INTRODUCTION

Halfaya Oilfield is located in Missan Province in the southeast of Iraq, the Middle East. In this oilfield, seven series of oil-bearing strata are vertically developed and divided into nine series of development strata. Its principal oil reservoir, Mishrif, is an immense marine carbonate reservoir, which is vertically thicker, better distributed laterally, and overall better in the base of physical properties. Under the joint effect of sedimentation and diagenetic reformation, the oil reservoir of Mishrif Formation is of strong heterogeneity vertically and laterally with local low-permeability zones areally. In this oilfield, seven series of oil-bearing strata are vertically developed and divided into nine series of development strata. Its principal oil reservoir, Mishrif, is an immense marine carbonate reservoir, which is vertically thicker, better distributed laterally, and overall better in the base of physical properties. Under the joint effect of sedimentation and diagenetic reformation, the oil reservoir of Mishrif Formation is of strong heterogeneity vertically and laterally with local low-permeability zones areally.2,3

1 Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, China
2 Petrochina (Halfaya), Middle East Branch, CNODC, Beijing, China
3 Anton Oil Company, Beijing, China

Correspondence
Dawei Zhu, Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, China.
Email: zhudawei69@petrochina.com.cn

Funding information
National oil and gas major projects—Research and Application of Key Technologies for Oil and Gas Development in Complex Carbonate Reservoirs in Central Asia and Middle East, Grant/Award Number: 2017ZX05030-005

Abstract
The oil reservoir of Mishrif Formation is of strong heterogeneity vertically and laterally, and its single-well production rate after conventional acidizing is low and declines fast. Therefore, we intend to carry out the pilot test on diverting acid fracturing so as to improve the stimulation effect of acid fracturing by enlarging the lateral and vertical stimulation range. In this paper, a series of experimental studies (e.g., rock mechanics, acid rheology, acid-rock reaction kinetics, and full-diameter core etching diversion) were carried out to deal with the reservoir characteristics and stimulation demand of Mishrif Formation, the principal oil reservoir in Halfaya Oilfield in Iraq, the Middle East. It is shown that calcite content of Mishrif Formation reservoir is higher than 95%, indicating the strong acid dissolution. As for rock mechanics, the characteristics of “low Young's modulus and high Poisson's ratio” are presented, and the stress-strain curves show certain elastic-plastic characteristics. Additionally, a large number of wormholes appear on the surface of the full-diameter cores after acid etching, so it is necessary to consider the serious filtration of acidizing fluid near the wellbore. The mechanical strength of rock plates decreases after acid etching, so it is recommended to adopt and optimize the closed acidizing technology so as to avoid excessive etching. Furthermore, the self-support flow conductivity of etched fractures is weak, so it is recommended to adopt the sand fracturing or the combined stimulation technology of acid fracturing + sand fracturing to improve the reservoir stimulation effects.

KEYWORDS
acid fracturing, carbonate oil reservoir, closed acid fracturing, flow conductivity of etched fracture, wormhole
this area, conventional acidizing operation is carried out, but single-well production rate is low and declines fast, and consequently the demand of production proration is not satisfied. After the reservoir characteristics and the stimulation potential are analyzed completely, it is proposed on site to carry out the pilot test of acid fracturing to explore the efficient way to produce the low-permeability reservoir of this kind of oil reservoirs.

There are two key factors for the effect of acid fracturing: the effective length of acid-etched cracks and the fracture conductivity.\(^4,5\) Reducing the loss of acid and slowing down the reaction rate of acid can effectively solve this problem. The common method is to increase the viscosity of acid system.\(^6,7\) Lizhong et al\(^8\) used prefluid + high temperature emulsifying acid + solid nitric acid fracture acidizing technology to acidize marl reservoir, effectively alleviating acid loss, and realizing long-distance acid fracturing. Haitao et al\(^9\) analyzed the acid leak mode during acid fracturing in dolomite reservoir. Alternate acid injection and additional preslug can control the acid leak well. At present, the feasibility of acid fracturing is often analyzed by the rheological property of acid fluid system and acid-rock reaction kinetics.\(^10-12\) The etching of full-diameter cores from carbonate reservoirs in the Middle East by acid solution and the formation of wormholes after reaction are seldom analyzed.

In this paper, a series of experimental studies, for example, rock mechanics, acid rheology, acid-rock reaction kinetics, full-diameter core etching diversion, and analysis of three-dimensional digital imaging technology were carried out on the cores of Mishrif Formation to analyze the stimulation feasibility of acid fracturing in Mishrif Formation, so as to provide the theoretical guidance for the optimal design of acid fracturing and the reference for the stimulation measures of similar reservoirs in the Middle East.

2 | ANALYSIS ON THE GEOLOGICAL CHARACTERISTICS AND ACID FRACTURING DIFFICULTIES OF MISHRIF FORMATION RESERVOIR

Mishrif Formation reservoir, as the principal horizon in Halfaya Oilfield, contributes 50% of the production. In Mishrif Formation reservoir, the reservoir of grain bank is mainly developed. Reservoir thickness is 120-350 m. It covers a large area vertically and is better distributed laterally. The cast thin section of cores shows that the micropores in Mishrif Formation reservoir are structurally complex with multiple pore types. Primary pores (e.g., intergranular pore, biological cavity pore, organic framework pore) and secondary pores (e.g., moldic pore, dissolved pore, intragranular dissolved pore, and intercrystal pore) are coexisted. The characteristic of multiple modal is presented and the heterogeneity is strong vertically and laterally.\(^1\) The measured parameters of physical property of reservoir core samples show that the average porosity of the cores taken from Mishrif Formation reservoir is in the range of 5.89%-26.37%, and the average permeability is \((0.34-109.70) \times 10^{-3} \text{ μm}^2\). Three types of reservoirs are developed, that is, high porosity and moderate-high permeability reservoir, moderate porosity and low-permeability reservoir, and moderate porosity and low-permeability reservoir, and the correlation between porosity and permeability is poor. X-diffraction bulk rock analysis shows that the calcite content of Mishrif Formation reservoir is higher than 95%, and its content of clay minerals is lower than 3%, so it is lithologically pure. The reservoir temperature is about 90°C and the formation pressure coefficient is 1.16.

Due to the characteristics of reservoir space, rock mechanics and oil reservoir structure, the porous carbonate reservoirs in Halfaya Oilfield are faced with the main technical difficulties of acid fracturing as follows.

1. The reservoir of Mishrif Formation is a layered oil reservoir with edge and bottom water. And especially for the well at the edge of the structure, its lower boundary of perforation interval is relatively close to the oil/water transition zone, so the height of artificial fracture shall meet a certain requirement.

2. The stress section shows that the vertical stress barriers in the reservoir are not developed significantly, and their sheltering capacity is poorer, so in a way, it is difficult to control the fracture height.

3. The reservoir is of strong heterogeneity vertically and laterally, so its acid fracturing is faced with the leak-off of working fluid and the limited propagation of etched fracture, and its sand fracturing is suffered from heavy leak-off at the fracture tip, difficult propagation, and high construction risk.

4. The carbonate mineral content of the reservoir is high, its clay content is low, and it is lithologically pure, so it is difficult to realize nonuniform etch by using the acidizing fluid.

5. The Young’s modulus of the rocks is low, and the self-support rock mechanical strength of etched fractures is low, so it is difficult to maintain the flow conductivity of etched fractures for a long term.

3 | ROCK MECHANICS TEST

The stress-strain relationship curve and the triaxial compression strength of rocks can be obtained by adopting RTR1000 static (dynamic) triaxial rock mechanics testing system to carry out triaxial compression test on the rocks. Young’s modulus and Poisson’s ratio of rocks are calculated based on the elastic stage of the stress-strain relationship...
The rock mechanics test results of the cores are shown in Table 1. Table 1 indicates that five groups of cores are similar in burial depth, but more different in rock mechanical characteristics. On the whole, the reservoir of Mishrif Formation is characterized by high Poisson’s ratio (average 0.333) and low Young’s modulus (average 17.231 GPa), which are the typical characteristics of elastoplasticity. Figure 1 shows the stress-strain relation of rock sample No. 1V. It presents the typical characteristic of elastoplasticity and the breakdown occurs (interior) until the vertical strain is higher than 1.3 from the curve but not obvious from the appearance of the sample. And it is indicated that 1V rock sample has characteristic of stronger plasticity. 11V rock sample also presents the typical characteristics of elastoplasticity (Figure 2) and it suffers shear damage along the weak plane.

To sum up, the rock samples of Mishrif Formation reservoir are more incompetent with stronger plasticity, so the fracturing pressure and propagation pressure of the rocks are higher.

### 4 | ACID RHEOLOGY EXPERIMENT

It is planned to adopt diverting acid fracturing to stimulate Mishrif Formation reservoir. And the formula of the diverting acid system in the experiment is 20 wt% HCl+7%ADZ diverting agent + 1.5%ADH corrosion inhibitor + 1.5%ADT multi-function additive.

Figure 3 shows the rheology experiment result of diverting acid under the shear effect for 60 min at the temperature of 90°C. It is indicated that the apparent viscosity of the diverting acid does not change greatly with the temperature. When the experiment temperature is kept at 90°C, the apparent viscosity is relatively stable at 20 mPa/s. And, it is revealed that this acid system has better temperature tolerance and shear resistance.

Figure 4 is the relationship curve of apparent viscosity vs. shear rate of diverting acid at the temperature of 90°C. Curve fitting shows that consistency coefficient (K) is 2558.1 mPa·sn and power law exponent (n) is 0.066, presenting the typical characteristics of non-Newtonian fluid. With the increase of the shear rate, the viscosity decreases and the fluidity increases.

### 5 | ACID-ROCK REACTION KINETICS EXPERIMENT

The dynamic parameters of acid-rock reaction are the basic parameters of acid fracturing design. In view of the lithologic characteristics of the reservoir, the rotating disk reactor is adopted to measure the acid-rock reaction rate of diverting acid. It is shown that the acid-rock reaction rate of diverting acid is lower and it is $2.5721 \times 10^{-5} \text{ mol/(cm}^2\text{s)}$, so it can be used for the treatment of deep zones. And the test results are shown in Table 2.

Figure 5 shows that after the acid-rock reaction, pores of different sizes emerge on the surface of the rock, and they are completely different from the etched products on tight carbonate rocks. And their formation is caused by the strong heterogeneity and good porosity-permeability structure of the rock.

### 6 | FULL-DIAMETER CORE ETCHING EXPERIMENT

Lab simulation on the reaction between the acidizing fluid and the rock of the fracture surface in the in-situ acid fracturing

---

**Table 1** Rock mechanics test results

| No. | Interval | Burial depth (m) | Confining pressure (MPa) | Temperature | Poisson’s ratio | Young’s modulus (MPa) | Compression strength (MPa) |
|-----|----------|------------------|--------------------------|-------------|----------------|----------------------|--------------------------|
| 1V  | Mishrif A2 | 2870.60          | 10.6                     | 90°C        | 0.333          | 15 320.2             | 92.1                     |
| 4V  | Mishrif B1-2B | 2951.88        | 10.9                     |             | 0.399          | 13 964.7             | 77.8                     |
| 7V  | Mishrif B1-2B | 2952.40        | 10.9                     |             | 0.159          | 26 379.2             | 107.3                    |
| 9V  | Mishrif B1-2B | 2954.31        | 10.9                     |             | 0.385          | 12 472.9             | 27.1                     |
| 11V | Mishrif B2  | 3002.00         | 11.1                     |             | 0.389          | 18 020.1             | 120.8                    |
| Average |        |                 |                          |             | 0.333          | 17 231.42            | 85.02                    |
condition has two functions. On the one hand, it can predict the acid fracturing effect so as to optimize the design of acid fracturing. And, on the other hand, it can quantitatively characterize the surface morphology of etched fractures and provide the authentic and reliable data for analyzing the change laws of the flow conductivity of etched fractures, as well as the reliable parameters for related mathematical models.

The full-diameter cores of Mishrif Formation reservoir are adopted in this experiment. After the cores are screened, they are processed into the etched rock plates which are in accordance with the API standard. The simulation system and flow chart adopted in this experiment are shown in Figure 6.

6.1 Weight change of rock plate after acid etching

The weight change of rock plates after acid etching is shown in Table 3. The total acid dissolution of No. 1 rock plate is 57.1 g and that of No. 2 rock plate is 19.62 g. And they account 8.62% and 3.83% of original total weight, respectively. Their difference is obvious, for the acid contact area of No. 1 rock plate is 28.4 cm² larger than that of No. 2 rock plate and more wormholes are formed during the etch of No. 1 rock plate to increase the acid-rock contact area further.

6.2 Surface morphology of rock plate before and after acid etching

No. 1 rock plate (Figure 7) suffers acid-rock reaction except the cementation position point. After acid etching, no obvious etched groove is formed on this rock plate (Figure 8), but a great number of wormholes emerge. In addition, the wormholes on Core No. 3 (the exit of the acid) are denser and deeper than those on Core No. 2, and through wormholes are observed even on the back face of Core No. 3. On Core No. 2, however, through wormholes are observed only at the inlet of acid (Figure 9).

Digital imaging of the surface of No. 1 rock plate (Figure 10) shows that more wormholes are formed on the surface of two pairs of rock plates after acid etching and even through wormholes emerge at the edge. The etching form of point pit occurs on the rock plate, but there is no obvious etched groove.

No. 2 rock plate is more complete. It is taken from Core No. 1 in the interval of 2957.43-2957.57 m. Core No. 1 is in the same horizon as Core No. 2 and Core No. 3 of No. 1 rock plate, that is, Mishrif B1-2B, and they are only 9.43 m away from each other. Filled natural fractures are observed obviously in the central part of No. 2 rock plate (Figure 11). After acid etching, wormholes that are distributed nonuniformly emerge on the whole surface (Figure 12), and obvious corrosion and wormholes occur on filled natural fractures (Figure 13). There are obviously wormholes at the end of the rock sample, and after acidizing fluid flows over, unconsolidation and even the indication of falling off emerge.

When observing further the forms after acid etching (Figure 14), we discover that many wormholes are formed on the surface of two pairs of rock plates after acid etching and the etching form is the typical pitting etch without obvious etched groove.
### TABLE 2  Test result of acid-rock reaction rate of diverting acid

| Acid system     | Before the reaction (g) | After the reaction (g) | Weight loss (g) | Reaction rate $\times 10^{-5}$ mol/(cm$^2\cdot$s) |
|-----------------|-------------------------|------------------------|-----------------|-----------------------------------------------|
| Diverting acid  | 26.6774                 | 24.7276                | 1.9498          | 2.5721                                         |

**FIGURE 5**  Comparison of rock surface before and after the acid-rock reaction of diverting acid

**FIGURE 6**  Physical simulation system and flow chart of acid etching

**FIGURE 7**  No. 1 rock plate before being etched by diverting acid
TABLE 3  Weight change of rock plates after acid etching

| Experiment No. | Rock plate No. | Contact area/cm² | Weight before the reaction/g | Weight before the reaction/g | Weight difference/g |
|---------------|----------------|-------------------|------------------------------|------------------------------|---------------------|
| 1             | Upper          | 61                | 327.69                       | 298.62                       | 29.07               |
|               | Lower          | 61                | 334.35                       | 306.32                       | 28.03               |
|               | Total          | 122               | 662.04                       | 604.94                       | 57.1                |
| 2             | Upper          | 46.8              | 261.48                       | 251.69                       | 9.79                |
|               | Lower          | 46.8              | 250.42                       | 240.59                       | 9.83                |
|               | Total          | 93.6              | 511.9                        | 492.28                       | 19.62               |

FIGURE 8  No. 1 rock plate after being etched by diverting acid

FIGURE 9  Through wormhole at the edge of No. 1 rock plate

FIGURE 10  Digital imaging of the surface of No. 1 rock plate
The average development length of wormholes is estimated by using the point cloud coordinate of 3D digital imaging, seeing Table 4 (Figure 15).

After acid etching, no obvious etched groove is formed on No. 1 and No. 2 rock plate, and pitting etch is dominant. The experimental phenomena are analyzed as follows.

1. After acid etching, a great number of wormholes are formed on the surface of No. 1 and No. 2 rock plate and some of them are even through wormholes. The density, average diameter, and length of wormholes on No. 1 rock plate are superior to those on No. 2 rock plate. As a result, the filtration of acidizing fluid in the process of acid fracturing is aggravated and its effective etching distance is decreased.

2. Obvious corrosion and deeper wormholes occur on the filled natural fractures of No. 2 rock plate. The filled natural fractures in the reservoirs are the potential pathways of acid filtration.

3. The phenomenon of rocks’ falling off occurs on the surface of No. 2 rock plate after acid etching. It is indicated that the mechanical strength of the rock plate is reduced after acid fracturing.

4. There are pitting etches on both No. 1 and No. 2 rock plate, but no obvious etched groove and “pillar”. After the fracture is closed, therefore, the contact area of upper and lower rock plate is large, and the fracture is narrow. In this way, the initial flow conductivity is lower and the self-support capacity of etched fractures is weak.

7 | CONCLUSIONS

1. The rocks of Mishrif Formation reservoir are of strong acid dissolution and the etched fractures are morphologically simple. Multistage alternative injection of fracturing fluid and acidizing fluid can be adopted into the acid fracturing process to increase the complexity of the etching morphology of etched fractures so as to improve their flow conductivity.

2. In the test of rock mechanical parameter, the whole reservoir presents the characteristics of elastoplasticity, that is, low Young's modulus and high Poisson's ratio. In the process of acid fracturing, rock fracturing pressure is high, the tip extension is hindered, and the propagation mechanism is complex. In the following step, it is necessary to study the propagation laws of artificial fractures so as to provide the guidance for treatment design and post-frac evaluation.
3. In the process of the full-diameter core etch experiment, a great number of wormholes are formed on the surface. During acid fracturing, therefore, it is necessary to consider the serious filtration of acidizing fluid near the wellbore to guarantee the etching distance of acidizing fluid, so that the expected stimulation effect can be realized. It is recommended to make use of fiber, ceramic powder, or other fluid loss additives to reduce the filtration of acidizing fluid, and adopt crosslinked fracturing fluid during the alternative injection of fracturing fluid and acidizing fluid. The self-support flow conductivity of etched fractures is weak, so it is suggested to adopt the sand fracturing technology or the combined stimulation technology of acid fracturing + sand fracturing to improve the reservoir stimulation effects.

4. After acid etching, the phenomenon of rock powder’s falling off occurs, leading to the serious decrease of rock mechanical strength. Therefore, attention shall be paid to the application of acidizing process and the determination of closed acid volume to avoid excessive etching near the wellbore.

**TABLE 4**  Length of wormhole

| Core No. | 1-upper | 1-lower | 2-upper | 2-lower |
|----------|---------|---------|---------|---------|
| Ave L, mm | 7.09    | 8.03    | 8.16    | 6.19    |

**FIGURE 14**  Digital imaging of the surface of No. 2 rock plate

**FIGURE 15**  Cloud chart of scanning points on the surface of the rock plate
ACKNOWLEDGMENTS

This study was supported by National oil and gas major projects—Research and Application of Key Technologies for Oil and Gas Development in Complex Carbonate Reservoirs in Central Asia and Middle East (Grant No.: ZX2017030005).

ORCID

Dawei Zhu https://orcid.org/0000-0003-0288-3110

REFERENCES

1. Jun W, Rui G, Limin Z, et al. Geological features of grain bank reservoirs and the main controlling factors: a case study on Cretaceous Mishrif Formation, Halfaya Oilfield, Iraq. Petrol Explor Dev. 2016;43(3):367-377.
2. Xinmin S, Yong L. Optimum development options and strategies for water injection development of carbonate reservoirs in the Middle East. Petrol Explor Dev. 2018;45(4):679-689.
3. Jixian G, Changbing T, Weimin Z, et al. Reservoir characteristics and development model of Middle Cretaceous Mishrif Formation, Persian Gulf Basin. Chin J Geol. 2013;48(1):304-316.
4. Tingxue J, Yiming Z, Xingkai F, et al. Hydraulic fracturing technology in clay-carbonate fractures reservoirs with high temperature and deep well depth. Petrol Explor Dev. 2007;34(3):348-353.
5. Jianghong M, Yumei Z. The discusses of acid fracture technique for carbonate rock storing layer. J Xinjiang Petrol Inst. 2003;15(1):77-80.
6. Subing W. Study on filtration control acid fracturing. Drill Prod Technol. 2001;24(5):51-53.
7. Yonggao X, Baochun C, Baoshan G, et al. Study and application of acid-fracturing techniques with viscousified acid in Changqing Oil Field. Nat Gas Ind. 2005;25(4):103-105.
8. Lizhong W, Xingzun W, Xiufeng L, et al. Application of emulsified and nitric acid fracturing in muddy limestone reservoirs. Oil Drill Prod Technol. 2005;27(3):63-66.
9. Haitao W, Xiangfang L, Xiangyi Y, et al. Filtration control of acidizing fluid in the process of acid fracturing in dolomite reservoirs. Nat Gas Ind. 2009;29(12):62-64.
10. Nianyin L, Liqiang Z, Qian Z, et al. Acid etched fracture conductivity study in acid fracturing. Drill Prod Technol. 2008;31(6):59-62.
11. Sarma DK, Rao YRL, Mandal B, et al. Application of self-diverting acid system for stimulation of multilayered wells in carbonate reservoir: a case study. SPE 154554, 2012.
12. Wang G, Gomaa AM, Nasr-el-din HA. Effect of initial HCl concentration on the performance of new VES acid system. SPE 14349, 2011.

How to cite this article: Zhu D, Hu Y, Cui M, et al. Feasibility analysis on the pilot test of acid fracturing for carbonate reservoirs in Halfaya Oilfield, Iraq. Energy Sci Eng. 2019;7:721-729. https://doi.org/10.1002/ese3.290