the experiments were carried out in 3 steps, crude oil

pretreatment, ultrasonic irradiation, and electric desalting and dewatering.

In pretreatment, the crude oil was heated to reduce its viscosity and became easy to flow in the pipes. And water (5% vs. crude oil, v.) was then injected into the pipeline containing demulsifier. The water and the heated crude oil were then mixed *via* static mixer. The purpose of this step was to mix the water with the crude oil sufficiently, forming W/O emulsion. In this way, the water dissolved the salts from the oil phase.

The second step in this work was to treat the emulsion by ultrasonic irradiation. The emulsion of crude oil was sent to the ultrasonic standing wave tube by proportional pump. In this step, the tiny water drops were agglomerated into bigger ones in the ultrasonic standing-wave field. It was helpful to the following step of electric desalting and dewatering.

The third step was to treat the crude oil by electric desalting and dewatering devices. In this step, the water particles collapsed and settled down in high electric intensity field. The salt was removed together with water. The salts in the crude oil were extracted in water in the first step. So the final salt content in the crude oil was determined by two factors. (1) The water should be mixed sufficiently with the oil to dissolve the salts. (2) The water containing the salts should be removed as much as possible. To reduce the energy loss in the experiments, all pipes were coated with insulation, and the standing-wave tube was also covered with insulation.

4 RESULTS AND DISCUSSION

4.1 Comparison of the electric process with and without ultrasonic at different temperatures

The results of crude oil desalting and dewatering by the ultrasonic-electric united process were compared with the electric process, as shown in Fig. 2. The controlling conditions were: oil fluid was $40 \text{ L}\cdot\text{h}^{-1}$, water fluid was $1.8 \text{ L}\cdot\text{h}^{-1}$, demulsifier dosage was $20 \mu\text{g}\cdot\text{g}^{-1}$, pressure drop of mixing was 0.5 MPa, electric intensity was $1.2 \text{ kV}\cdot\text{cm}^{-1}$, and 20 kHz ultrasonic power was 150 W.

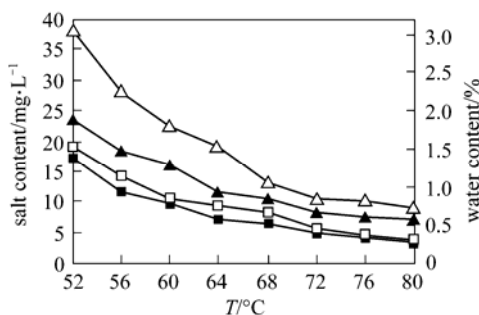


Figure 2 Comparison of the ultrasonic-electric united process with the electric process (oil fluid $40 \text{ L}\cdot\text{h}^{-1}$, water fluid $1.8 \text{ L}\cdot\text{h}^{-1}$, demulsifier dosage $20 \mu\text{g}\cdot\text{g}^{-1}$, pressure drop of mixing 0.5 MPa, ultrasound frequency 20 kHz, ultrasound power 150 W, electric intensity $1.2 \text{ kV}\cdot\text{cm}^{-1}$, origin salt content 40–70 $\text{mg}\cdot\text{L}^{-1}$)
water content: \triangle electric treatment; \square ultrasonic-electric united treatment
salt content: \blacktriangle electric treatment; \blacksquare ultrasonic-electric united treatment

The results showed that the salt content of the crude oil was decreased from $39.463 \text{ mg}\cdot\text{L}^{-1}$ to $7.125 \text{ mg}\cdot\text{L}^{-1}$, and the water content was decreased from 5% to 0.72% after the electric process treatment only. But the salt content of the crude oil was decreased to $3.243 \text{ mg}\cdot\text{L}^{-1}$, and the water content was decreased to 0.24% after the ultrasonic-electric united process treatment. The best result was obtained on the highest experiment temperature, 80°C . A conclusion can be drawn that the overall performances of the ultrasonic-electric united process are more effective than that of the electric process.

4.2 Influences of the desalting tank temperature

The influences of the desalting tank temperature were also studied on the same condition as described in Section 4.1.

As shown in Fig. 3, high temperature (80°C) was helpful, but the trend of salt content decreasing became slow with increase in the temperature. The reason was that the strength of the interfacial tension of crude oil and water could decrease on higher temperature, which made the emulsion unsteady. On other hand, the viscosity of the oil was decreased, and the water particles were settled down easily with the increase in the temperature.

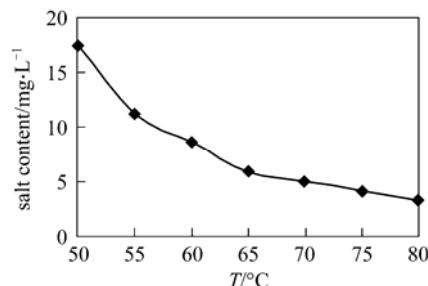


Figure 3 Influences of the desalting tank temperature on the desalting results

(oil fluid $40 \text{ L}\cdot\text{h}^{-1}$, water fluid $1.8 \text{ L}\cdot\text{h}^{-1}$, demulsifier dosage $20 \mu\text{g}\cdot\text{g}^{-1}$, pressure drop of mixing 0.5 MPa, ultrasound frequency 20 kHz, ultrasound power 150 W, electric intensity $1.2 \text{ kV}\cdot\text{cm}^{-1}$, origin salt content 40–70 $\text{mg}\cdot\text{L}^{-1}$)

4.3 Influences of ultrasound frequency

The desalting and dewatering results were also influenced by the ultrasonic frequency. The experiment conditions in this study were oil flow velocity $20 \text{ L}\cdot\text{h}^{-1}$, water flow velocity $0.9 \text{ L}\cdot\text{h}^{-1}$, demulsifier dosage $30 \mu\text{g}\cdot\text{g}^{-1}$, differential pressure of mixing 0.4 MPa, electric intensity $1.2 \text{ kV}\cdot\text{cm}^{-1}$, and ultrasonic power 150 W.

The influences of different ultrasonic frequencies were studied on different temperatures, as shown in Fig. 4. The results of using the 10-kHz device were better than that of using the 20 kHz on the same conditions. As reported [11], there was an optimal frequency, which matched to a given diameter dispersion of small particles. The experiments showed that to treat the LU-NING pipeline oil, the 10-kHz device was more suitable than the 20-kHz device.

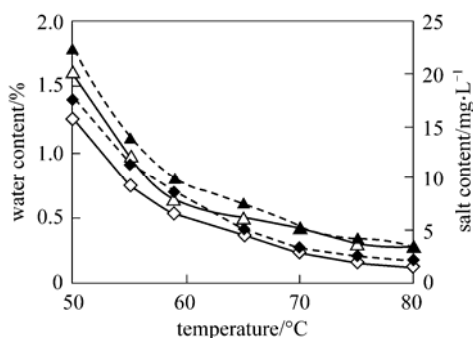


Figure 4 Influences of ultrasonic frequency on desalting and dewatering results on different temperatures

(oil fluid 20 L·h⁻¹, water fluid 0.9 L·h⁻¹, demulsifier dosage 30 μg·g⁻¹, pressure drop of mixing 0.4 MPa, ultrasound power 150 W, electric intensity 1.2 kV·cm⁻¹, origin salt content 40–70 mg·L⁻¹)
 water content: ◇ 10 kHz; △ 20 kHz
 salt content: ◆ 10 kHz; ▲ 20 kHz

4.4 Influences of ultrasound output power

The same conditions as mentioned in Section 4.1 and Section 4.2, 20 kHz, 80°C, the influences of ultrasound output power were also studied.

There was an optimal value of ultrasound output power as shown in Fig. 5, which was about 150 W. The ultrasonic irradiation condition was very important in the whole process. There were two mechanisms that could explain the ultrasonic influences. (1) Aggregating effect. The water drops aggregated with the ultrasound irradiation, which was helpful to the emulsion demulsify. (2) Cavitation effect. The ultrasound cavitation had the emulsification affection. When the intensity of ultrasound was below the cavitation threshold, the aggregation appeared, the results of ultrasound irradiation being demulsified. When the intensity of ultrasound increased over the cavitation threshold, the results of ultrasound irradiation were shown as emulsification.

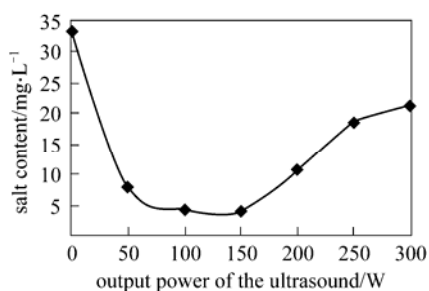


Figure 5 Influences of the ultrasound output power on the desalting results

(oil fluid 40 L·h⁻¹, water fluid 1.8 L·h⁻¹, demulsifier dosage 20 μg·g⁻¹, pressure drop of mixing 0.5 MPa, ultrasound frequency 20 kHz, electric intensity 1.2 kV·cm⁻¹, temperature 80°C, origin salt content 40–70 mg·L⁻¹)

4.5 Influences of the mixing pressure drop

Influences of the mixing pressure drop were also studied on the same conditions as in section 4.1, 4.2, and 4.4. As shown in Fig. 6, there was an optimal mix-

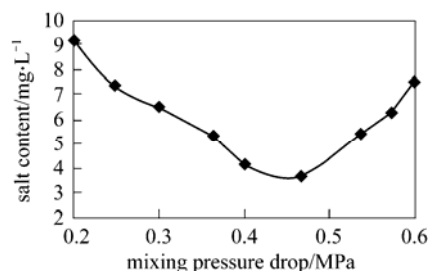


Figure 6 Influences of the mixing pressure drop on the desalting results

(oil fluid 40 L·h⁻¹, water fluid 1.8 L·h⁻¹, demulsifier dosage 20 μg·g⁻¹, ultrasound frequency 20 kHz, ultrasound power 150 W, electric intensity 1.2 kV·cm⁻¹, temperature 80°C, origin salt content 40–70 mg·L⁻¹)

ing pressure drop value for desalting. It was about 0.45 MPa. The reason was that the rate of dissolving salt increased with the increase of oil-water mixing intensity. However, when the mixing intensity was too higher, the oil and the water would be emulsified seriously and it would be hard to remove the water from the oil.

4.6 Influences of demulsifier dosage

The experiment conditions were the same as in section 4.3, 10 kHz. The influences of demulsifier dosage were shown in Fig. 7. The salt and water contents of the oil decreased if the NP-1 demulsifier was added. The water content could meet the need of refinery standard by adding 10 μg·g⁻¹ demulsifier, but the salt content was still much higher than the standard. The best dosage was about 30 μg·g⁻¹ according to Fig. 7. The water and the salt contents increased slightly after dosage was added over the optimal value. It should be explained by using the critical congregate concentration mechanism [12]. The water content decreased with the increasing of the demulsifier dosage when the dosage of demulsifier was below the critical concentration. The demulsifier dosage influenced dewatering slightly when it was added over the critical concentration. Considering the cost and the treatment results, the proper dosage concentration was about 20–30 μg·g⁻¹ in the ultrasonic-electric united process.

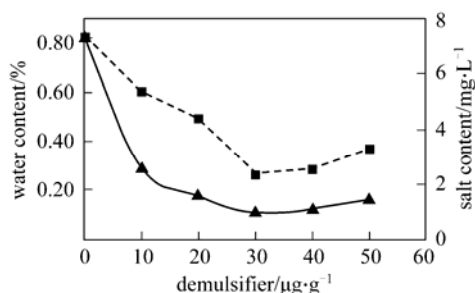


Figure 7 Influences of demulsifier dosage on the results

(oil fluid 20 L·h⁻¹, water fluid 0.9 L·h⁻¹, pressure drop of mixing 0.4 MPa, ultrasound frequency 10 kHz, ultrasound power 150 W, electric intensity 1.2 kV·cm⁻¹, temperature 80°C, origin salt content 40–70 mg·L⁻¹)

▲ water content; ■ salt content

4.7 Influences of water injection

In refinery, commonly 5%–7% (vs. crude oil, v.) fresh water was injected into the crude oil for desalting. The salts dissolved into the water phase when the crude oil and water passed through the static mixer. Thus, the amount of injected water also affected the dewatering and the desalting. As shown in Fig. 8, the addition of water was propitious to dissolve the salts, and it would decrease the salt content in crude oil. But the final water content in crude oil was increased. It could be found that about 5% water injection was optimal, as shown in Fig. 8. It would cost more energy with adding more water because the water must be heated to a high temperature as oil. Furthermore, more waste water would be ejected.

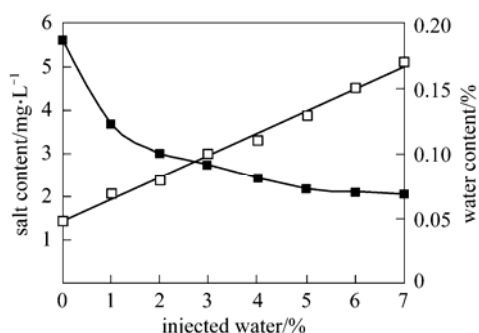


Figure 8 Influences of injected water on the results (oil fluid $20 \text{ L}\cdot\text{h}^{-1}$, pressure drop of mixing 0.4 MPa , demulsifier dosage $20 \mu\text{g}\cdot\text{g}^{-1}$, ultrasound frequency 10 kHz , ultrasound power 150 W , electric intensity $1.2 \text{ kV}\cdot\text{cm}^{-1}$, temperature 80°C , origin salt content $40\text{--}70 \text{ mg}\cdot\text{L}^{-1}$)
 □ water content; ■ salt content

4.8 Running results under the optimized conditions

The conditions of the ultrasonic-electric united process to treat the LU-NING piping oil were discussed above.

An experiment of the devices had also been carried out on the best conditions. The temperature was about $83\text{--}89^\circ\text{C}$. The relationships of water content and salt content vs. running time at the best conditions were shown in Fig. 9 and Fig. 10. The original salt content of the crude oil was $67.5 \text{ mg}\cdot\text{L}^{-1}$. After 40 h , the salt content in the oil was steady at $4.0\text{--}5.5 \text{ mg}\cdot\text{L}^{-1}$. The best desalting result was $3.97 \text{ mg}\cdot\text{L}^{-1}$. Its desalting ratio was over 90%. The water content after treat-

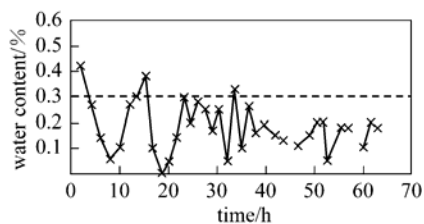


Figure 9 Water content versus time at the best conditions (oil fluid $20 \text{ L}\cdot\text{h}^{-1}$, water fluid $1.12 \text{ L}\cdot\text{h}^{-1}$, pressure drop of mixing 0.45 MPa , demulsifier dosage $20 \mu\text{g}\cdot\text{g}^{-1}$, ultrasound frequency 10 kHz , ultrasound power 150 W , electric intensity $1.2 \text{ kV}\cdot\text{cm}^{-1}$, temperature $83\text{--}89^\circ\text{C}$, origin salt content $67.5 \text{ mg}\cdot\text{L}^{-1}$)

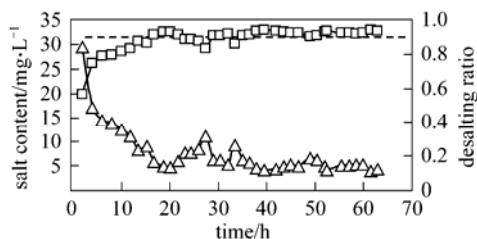


Figure 10 Salt content versus time at the best conditions (oil fluid $20 \text{ L}\cdot\text{h}^{-1}$, water fluid $1.12 \text{ L}\cdot\text{h}^{-1}$, pressure drop of mixing 0.45 MPa , demulsifier dosage $20 \mu\text{g}\cdot\text{g}^{-1}$, ultrasound frequency 10 kHz , ultrasound power 150 W , Electric intensity $1.2 \text{ kV}\cdot\text{cm}^{-1}$, temperature $83\text{--}89^\circ\text{C}$, origin salt content $67.5 \text{ mg}\cdot\text{L}^{-1}$)
 △ salt content; □ desalting ratio

ment was usually below 0.30%. The data from the refinery of YPC was shown in Fig. 11. When the original salt content was as high as $40 \text{ mg}\cdot\text{L}^{-1}$, the final salt content was still above $10 \text{ mg}\cdot\text{L}^{-1}$ after two-stage electric desalting treatment at 140°C . The comparison of those two processes showed that the ultrasonic-electric united process was better; especially treating the high salts containing crude oil. Such a novel technology could be considered to ensure the salt content of crude oil to meet the need of refinery.

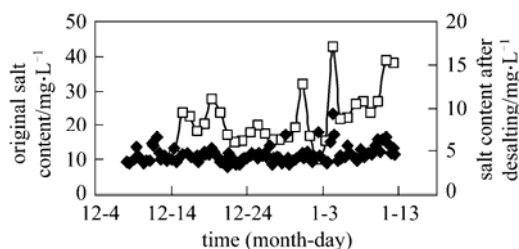


Figure 11 Field test data from the refinery of YPC, SINOPEC
 □ original salt concentration; ◆ salt content after desalting

5 CONCLUSIONS

Ultrasonic-electric united process could enhance the desalting and the dewatering process of the crude oil.

The best treating conditions were discussed in this article. The best condition was 5% (by volume) injected water, $30 \mu\text{g}\cdot\text{g}^{-1}$ demulsifier, 0.45 MPa pressure drop of mixing, 10 kHz and 150 W ultrasound (standing-wave field), 3–5 min ultrasonic irradiation, $1.2 \text{ kV}\cdot\text{cm}^{-1}$ electric intensity when oil flow velocity was $20 \text{ L}\cdot\text{h}^{-1}$, and the treating temperature was 80°C .

The experimental results of the ultrasonic-electric united process and the electric process of YPC were compared. It was hard to treat the high salt-containing oil, which original salt content was $40\text{--}70 \text{ mg}\cdot\text{L}^{-1}$ for refineries. The salt content was still above $10 \text{ mg}\cdot\text{L}^{-1}$ after two-stage of electric desalting. This could not meet the need of refinery ($<3 \text{ mg}\cdot\text{L}^{-1}$ NaCl). The ultrasonic-electric united process was more useful for high salt-containing oil. The salt content decreased from $67.5 \text{ mg}\cdot\text{L}^{-1}$ to $3.97 \text{ mg}\cdot\text{L}^{-1}$ at lower temperature (80°C) in one-stage treatment.

The device of the ultrasonic-electric united process

was still a lab scale. It was hard to improve the temperature to more than 90°C during the experiments, because the power of heater was not enough. Furthermore, the desalting device contained only one-stage of desalting tank. Thus, the desalting results (3.97 mg·L⁻¹) could not meet the requirement of plant. If temperature would be increased to 140°C and two-stage of process were carried out, the desalting results should be improved and the salt content should be decreased to below 3.0 mg·L⁻¹. Anyway, ultrasonic technology improved the desalting results considerably. Pilot-scale experiments with the ultrasonic-electric united devices were planned to carry out. To the high salt-containing crude oil, the novel ultrasonic-electric united technology could be considered. With the development of the ultrasonic technology, it would be a useful technology in the scaled process in future.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the YPC, SINOPEC, and Sino-America Zhenjiang Jinmen Industry Co., LTD.

NOMENCLATURE

a	radius, m
c_0	sound velocity in the oil, m·s ⁻¹
d	diameter of the tube, m
f_c	cut-off frequency, Hz
k	wave number
L	length, m
p	sound pressure, Pa
r_p	coefficient of the amplitude reflection
S	sectional area, m ²
t	time, s
u	velocity, m·s ⁻¹
V	flow rate, m ³ ·s ⁻¹
x	distance, m
Z_s	acoustic impedance, kg·m ⁻² ·s ⁻¹

ρ	density, kg·m ⁻³
ω	angular velocity, r·s ⁻¹

Subscripts

a	amplitude
i	incident
r	reflect

REFERENCES

- Hu, T.L., Yang, K., Ma, L.J., Ye, W., Zhao, S.L., "Research progress of desalting and dewatering from crude oil", *J. Fushun Petroleum Institute*, **23** (3), 1-4 (2003). (in Chinese)
- Qi, G.M., Lu, X.P., "The research advance of crude oil emulsions breaking via ultrasound", *Chem. Ind. Times*, **24** (6), 11-14 (2001). (in Chinese)
- Kumar, K., Nikolon, A.D., Wasan, D.T., "Mechanisms of stabilization of water-in-crude-oil emulsion", *Ind. Eng. Chem. Res.*, **40** (14), 3009-3014(2001).
- Cai, Y.W., Xie, W., Lu, X.P., Han, P.F., "Demulsification and dehydration of crude oil in ultrasonic standing wave field", *Petrol. Process. Petrochem.*, **36** (5), 13-17(2005). (in Chinese)
- Han, P.F., Qi, G.M., Xu, N., "Study on crude oil emulsion breaking via ultrasound", *J. Nanjing Univ. Technol.*, **24** (6), 30-34 (2002). (in Chinese)
- Sun, B.J., Yan, D.C., Qiao, W.X., "The study of demulsification with ultrasonic irradiation on oil emulsion", *Acta Acust.*, **24** (3), 327-331 (1999). (in Chinese)
- Yu, J.Y., Yuan, P., Yu, L., "Experiment study on the sound-field parameters for crude-oil dehydration by ultrasonic demulsification", *Appl. Acoust.*, **20** (3), 27-30 (2001). (in Chinese)
- Han, P.F., Qi, G.M., Lu, X.P., "Study of crude oil emulsion breaking via ultrasound", *Chem. Eng.*, **32** (1), 42-46 (2004). (in Chinese)
- Zhang, Y.M., Peng, F., Lu, X.P., "Study of ultrasonic demulsification and dehydration of refinery waste oil", *Petrol. Process. Petrochem.*, **35** (2), 67-71 (2004). (in Chinese)
- Ye, G.X., Lu, X.P., Peng, F., Wang, Y.R., Han, P.F., Gu, H.P., "Application of ultrasound in dewatering of crude oil", In: WCU/UI, Beijing, 49 (2005).
- Kotlyusov, A.N., Nemtsov, B.E., "Induced coagulation of small particles under the action of sound", *Acust. Acta Acust.*, **82** (3), 459-463 (1996).
- Qiao, J.J., Zhan, M., Zhang, Y.A., Wen, J.F., Li, C.L., "Study on the mechanism of petroleum emulsion's breaking I. Effect of interfacial tension on the effectiveness of demulsification", *Acta Petrol. Sin.*, **15** (2), 1-5 (1999). (in Chinese)