Study on frequency optimization and mechanism of ultrasonic waves assisting water flooding in low-permeability reservoirs

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1. Introduction

With the increasing demand for fuel and energy, the unconventional resources such as shale gas/oil, tight gas/oil and coalbed gas, play a growing important role in global energy supply [1,2]. In order to realize the industrial hydrocarbon production, petroleum engineers usually adopt the hydraulic fracturing to improve the inflow in low-permeability reservoirs [3]. The artificial cracks contribute to the oil displacement near the fracture surface, but more oil is still trapped in the small and nano pores within matrix. In the water-wet low-permeability matrix, the strong capillarity will strengthen the spontaneous water imbibition [4]. Some chemical agents can alter the surface properties of porous media and help to further enhance the oil recovery by spontaneous imbibition. However, on the one hand, the enhanced oil recovery (EOR) performance of chemical agents highly depends on the properties of oil and rock surface, so the heterogeneity of unconventional formations may limit the application of chemical flooding [5-7]. On the other hand, some chemicals may cause the formation damage at the late stage, leading to little improvement on the ultimate oil recovery [8]. Therefore, the physical methods (such as the microwaves and plasma pulse shock), especially the ultrasonic wave, are promising strategies to assist in water flooding for EOR [9-11].

The ultrasonic wave technique has been widely used in petroleum engineering. For example, ultrasonic waves help to mitigate the formation damage caused by water blocking or clay swelling [9]. After the polymer or surfactant flooding, one can adopt the ultrasonic technique for gel-breaking or demulsification to extract oil [8,12]. For heavy oil production, ultrasonic wave can induce the aquathermolysis reaction to reduce the viscosity of heavy oil and eventually lead to the improvement of oil flow ability and recovery [13]. Some researchers indicated that ultrasonic waves are suitable for removing plugging materials caused by drilling mud or paraffin near the wellbore regions and exhibit a cost-advantage compared with the traditional methods including hydraulic fracturing and acidizing [14,15]. Recent field applications have coupled ultrasonic waves with traditional EOR methods to further improve oil recovery. For instance, some experimental studies proved...
that ultrasonic waves can mitigate fingering effects and improve sweep efficiency during CO₂ flooding operation through reducing the interfacial tension [16]. The ultrasonic waves also contribute to oil-viscosity reduction and emulsification, resulting in higher oil recovery yielded by water or surfactant flooding [17,18]. However, the diverse properties of low-permeability reservoirs (including permeability, porosity and wettability) raise the difficulties in determining the working parameters of ultrasonic waves. Until now, there are lack of comprehensive studies on the mechanism of ultrasonic-assisted EOR in unconventional reservoirs. Therefore, it is necessary to propose a theoretical guidance of ultrasonic waves for EOR in low-permeability reservoirs.

The acoustic frequency plays a dominating role in the EOR performance of ultrasonic waves and is usually optimized through a series of experiments conducting on a given rock sample [8,9]. If we classify the low-permeability cores reasonably, we would directly obtain the optimized EOR working parameters for a group of low-permeability reservoirs and slash the experimental time and costs. In the past, the engineers usually classified core samples with regard to permeability [19,20]. However, such empirical grouping method has strong limitations in low-permeability reservoirs due to the diverse properties [21–23]. Besides permeability, the porosity and wettability are also the important factors affecting the oil extraction from low-permeability reservoirs [24,25]. It is a challenge to develop an appropriate and robust grouping method for unconventional cores in comprehensive consideration to permeability, porosity and wettability. With the advent of advanced computational techniques, the unsupervised learning method may be a promising tool to address the grouping issue. As one of classic unsupervised learning methods, the clustering algorithm can take various reservoir properties into account at the same time and optimize the number of clusters as well as the components within each cluster [26]. Compared with the orthogonal experimental method, the clustering algorithm will reduce many experimental workloads and provide more reliable grouping results for low-permeability cores [27].

A reasonable grouping method for low-permeability cores is inadecquate to assure the success of ultrasonic waves in assisting waterflooding. More efforts should be invested to reveal the EOR mechanism of ultrasonic waves in low-permeability reservoirs because of the different fluid properties and reservoir characters from those in traditional reservoirs. For instance, the ultrasonic wave is able to effectively reduce the viscosity of heavy oil through aquathermolysis reaction, but such effect becomes pale in the light oil stored in low-permeability reservoirs due to the low viscosity in its nature [28,29]. Recently, the ultrasonic wave has also been proved to change the relative permeability of oil in low-permeability reservoirs [16,30–35]. In addition, with high energies, the ultrasonic waves may also change the microstructure of cores [36]. Therefore, we would better conduct more analyses to set those issues straight and guide the optimization of ultrasonic frequency.

In this study, we would first group the low-permeability cores by different clustering algorithms. Then we verified the grouping results based on the primary oil recovery yielded by water flooding and determined the optimized ultrasonic frequency for each group according to the oil recovery enhancement. Finally, we tried to reveal the EOR mechanism of ultrasonic waves in low-permeability reservoirs through a series of analysis experiments, including scanning electron microscope (SEM) observation, infrared characterization, interfacial tension and oil viscosity measurement. The grouping method and experimental results displayed in this paper may lay the foundation for the design of ultrasonic waves assisting water flooding in low-permeability reservoirs.

2. Methodology and experimental section

2.1. Materials

In this study, we adopt a kind of brine water as flooding water. The brine water was prepared by the weight proportion of NaCl:CaCl₂:MgCl₂:6H₂O = 7:0.6:0:4. NaCl and CaCl₂ were purchased from Aladdin Chemical Reagents Company and MgCl₂ was purchased from Jiangsu Baomo Company. Crude oil was collected from Yanchang Oilfield and the properties are given in Table 1.

Total 100 natural core samples were obtained from Ordos Basin in the northwest of China. The characteristics of these cores (including permeability, porosity and wettability) are presented in Table 2.

2.2. Clustering methodology

Clustering is one of unsupervised learning tasks and served in grouping data based on their inherent natures and relationships [37]. Clustering algorithm includes density-based clustering, K-Means, Agglomerative clustering, Mean Shift clustering and so on. The K-Means clustering algorithm divides samples into different clusters based on distance measurement [38]. Mean Shift clustering is an advanced K-means clustering and can determine arbitrarily shaped clusters through density gradient ascent paths [39]. Agglomerative clustering is a hierarchical-based clustering method that can produce an informative hierarchical structure of clusters [40]. The DBSCAN algorithm (Density-Based Clustering of Application with Noise) is a widely-used density-based clustering algorithm [41]. The sample set will be divided into core points, boundary points and noise points according to the set radius (Eps) and the number of samples (MinPts). In the circle with a set radius, the points containing more or equal number of samples than MinPts name the core point; the points containing less number of samples than MinPts and neighboring the core point name the boundary point; the rest points are the noise point [42]. To take care of the permeability, porosity and wettability of core samples, our DBSCAN algorithm randomly selected a sample as the subject and drew a sphere around the subject with set radius instead of a circle. All the samples in the sphere were subject to the same cluster to the selected one. Then we drew new spheres around other samples in the cluster with Eqs. Continue to draw spheres until no more samples could be added into the available cluster; we got one of final clusters. For the remaining samples, repeat such procedure until all the samples were included.

2.3. Oil displacement experiment

In order to investigate the effect of ultrasonic wave on EOR performance yielded by water flooding, we developed an ultrasonic-assisted water flooding equipment. The schematic diagram of self-developed ultrasonic-assisted water flooding equipment is shown in Fig. 1. The ultrasonic generators are manufactured by Hangzhou Success Ultrasonic Company Ltd, China and other experimental sections are produced by Haian manufactory, China. There are five ultrasonic frequencies adopted in this study: 15 kHz, 18 kHz, 20 kHz, 25 kHz and 28 kHz.

A representative oil displacement procedure is presented here. The clean core was fixed into the core holder. We injected the crude oil into the core with the rate of 0.8 mL/min until the core was saturated by crude oil. Then we injected brine water into core with the rate of 1.6 mL/min and obtained the primary recovery factor (η₁) when the volume of injected water reached at 4 pore volumes (PVs). Subsequently, core sample was treated by ultrasonic wave for 60 min in an intermittent way (working 5 min and then stopping 5 min). We determined the secondary recovery factor (η₂) when the water fraction at the outlet reached at 98%. The above procedures were repeated with

| Table 1
| Testing results of oil sample. |
|-----------------------------|-------------------------------|
| Density (g/cm³) | Viscosity (mPas) | Freezing Point | Surface tension (mN·m⁻¹) |
| 0.799 | 6.97 | ≤5 °C | 17.38 |

NaCl:CaCl₂:MgCl₂:6H₂O = 7:0.6:0:4. NaCl and CaCl₂ were purchased from Aladdin Chemical Reagents Company and MgCl₂ was purchased from Jiangsu Baomo Company. Crude oil was collected from Yanchang Oilfield and the properties are given in Table 1.
different ultrasonic frequencies. Finally, we could get the recovery enhancement value ($\Delta q = q_2 - q_1$) yielded by the ultrasonic wave with a set frequency through comparing the primary and second recovery factors. The testing temperature was 80 °C which was close to the reservoir condition.

2.4. Characterization of crude oil and core samples treated by ultrasonic waves

In order to reveal the EOR mechanism of ultrasonic wave, this study conducted a series of analysis experiments including oil viscosity and interfacial tension (IFT) measurements, Fourier transform infrared spectroscopy (FT-IR) characterization and scanning electron microscope (SEM) observation.

Firstly, we needed to treat the crude oil samples and core slices by ultrasonic waves with different frequencies (15, 18, 20, 25, 28 kHz). We put 200 g crude oil or a core slice into a self-made high-temperature and high-pressure reaction tank equipped with the ultrasonic generator. Then we filled the reaction tank by nitrogen and set the reaction pressure at 5 MPa. The reaction tank was placed into a water bath with 80 °C. Finally, we opened the ultrasonic generator. The ultrasonic treatment was intermittent: working 5 min and then stopping 5 min; the treatment loop was repeated 3 times for each sample. Please note that the core slices needed to be saturated with crude oil before ultrasonic treatment and cleaned by oil washing instrument after treatment.

The viscosities of original oil and the oil treated by ultrasonic waves were determined by Brookfield viscometer (produced by AMETEK Brookfield Company, U.S.A.). The interfacial tension between crude oil and brine water was determined by the ring method and conducted by DSA-100 interfacial tension tester (KRüSS Company in Germany). The interfacial tension (IFT) measurements, Fourier transform infrared spectroscopy (FT-IR) characterization and scanning electron microscope (SEM) observation.

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We also verified whether ultrasonic waves can induce the aquathermolysis reaction in the light oil stored in low-permeability reservoirs. The chemical bonds of light oil both before and after ultrasonic treatments were determined by Nexus fourier transform infrared spectroscopy (FT-IR). Finally, the morphology of low-permeability core
slices was characterized by a scanning electron microscope (SEM) (produced by Hitachi S4800, Japan). We would visually compare the differences of microstructures in the core slices treated by ultrasonic waves with different frequencies.

3. Results and discussion

3.1. Clustering analysis and evaluation

In this study, we normalized the basic data of low-permeability cores and grouped 100 core samples based on different cluster methods including DBSCAN, K-means, Mean Shift and Agglomerative clustering algorithms. The grouping results are shown in Fig. 2.

One can observe that the grouping results yielded by different clustering algorithms are different, so this study adopts silhouette coefficient to compare these clustering algorithms. The silhouette coefficient is from −1 to 1 and a high silhouette coefficient usually indicates a good clustering performance. As seen in Table 3, the silhouette coefficients of DBSCAN, K-means, Mean Shift and Agglomerative Cluster algorithms are approximate and all higher than 0.6. This proves that unsupervised learning is a feasible process to group core samples. It is noteworthy that only the DBSCAN algorithm can screen out outliers while the other three clustering methods cannot (Fig. 2). This indicates that the DBSCAN algorithm may eliminate abnormal points and contribute to a more robust grouping result. Therefore, we recommend DBSCAN algorithm to cluster low-permeability cores and the grouping results are shown in Table 4.

We randomly selected five samples in each cluster to conduct the water flooding experiments to further check the grouping performance of DBSCAN algorithm and the results are shown in Table 5. The primary recovery factors ($\eta_1$) of different samples in a given cluster are distributed in a narrow range (i.e., Cluster #1:39.36 ~ 53.32%; Cluster #2: 65.67 ~ 74.27%; Cluster #3: 77.94 ~ 83.69%; Cluster #4: 52.35 ~ 58.93%; Cluster #5: 59.38 ~ 70.31%). More importantly, the cores in cluster #3 possess dramatically lower permeability than those in cluster #4 and cluster #5 but yields a higher primary recovery factor. As such, the traditional experimental method which regards permeability as the only measure of core samples has strong limitations in representing all kinds of low permeability reservoirs. In addition, the cores #8 and #14 (both in Cluster #3) have distinctly different contact angles and porosities, but they yield approximate primary recovery factors while their permeabilities are also similar. This shows that besides permeability, the DBSCAN algorithm can give consideration to both the contact angle and porosity for core grouping. In generally, these results prove that the DBSCAN method adopted in this study can take permeability, porosity and wettability into account and provide an authentic grouping for low-permeability core samples.

3.2. Water flooding experiment coupled with ultrasonic wave

In order to verify the EOR performances of ultrasonic waves in low-permeability reservoirs, we would determine the optimal ultrasonic working frequencies for different clusters of core samples. We treated the five cores in each cluster by different ultrasonic frequencies and determined the secondary recovery factors. As shown in Table 6, we can see that the secondary oil recovery factors of all the core samples are noticeably higher than the primary ones. This demonstrates that the ultrasonic wave has a good performance on assisting water-flooding in low-permeability cores. According to the $\eta_2 - \eta_1$ values in each cluster, the optimal ultrasonic frequencies of the five clusters are 25 kHz, 20 kHz, 20 kHz, 28 kHz and 25 kHz, respectively.

On the whole, the EOR performances of ultrasonic waves in cluster #1, #4 and #5 are better than that in cluster #2 and #3. It means that the ultrasonic wave performs better in the oil-wet and weakly water-wet low-permeability cores than in the strongly water-wet ones. We may explain this phenomenon through a capillary bundle model as shown in Fig. 3.

The flow rate of fluid across the capillary bundle model can be determined according to the Poiseuille equation as:

$$Q = nA\frac{\pi r^4 (p_1 - p_2)}{8\mu L}$$  \hspace{1cm} (1)

where $Q$ is the flow rate, $n$ is the number of capillary tubes per unit area, $A$ is the side area of the model, $p_1$ and $p_2$ represent the inlet and outlet pressure, $\mu$ is the fluid viscosity, and $L$ represents the length of the model. If we define $n^* r^*$ as the permeability $k$, we can get the Darcy equation as:

$$Q = kA\frac{\pi (r_1^2 - r_2^2)}{8}$$  \hspace{1cm} (2)

Please note that the permeability is proportional to the fourth power of pore radius, so the permeability highly depends on the pore radius. For the oil-wet and weakly water-wet core samples, the crude oil easily adheres on pore surface as oil film. If we set the thickness of adhesive layer as $r'$, the permeability can be expressed as:

$$k = n^* \pi (r - r')^4$$  \hspace{1cm} (3)

Eq. (3) states that the adsorption layer can dramatically reduce the permeability, leading to a low primary recovery factor ($\eta_1$) in the oil-wet and weakly water-wet cores (i.e., cluster #1, #4 and #5 adopted in this study). Ultrasonic wave may engender a non-homogeneous vibration in matrix and fluid, which helps to mitigate the oil adsorption and alter the wettability of rock surface. As a result, the ultrasonic wave yields a more noticeable oil recovery improvement in the oil-wet and weakly water-wet cores.

On the other hand, the optimized ultrasonic frequencies for different low-permeability core clusters are different. For the oil-wet cores (cluster #4 and #5) and weakly water-wet cores (cluster #1), the ultrasonic waves with higher frequencies (25 kHz and 28 kHz) perform better on displacing oil. For example, in the cluster #5, the difference of $\eta_2 - \eta_1$ values between core #20 (treated by 25 kHz ultrasonic wave)
and core #5 (treated by 15 kHz ultrasonic wave) was 4.01%. In contrast, for the strongly water-wet cores (cluster #2 and #3), the oil recovery enhancement appears to be relatively insensitive to the frequency of ultrasonic wave and 20 kHz ultrasonic wave yields best performance on oil recovery. Overall, the ultrasonic wave with medial frequency (20 kHz) is recommended for assisting in water flooding within strongly water-wet low-permeability cores, while high-frequency ultrasonic waves have better EOR performances in oil-wet and weakly water-wet low-permeability cores. Furthermore, this study would try to reveal the EOR mechanisms of ultrasonic waves in low-permeability reservoirs via microscopic analyses in following sections.

3.3. EOR mechanism of ultrasonic waves

3.3.1. Viscosity reduction

The viscosity reduction is deemed as one of the major mechanisms for improving heavy oil recovery and this study also investigated the effects of ultrasonic waves with different frequencies (15–28 kHz) on the viscosity of crude oil stored in low-permeability reservoirs. The original viscosity of the oil is 6.97 mPa·s (i.e., a light oil). As shown in Fig. 4, the oil viscosity decreases with increasing ultrasound frequency over 15–25 kHz and the reduction rate of oil viscosity yielded by 28 kHz is similar to that yielded by 25 kHz. However, the reduction rates yielded by ultrasonic waves with different frequencies for this light oil viscosity were all lower than 12%, which are much less than that for heavy oil (about 45%) in previous experiments [43]. Hence, the oil viscosity reduction yielded by ultrasonic wave may not play a dominating role for the EOR in unconventional reservoirs and other mechanisms need to be disclosed.

3.3.2. Interfacial tension measurement

In the low-permeability reservoirs, it is more affected by Jamin effect on displacing oil than conventional reservoirs due to smaller pore radius [44]. As shown in Fig. 5, the Jamin effect is defined as the resistance to liquid flow through capillaries which is due to the presence of droplets.

The micro-capillary force acting on the oil droplets can be expressed as:

$$R_c = R_1 - R_2 = 2\sigma \left( \frac{1}{R_1} - \frac{1}{R_2} \right)$$

(4)

where, \(p_c\) is the additional resistance yielded by Jamin effect, \(R_1\) and \(R_2\) are the principal radii of droplet, \(\sigma\) is the IFT. Thus, a lower oil-water IFT helps to relieve Jamin effect and leads to the oil recovery enhancement in unconventional reservoirs. In order to verify whether the ultrasonic wave is able to alter IFT, this study determined the IFT between brine and the crude oil treated by ultrasonic waves with different frequencies. In this research, the initial interfacial tension between crude oil and brine is 17.38 mN/m. The oil-water IFT variations yielded by ultrasonic treatment are presented in Fig. 6.

The ultrasonic waves with different frequencies reduce the oil-water interfacial tension in varying degrees. The ultrasonic waves with 25 and 28 kHz yields more distinct IFT reduction than those with 15 and 18 kHz. This states that the IFT reduction yielded by ultrasonic wave has positive relation to the frequency. It is widely known that the
ultrasonic wave is capable to change the oil components through aquathermolysis and heating effects and the intermolecular force becomes weak due to the increasing molecular distance, leading to a lower interfacial tension [45]. Admittedly, the IFT reduction yielded by ultrasonic wave is not as effective as surfactant. It is worthwhile to note that their mechanisms for IFT reduction are essentially different: surfactants reduce the interfacial tension through the interface adsorption, while ultrasonic waves cause the irreversible modification of oil compounds. Hence, the IFT reduction yielded by ultrasonic wave may be more environmental-friendly and more effective in a long-term.

### 3.3.3. FT-IR analysis

In order to verify the effects of ultrasonic waves on the compounds of light crude oil, we adopted FT-IR to determine the chemical bond changes of oil sample treated by ultrasonic waves with different frequencies (15–28 kHz). Fig. 7 shows the infrared spectra of crude oil before and after ultrasonic treatments and some typical characteristic wave numbers have been marked. Obviously, these infrared spectra are similar and all possess the absorption peak at 2922, 2852, 1460, and 721 cm⁻¹, which indicate the –CH₂–, –CH₃, –C–CH₃, and aromatic ring, respectively. The only difference occurs at the absorption peak of 1055 cm⁻¹: such absorption peak becomes weak at the infrared spectra of oil treated by 20 and 28 kHz ultrasonic waves. The change of absorption peak at 1055 cm⁻¹ states a hydrodesulfurization reaction and a few component changes in light oil. Previous researches have shown that ultrasonic waves can induce the hydrodesulfurization reaction and effectively lessen the molecular weight of heavy crude oil, resulting in the oil viscosity reduction and oil recovery improvement [46]. Although the ultrasonic wave cannot improve the components of light oil as dramatically as those of heavy oil, such compound changes still contribute to the viscosity reduction and oil-water IFT reduction.

### 3.3.4. Scanning electron microscope (SEM) analysis

Previous researches concentrated on the impacts of ultrasonic waves on physicochemical properties of crude oil [13,29]. It is noteworthy that the ultrasonic energy is high and offers great potential in ameliorating the microstructure of rocks [34]. Thus, in this study, we observed the micromorphology of low-permeability cores after treated by

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**Table 4**

| Cluster # | Core numbers # |
|-----------|----------------|
| 1         | 2,9,13,29,36,39,40,45,49,51,52,61,62,63,66,72,76,77,82,84,89,92,93,98,100 |
| 2         | 4,12,16,24,25,27,38,44,48,73,78,79,91 |
| 3         | 6,7,8,11,14,17,22,23,32,35,37,47,50,54,55,56,57,59,64,67,68,69,81,94,97,99 |
| 4         | 1,3,10,15,30,41,42,43,46,53,58,60,70,71,80,83,85,86,88,95,96 |
| 5         | 5,18,19,20,21,26,33,34,65,87,90 |
| Outlier   | 28,31,74,75 |

**Table 5**

| Cluster # | Core # | Permeability (10⁻⁴ μm²) | Porosity (%) | Contact angle (°) | η₁ (%) |
|-----------|--------|---------------------------|--------------|-------------------|--------|
| 1         | 2      | 0.021                      | 9.56         | 81.41             | 39.36  |
| 2         | 4      | 0.985                      | 7.85         | 45.17             | 74.27  |
| 3         | 6      | 1.125                      | 14.59        | 26.76             | 79.75  |
| 4         | 1      | 1.839                      | 12.02        | 26.04             | 83.52  |
| 5         | 5      | 3.106                      | 14.59        | 26.76             | 79.75  |

| Cluster # | Core # | Frequency (kHz) | η₁ (%) | η₂ (%) | η₂-η₁ (%) |
|-----------|--------|-----------------|--------|--------|------------|
| 1         | 2      | 15              | 39.36  | 45.01  | 5.65       |
| 9         | 18     | 24              | 41.29  | 47.53  | 6.22       |
| 13        | 20     | 25              | 47.65  | 54.44  | 6.79       |
| 29        | 25     | 25              | 54.97  | 57.27  | 2.73       |
| 36        | 28     | 28              | 53.32  | 60.83  | 7.51       |
| 2         | 4      | 15              | 74.27  | 78.3   | 4.03       |
| 12        | 18     | 18              | 70.36  | 75.48  | 5.12       |
| 16        | 20     | 20              | 65.67  | 72.23  | 6.56       |
| 24        | 25     | 25              | 73.91  | 79.74  | 5.83       |
| 25        | 28     | 28              | 66.88  | 72.75  | 5.87       |
| 3         | 6      | 15              | 79.75  | 83.36  | 3.61       |

**Table 6**

| Cluster # | Core # | Frequency (kHz) | η₁ (%) | η₂ (%) | η₂-η₁ (%) |
|-----------|--------|-----------------|--------|--------|------------|
| 1         | 2      | 15              | 39.36  | 45.01  | 5.65       |
| 9         | 18     | 24              | 41.29  | 47.53  | 6.22       |
| 13        | 20     | 25              | 47.65  | 54.44  | 6.79       |
| 29        | 25     | 25              | 54.97  | 57.27  | 2.73       |
| 36        | 28     | 28              | 53.32  | 60.83  | 7.51       |
| 2         | 4      | 15              | 74.27  | 78.3   | 4.03       |
| 12        | 18     | 18              | 70.36  | 75.48  | 5.12       |
| 16        | 20     | 20              | 65.67  | 72.23  | 6.56       |
| 24        | 25     | 25              | 73.91  | 79.74  | 5.83       |
| 25        | 28     | 28              | 66.88  | 72.75  | 5.87       |
| 3         | 6      | 15              | 79.75  | 83.36  | 3.61       |

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Fig. 3. Sketch for the fluid flowing through the capillary bundle model (L is the length of the model, r is the radius of capillary tube, A is the side area of the model, p₁ is the inlet pressure and p₂ is the outlet pressure).
ultrasonic waves via SEM and some representative SEM photos are given in Fig. 8. One may spot small pores and narrow throats in the low-permeability core without the ultrasonic treatment (Fig. 8(a)). These pores and throats are separated and tiny, leading to the low permeability of rocks and poor flowability of fluid within the matrix. After treated by 15 kHz (Fig. 8(b)) and 18 kHz (Fig. 8(c)) ultrasonic waves, the core slices exhibit few changes compared to the original one (Fig. 8(a)). This states that the ultrasonic waves with low frequencies hardly affect the micromorphology of low-permeability cores because of the low efficiency on energy transfer. As shown in Fig. 8(d), there are some micro-fractures in the core slice treated by 20 kHz ultrasonic wave. The formation of micro-fractures may be attributed to ultrasonic cavitation effect. Ultrasonication generates fluctuating low-pressure and high-pressure waves in the liquid phase, resulting in the formation and violent collapse of small vacuum bubbles [47]. Such phenomenon is called cavitation and yields high-energy impinging liquid jets and strong hydrodynamic shear-forces. As a result, the individual small pores and throats will be connected and the micro-fractures will be widened in the low-permeability core samples. These micro-fractures may improve the permeability of rocks and contribute to the oil displaced by flooding water. With the ultrasonic treatments of 25 kHz (Fig. 8(e)) and 28 kHz (Fig. 8(f)), the pores and throats become larger than those in the original core (Fig. 8(a)), which gives a better connectivity and enhances the capacity in allowing fluid flow through the matrix. However, we hardly spot the micro-fractures in these two core slices. This is because the intensity of the cavitation effect yielded by ultrasonic wave would be comparatively less at higher frequency and the alternating times are too short to make the vacuum bubbles large enough and violently implode [47].

Based on above analysis results, we can attribute the EOR mechanism of ultrasonic waves to the synergies gained from oil-viscosity reduction, oil-water IFT reduction and the micro-structure modification of rock in the low-permeability reservoirs. Especially, in the oil-wet and weakly water-wet low-permeability cores, the ultrasonic waves with higher frequencies (25 kHz and 28 kHz) exhibit better EOR performances because their strong ability to reduce the oil-water IFT and relieve the oil film adsorbed to the rock surface. In the strongly water-wet core samples, the ultrasonic wave with a media frequency (20 kHz) performs better on EOR because of the formation of micro-fractures and the enhancement of pore connectivity within the cores. In general, coupled with DBSCAN clustering algorithm proposed in this study, these experimental observations probably provide a reliable guidance for the optimization of ultrasonic wave frequency in EOR purposes.
Ultrasonic wave is a promising method to further improve the water-flooding oil recovery in low-permeability reservoirs. In order to provide a theoretical guidance of ultrasonic wave in EOR, this study has developed an algorithm for grouping the low-permeability cores and determined an optimal frequency of ultrasonic wave for each core cluster. Furthermore, we have explained the EOR mechanism of ultrasonic waves in low-permeability reservoirs via SEM observation, interfacial tension measurement and infrared characterization. The major

**Fig. 8.** SEM photos of low-permeability cores treated by ultrasonic waves with different frequencies: (a) original core samples; (b) with 15 kHz ultrasonic treatment; (c) with 18 kHz ultrasonic treatment; (d) with 20 kHz ultrasonic treatment; (e) with 25 kHz ultrasonic treatment; (f) with 28 kHz ultrasonic treatment.

### 4. Conclusion

Ultrasonic wave is a promising method to further improve the water-flooding oil recovery in low-permeability reservoirs. In order to provide a theoretical guidance of ultrasonic wave in EOR, this study has developed an algorithm for grouping the low-permeability cores and determined an optimal frequency of ultrasonic wave for each core cluster. Furthermore, we have explained the EOR mechanism of ultrasonic waves in low-permeability reservoirs via SEM observation, interfacial tension measurement and infrared characterization. The major
research findings are as follows:

(1) Unsupervised learning method serves as a reliable tool for grouping low-permeability cores. DBSCAN clustering algorithm adopted in this study can take porosity, permeability and contact angle into consideration and classify 100 core samples into five categories while eliminate four abnormal points.

(2) Ultrasonic wave has a good EOR performance on assisting waterflooding in low-permeability cores, especially in the oil-wet and weakly water-wet cores. The ultrasonic wave with medial frequency (20 kHz) is recommended in strongly water-wet low-permeability cores, while a high-frequency ultrasonic wave has a better EOR performance in oil-wet and weakly water-wet low-permeability cores.

(3) Although the ultrasonic wave cannot ameliorate the components of light oil as dramatically as those of heavy oil, such compound changes still contribute to the oil viscosity and oil-water IFT reductions.

(4) Ultrasonic wave can alter the micromorphology of low-permeability cores and improve the pore connectivity. With a media frequency (20 kHz), the ultrasonic wave may cause the formation of micro-fractures.

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