CSCanada
Advances in Petroleum Exploration and Development
Vol. 12, No. 2, 2016, pp. 13-18
DOI:10.3968/8991

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

Influence of Filling Medium on Water Injection in Fracture-Vuggy Reservoir

XIE Haojun[a]; LI Aifen[a],*; LÜ Aimin[a]; LI Gangzhu[a]

[a]School of Petroleum Engineering, China University of Petroleum, Qingdao, China.
*Corresponding author.

Supported by National Science and Technology Major Project of China (2016ZX05014-003-002, 2016ZX05009-001-007).

Received 7 November 2016; accepted 5 December 2016
Published online 28 December 2016

Abstract

The Tahe oilfield is characterized with high degree of filling medium in an underground caves and shortage of bottom water in some unites. In addition, it has poor oil displacement effect with water injection, and low recovery rate. Considering geological interpretation results, the cave filling models with different filling mediums are designed. Through physical simulation experiments, the displacement mechanism between the un-filled areas and the filling medium were fully studied. Meanwhile, the effect of filling medium's wettability, pore size and fluid elastic energy on the oil-water displacement efficiency were clarified. The results showed that: In the process of oil-water displacement, the capillary resistance in the oil-wet filling medium may hinder the oil-water gravity differentiation, making it impossible for the oil in the filling medium to be replaced effectively, so there is a large amount of remaining oil in the filling medium. The stronger the oil wettability of the filing medium and the smaller pore size, the lower the displacement efficiency. Increasing injecting pressure could only increase the formation energy and improve oil production at the beginning, but it could not improve oil displacement efficiency in filling medium. Injection of surfactant could reduce the oil-water interfacial tension and improve the oil phase utilization degree of the filling medium effectively. Field application has the same results with the experiment, so the surfactant injection is an EOR method to improve oil displacement for fracture-cave reservoir with high degree of filling medium.

Key words: Fracture-vuggy reservoir; Filling medium; Water injection; Gravity differentiation; Remaining oil

Xie, H. J., Li, A. F., Lü, A. M., & Li, G. Z. (2016). Influence of filling medium on water injection in fracture-vuggy reservoir. *Advances in Petroleum Exploration and Development*, *12*(2), 13-18. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/8991
DOI: http://dx.doi.org/10.3968/8991

INTRODUCTION

For fractured-vuggy carbonate reservoirs of Tahe Oilfield in China, caves and fractures are main spaces for fluid storage and flow, in contrary the carbonate rock matrix has little capacity since it has low porosity and permeability. There are huge variations of production data between wells because of the strong heterogeneity and randomly distributed caves in fractured-vuggy reservoirs. The huge caves are normally filled with collapsing rocks, carried sands or chemical sedimentation, while different kinds of filling mediums have different wettability and permeability[1]. Typical cave with filling medium of field outcrop is shown in Figure 1. Since these filling mediums have high porosity and permeability compared with carbonate matrix, they cover a great part of original oil in reservoirs. Most wells can only be drilled to the top of the cave with barefoot completion because of heavy loss of drilling fluid in caves, so we usually use gravity differentiation effect to displace the oil by gravity in Tahe oilfield[2]. In recent years, many physical and numerical simulations have been conducted for the flow mechanism and remaining oil distribution in fractured-vuggy media.

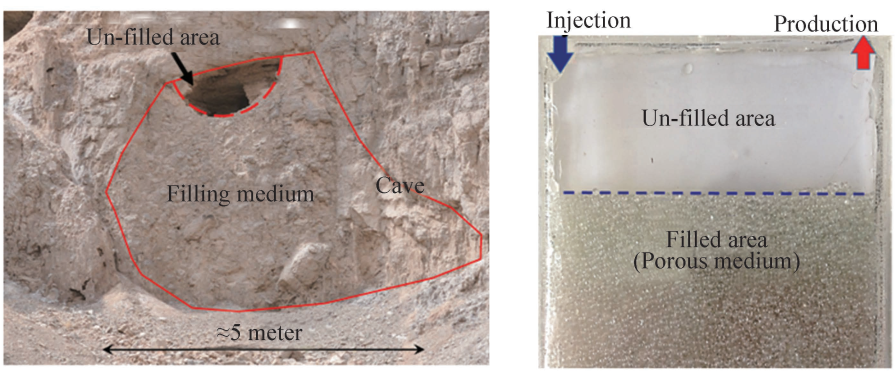
Using vuggy rocks flooding experiment and numerical simulations, Moctezuma (2000), Cruz (2011), Arbogast (2004), and Zhang et al. (2005) studied the fluid flow behavior in fractured-vuggy media[3-6]. Egermann and Laroche (2007) use the tight matrix rocks with large vugs to evaluate the matrix-imbibition phenomenon and complex water-gas-flow interactions between vugs and micro-pores[7]. Omer (2010) also used vuggy cores to study the acidizing process[8]. Then Kang (2007), Wang (2011) and Rezaei et al. (2014) used glass etched microscopic model to stimulate the water injection process in fracture and vug in low pressure[9-11]. While Li (2010) built a large size PVC tank to simulate the fracture-vuggy reservoirs, and considering the filling medium using glass balls without cemented in the cave[12]. After that, Zhang (2012) conducted the elastic recovery experiment in insular cavity using high-pressure container[13]. Also, Wang (2012) used full diameter cores with drilled vugs to study the distribution and mechanism of remaining oil[14]. Although some experiment considering the filling medium, but they use only glass balls or carbonate rocks, and the wettability, porosity, permeability and cementing properties are not considered. Besides, some researchers did many works on the single-phase coupling flow in fractured-vuggy media[15-17], which is different with the two-phase flow in reservoirs.

In order to study the oil-water exchange mechanism, we design the cave filling model considering the physical properties of the filling medium according to the reservoir geologic information. By experiments of water injection substituting oil, we analyze the influence of wettability, pore size and fluid elastic energy on the displacement efficiency and remaining oil distribution. The result indicated that, water injection substituting oil could increase the formation pressure and the oil production temporarily, but the capillary force is the main reason for the remaining oil and low oil recovery in the filling medium. Therefore, this study will analyze the EOR mechanism using surfactant in fractured-vuggy reservoirs to improve displacement efficiency and oil recovery in the filling medium.

1. PHYSICAL MODEL AND METHODS

1.1 Physical Model

Visible physical models were built to study the oil-water exchanging mechanism according to the field outcrop (Figure 1). The model used PMMA (polymethyl methacrylate) as transparent boundary to simulate the cave. The glass beads were cemented by epoxy in bottom of the model, to simulate filling medium area in the cave. The empty part at the top is the unfilled area, as it is shown in Figure 1(b). Size of the model is 10 cm × 10 cm × 1 cm; filling degree in caves is about 50%; the particle size of filling medium is 0.6 mm and 0.3 mm, while porosity of the filling medium is about 35%. Injection well and production well were drilled at two sides on the top of the model as shown in Figure 1(b).



(a) Field Outcrop of Filled Cave **(b) Physical Model**

Figure 1
Field Outcrop and Physical Model of Filled Cave

1.2 Material

In this experiment, saline water (5,000 mg/L) and kerosene were used as formation water and oil. And the kerosene was colored by Sudan III. The surfactant HFYQ-B solutions (0.2% wt) with the formation water were prepared. Using the Spinning Drop Interfacial Tensiometer, interfacial tensions (IFT) were measured at 20 °C. The interfacial tensions between the saline water and the oil is about σ_{wo} = 25 mN/m. The interfacial tensions between the solutions and the simulated oil is about σ_{so} = 1.8 mN/m.

Wettability of the pore surface in filling medium was controlled by the epoxy[18]. The contact angle of saline water and kerosene on water-wet and oil-wet pore surface is about 81° and 108° at 20 °C.

1.3 Experiment Procedures

The experiment flow chart is shown in Figure 2, and the procedures are as follows:

(a) Fully saturate the model with oil, and measure the oil volume in the model.

(b) Inject water with a low flowrate of 1 ml/min and produce liquid under atmospheric pressure. Keep water injection for 48 hours and record the process of water displacing oil under gravity.

(c) Record fluid flow dynamic and liquid production, then clean and dry the model.

(d) Change the injection fluid or models, then repeat the process (1) - (3).

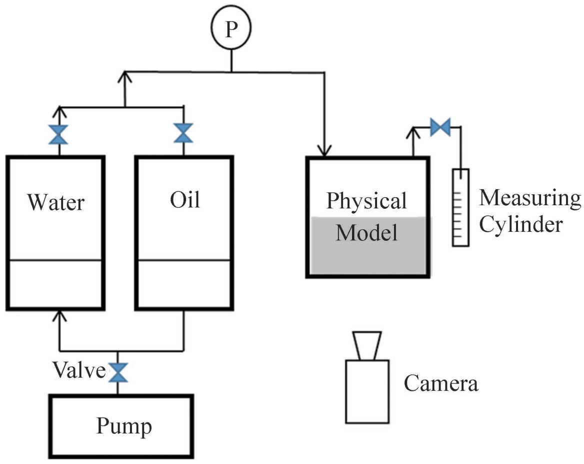


Figure 2
Experiment Flow Chart

2. RESULTS AND DISCUSSION

2.1 Experiment Results

The physical model parameters and experiment results were shown in Table 1. Models 1 to 3 are visible models for low pressure water injection experiment. Model 4 was made by cementing the filling medium of oil-wet in the high-pressure container to simulate the cyclic water-flooding production.

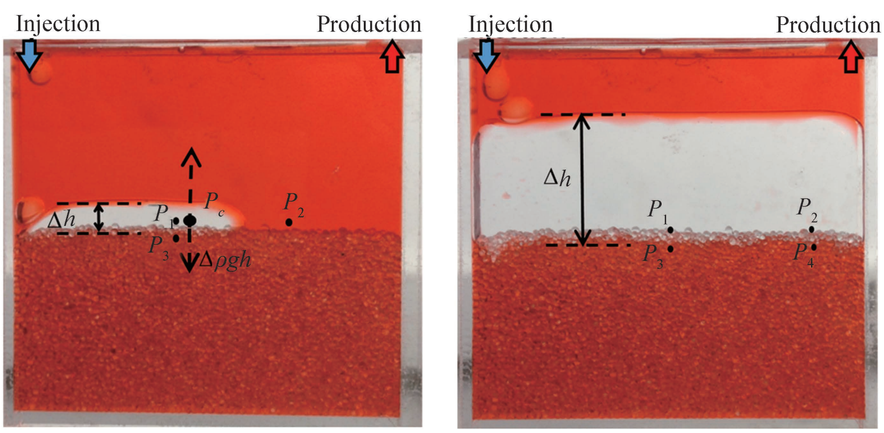
The filling degree is about 50% and the porous medium porosity is about 35%, so the initial oil in un-filled area occupy about 74.1% of the initial oil saturated in the whole model. In all experiments, the oil recovery after water injection can exceed 72%, which means that the oil in un-filled area can be displaced by water. Since the model in this paper is simplified and is ideal from formation, the oil recovery is much higher than the reservoirs. However, the oil recovery varied for different models and injected fluids, we will discuss the results by different factors afterwards.

Table 1
Physical Parameters and Oil Recovery of the Models

Model	Model type	Wettability	Diameter of particle	Diameter of minimum pore	Oil recovery after water injection	Oil recovery after surfactant injection
1	Low pressure	Oil-wet	0.6 mm	About 0.2 mm	72.8%	92.6%
2	Low pressure	Water-wet	0.6 mm	About 0.2 mm	94.3%	94.3%
3	Low pressure	Oil-wet	0.3 mm	About 0.1 mm	72.0%	72.0%
4	High pressure	Oil-wet	0.6 mm	About 0.2 mm	73.1%	93.7%

2.2 Capillary Force and Gravity Analysis

Taking the Model 1 as the example, oil distributions in water injection at different time were shown in Figure 1, in which the oil is red and water is colorless. At the beginning of water injection, the water droplets dropped on the surface of the filled area under gravity, and then spread on the surface with a height ($\triangle h$) of about 0.8 cm as shown in Figure 3(a). We choose 3 points at almost the same height on the surface of filling medium to calculate the capillary pressure and gravity. Point 1 is at the surface of filling medium in water phase, point 2 is just below the surface of the filling medium in oil phase, point 3 is at the surface of filling medium in the oil phase.



(a) 5 min **(b) 30 min**

Figure 3
Oil Distribution of Model 1 at Different Time of Water Injection

Since the filling medium of Model 1 is oil-wet, the capillary force at the surface is opposite to the gravity. Water injection flow rate is just 1 ml/min, so the injection-production pressure difference can be neglected because of the free flow in un-filled area. The pressure relationships between these points are as follows:

$$P_c = P_1 - P_3\,, \tag{1}$$

$$P_2 = P_3\,, \tag{2}$$

$$\Delta P = P_1 - P_2 = (\rho_w - \rho_o)g\Delta h\,, \tag{3}$$

$$P_c = \frac{2\sigma\cos\theta}{r}\,. \tag{4}$$

Where: P_c, capillary pressure, Pa; σ, interfacial tension, mN/m; θ, contact angle, degree; P_1, P_2, P_3, P_4, pressures at different points, Pa; ΔP, pressure difference between P_1 and P_2; ρ_w, water density, kg/m^3; ρ_o, oil density, kg/m^3; g, gravity, m/s^2; Δh, height of water phase, m; r, pore radius in filling medium, m.

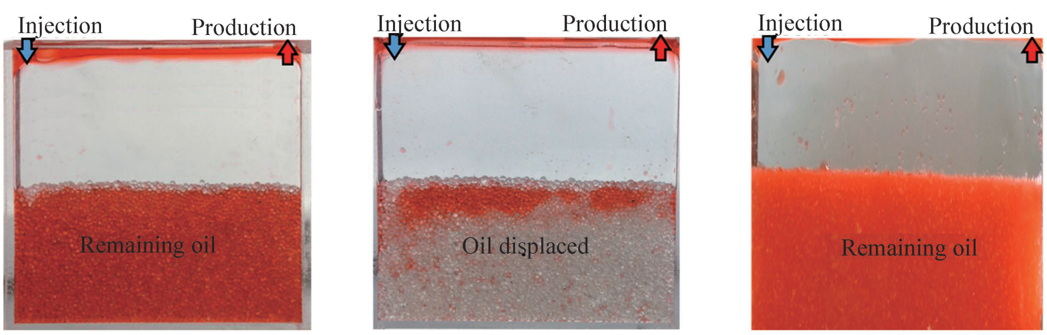
Substituting the parameters of fluid and model properties, we can calculate that ΔP is about 15.7 Pa. But for the minimum pores in filling medium of Model 1, the maximum capillary pressure would be about 155 Pa, which is the opposite direction of gravity. Since the maximum capillary pressure is much bigger than the ΔP, so the water phase would not get into the pores by gravitational differentiation.

Continue the water injection process until water phase covers the whole surface of the filling medium. Then, the height of the water phase and oil-water interface will increase as shown in Figure 3(b). We choose point 4 the same height as point 3 in filling medium, and it is just below point 2. Since the pressure difference for free fluid flow in un-filled area can be neglected, then pressures at the same height can be considered the same. Then $P_1 = P_2$, $P_3 = P_4$ and the oil in the filling medium were trapped in porous media. So the filling medium is the mean storage space for remaining oil.

2.3 Interface Tension and Pore Size

For model 1, oil in the oil-wet filling medium can hardly be displaced by injected water because of capillary pressure, and the oil recovery is 72.8%. The surfactant can reduce the capillary pressure to 11 Pa in minimum pores, which is lower than ΔP, so the surfactant solution can flow into porous media and increase the oil recovery to 92.6%. The oil saturation after surfactant injection was shown in Figure 4.

For Model 3, the minimum pore diameter is about 0.1 mm, and the capillary pressure for surfactant-oil for minimum pore was about P_c = 22 Pa, which is still higher than ΔP. So the oil in filling medium can't be displaced even using surfactant injection as shown in Figure 4(c), and the oil recovery maintained at 72%. Thus, lower interface tension surfactant should be used to reduce the remaining oil.

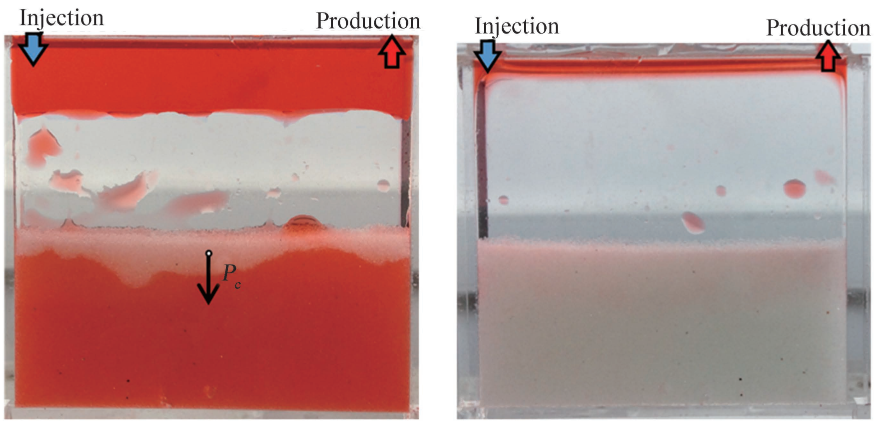


(a) Model 1 After Water Injection (b) Model 1 After Surfactant Injection (c) Model 3 After Surfactant Injection

Figure 4
Remaining Oil of Different Models

2.4 Wettability of Filling Medium

For the oil-wet filling medium of Model 1, oil in porous media can't be displaced by water. But for water-wet filling medium of Model 2, capillary force and gravity are in the same direction and they can work in collaboration. So the water can be imbibed into pores and oil can be displaced as shown in Figure 3(a). After water injection of 48 hours, most oil in filling medium can be displaced, and the oil recovery can reach to 94.3%.



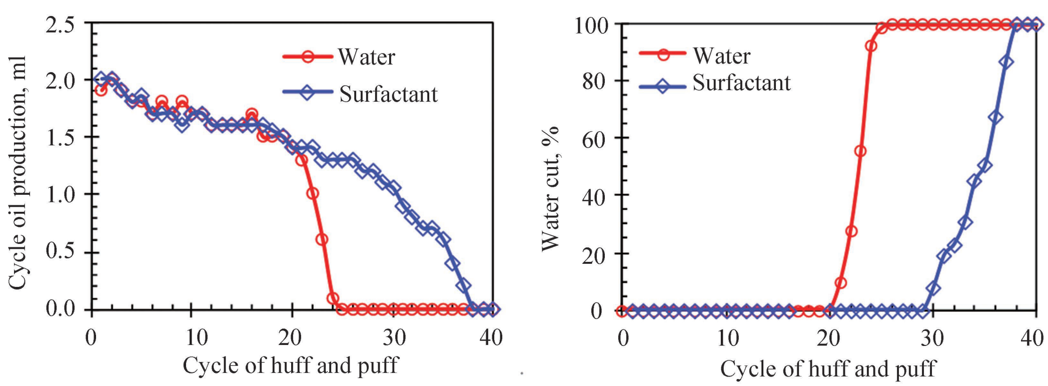
(a) 30 min (b) 48 hour

Figure 5
Oil Distribution of Model 3 at Different Time

2.5 Water Huff and Puff Considering Elastic Energy

For some single cave formations with single well, the oil filed usually use huff and puff method. The pressure difference between production and injection can be several or dozens of MPa for single well water huff and puff in oilfield. The experiments above were conducted under low pressure, then we cemented the filling medium of oil-wet in the high-pressure container in model 4 to consider the elastic energy. Pressure difference between injection and production was 30 MPa, soaking time for each cycle is 2 hours. Then we got the cycle water cut and oil production curves, which is shown in Figure 6.

In the early 20 cycles of the huff and puff, the water cut maintains 0% and the oil in the un-filled area was displaced by gravity. After 20 cycles of water injection, the water cut quickly increase to 100% and the oil production decreased to zero. The oil recovery is 73.1%, which is almost the same with model 1, so the oil in filling medium had not been displaced. But for the surfactant huff and puff, the water cut start to increase after 29 cycles, and it increased slower than the water injection. Finally, the oil recovery reached 93.7% just as model 1 did, which indicates surfactant effectiveness in the displacement of the remaining oil in the filling medium. So high injection pressure has little effect on the oil displacement in the filling medium.



(a) Cycle Oil Production (b) Water Cut

Figure 6
Oil Production and Water Cut Curves

3. FIELD APPLICATION

Well TH10323X was located in a fractured-vuggy reservoir with high filling degree, and it has high oil production and low water cut in natural energy development stage. After changing to water huff & puff period, the water cut quickly increased to nearly 100% and the produced liquid contains little oil. Then it was changed to surfactant huff & puff, the cumulative oil production in four months was increased to over 650 tons, which means the remaining oil in filling medium was displaced by surfactant. This production data proved that the surfactant could reduce the capillary force and improve the oil displacement efficiency in filling medium, which is the same with the experiments results.

CONCLUSION

(a) For the caves with filling medium of oil-wet, water huff and puff is a proper method to increase the formation energy and produce the oil in un-filled area. But it can't displace the oil in filling medium because of capillary force, and the water does not flow into the porous media under gravity differentiation.

(b) Properties of filling medium determine the remaining oil and oil recovery in filling medium. The smaller the pore size and strong oil wettability, the lower the displacement efficiency in filling medium. The capillary force is the momentum of water imbibition in water-wet filling medium, and it leads to high displacement efficiency and oil recovery.

(c) Surfactant could decrease the capillary force and increase displacement efficiency in filling medium. The field applications of surfactant huff & puff also have positive effect on increasing oil production. Therefore, this would be a good method to enhance oil recovery in fractured-vuggy reservoirs.

REFERENCES

[1] Xu, T., Lun, Z. M., & Zhang, X. H. (2010). Gravity drainage in oil-wet carbonate matrix rock system. *Petroleum Exploration and Development*, *37*(3), 358-362.

[2] Lü, A. M., & Yao, J. (2007). The variation of water cut in fractured-vuggy reservoir with bottom water. *Xinjiang Petroleum Geology*, *3*, 23.

[3] Moctezuma-Berthier, A., & Fleury, M. (2000, January). *Permeability mapping on vuggy core sample using tracer experiments and stream-line simulations*. Paper presented at SPE International Petroleum Conference and Exhibition in Mexico.

[4] Cruz-Hernandez, J., Islas-Juarez, R., Perez-Rosales, C., Rivas-Gomez, S., Pineda-Munoz, A., & Gonzalez-Guevara, J. A. (2001, January). *Oil displacement by water in vuggy fractured porous media*. Paper presented at SPE Latin American and Caribbean Petroleum Engineering Conference.

[5] Arbogast, T., Brunson, D. S., Bryant, S. L., & Jennings, J. W. (2004). A preliminary computational investigation of a macro-model for vuggy porous media. *Developments in Water Science*, *55*, 267-278.

[6] Zhang, L., Nair, N. G., Jennings, J. W., & Bryant, S. L. (2005). *Models and methods for determining transport properties of touching-vug carbonates*. Paper presented at SPE Annual Technical Conference and Exhibition.

[7] Egermann, P., Laroche, C., Manceau, E., Delamaide, E., & Bourbiaux, B. J. (2007). Experimental and numerical study of water-gas imbibition phenomena in vuggy carbonates. *SPE Reservoir Evaluation & Engineering*, *10*(1), 86-96.

[8] Izgec, O., Zhu, D., & Hill, A. D. (2010). Numerical and experimental investigation of acid wormholing during acidization of vuggy carbonate rocks. *Journal of Petroleum Science and Engineering*, *74*(1), 51-66.

[9] Kang, Z. H. (2006). Principium experiment of oil seepagedriven by water in fracture and vug reservoir of carbonater ocks. *West China Petroleum Geosciences*, *2*(1), 87-90.

[10] Wang, L., Dou, Z. L., Lin, T., Zhao, H. Y., & Luo, J. (2011). Study on the visual modeling of water flooding in carbonate fracture-cavity reservoir. *Journal of Southwest Petroleum University* (*Science & Technology Edition*), *33*(2), 121-124.

[11] Rezaei, N., Mohammadzadeh, O., James, L. A., & Chatzis, I. (2014). Experimental investigation of the VAPEX process in vuggy porous media. *SPE Journal*, *19*(1), 101-108.

[12] Li, S., & Li, Y. (2010). An experimental research on water injection to replace the oil in isolated caves in fracture-cavity carbonate rock oilfield. *Journal of Southwest Petroleum University* (*Science & Technology Edition*), *1*, 21.

[13] Li, A. F., Zhang, D., & Gao, C. H. (2012). Law of water injector production in fractured-vuggy unit with enclosed boundry and constant volume. *PGRE*, *19*(3), 94-97.

[14] Wang, J., Liu, H. Q., Xu, J., & Zhang, H. F. (2012). Formation mechanism and distribution law of remaining oil in fracture-cavity reservoirs. *Petroleum Exploration and Development*, *39*(5), 585-590.

[15] Brinkman, H. C. (1947). A calculation of the viscous force exerted by a flowing fluid on a dense swarm of particles. *Appl. Sci. Res.*, *1*(1), 27-34.

[16] Firoozabadi, A., & Markeset, T. (1992, January). *An experimental study of capillary and gravity crossflow fractured porous media*. Paper presented at SPE Annual Technical Conference and Exhibition.

[17] Fumagalli, A., & Scotti, A. (2013). A numerical method for two-phase flow in fractured porous media with non-matching grids. *Advances in Water Resources*, *62*, 454-464.

[18] Xie, H. J., Li, A. F., Qin, J. F., & Lazaro, B. (2016, August). *Manufacture of water wet artificial core by chemical modification method*. Paper presented at the International Symposium of the Society of Core Analysts held in Snowmass, Colorado, USA.

