 SL, vol.10, no.1, pp.59-70, 2013

Research on Influence Rules of Pore Structure on Water & Polymer Flooding using Etched Glass Micro-model

Yuan Ying-jie[1,2], Hou Ji-rui[1], Zhao Feng-lan[1], Yu Chun-sheng[3] and Zhang Feng-min[1,2]

Abstract: In this paper, visual micro-model technology has been applied to investigate the influence rules of pore structure on water and polymer flooding, by observing multiphase flow in porous media under the ZEISS 2000-C microscopy. To make the transparent etched glass micro-model representative, the image of target reservoir layer from Shuanghe Oil field, was selected by using laser confocal scanning technology. To ensure effective flow, pore channels with dead-end were gotten through artificially, then the fine-adjustment-image was etched into two glass plates and a specific cementing process was used. The main characteristic of this micro-model is that it preserves the typical pore structure and can be observed at the pore level clearly.

As an enhanced oil recovery technology, polymer injection has been studied and applied for some time; however, the mechanism about how polymer flows in heterogeneity reservoir with high water-cut is not very clear. Total 4 micro-models with 600 md permeability, oil-wet, were used for displacing test at room temperature. Two parameters: pore-throat ratio (PTR) and coordination number (CN) were used to describe heterogeneity of model, and each model was different with others in these 2 parameters. The result shows that owing to the "macro holes surrowned by keyholes" mechnism, large amount of oil was left behind after water flooding. The bigger the value of PTR, the more the residual oil exists; polymer solution with higher-viscosity can enlarge sweeping volumn and reduce the amount of residual oil at the same time by draging oil droplets into oil threads and peeling oil film; fixing permeability, the less the PTR, the biger EOR can polyer flooding get; with the same PTR, the bigger the CN, the higher the EOR. Polymer flooding is with great application prospect in high water-cut Shuanghe oil field.

This study also shows that displacing experiments on these glass-etched micro-models do provide visual results, which revealing the flow procedure of water and

[1] Enhanced Oil Recovery Institute, China University of Petroleum, Beijing 102249.
[2] Key Laboratory of Petroleum Engineering, Ministry of Education, Beijing 102249, China.
[3] Petroleum Engineering Istitute, He'nan Oil Field, Nanyang, 473132.

polymer flooding in porous media with typical structure of target reservoir. However, the artifically-fine conductivity is less real to the sandstone realistically, so the combined results from both glass and sandstone micro-model are more valuable.

1 Introduction

After long period water flooding, Shuanghe oilfield, locating in the middle-east of China, has entered the later high water-cut stage with a composite watercut 95.0%. Sealing core data shows that it is the severe inhomogeneity of water flooding degree that leads to mass of oil left behind in the reservoir, and residual oil reserve accounts for 40%$\sim$60% OOIP of that zone. To further develop wisely, all about the remaining's distribution, type, and mobility trend is with great importance.

As one of the enhanced oil recovery (EOR) technologies, polymer flooding keeps ahead of others for its clear mechnism and the uncomplicated operation-needed. Although field tests concerning polymer-injection had started in Canada, Britian, the former Soviet Union, France, Romania, German, etc, since 1970s, and more than 200 oil fields and blocks were successful, the influence rules about reservoir structure on polymer-driving effect in high-watercut is still rarely studied.

Aimed at this issue, this paper describes an experimental study, in which the visualization displacing technology was carried out on micro-models. Besides pore channels with dead-end getting through artificially to ensue effective flow, the models are manufactured strictly according to the real characteristic of target layer VI in Shuanghe oilfield. Models with two parameters: pore-throat ratio (PTR) and coordination number (CN) to describe heterogeneity, and the effect of PTR and CN on water and polymer flooding was investigated to provide theoretical guidance for Shuanghe oilfield of high water-cut.

2 Experiment

2.1 Etched glass micro-model

The glass micro-models we used in this study were manufacrered according to the image, which obtained by using laser confocal scanning technology to the target layer VI in Shuanghe oilfield. After transforming dead-end channels into connected ones artificially, the glass was etched following the fine-adjustment image and the conductivity of each model was increased as a result. With initial oil-wet, the dimension of the models is 3 cm$\times$2 cm$\times$0.04 cm, and the range of channel diameter varies from 1$\sim$100μm. There are an injector and producer at each side of the micro-model. The fabricated micro-model can bear a pressure up to 2 MPa at room temperature. Figure 1 shows the picture of etched glass micro-models used for this study. 4 models shared the same permeability 600 md, which was typical in layer VI, and differed in two parameters as follows.

NO.	1	2	3	4
Pore Throat Ratio (PTR)	4	4	9	9
Coordination Number (CN)	3	5	3	5

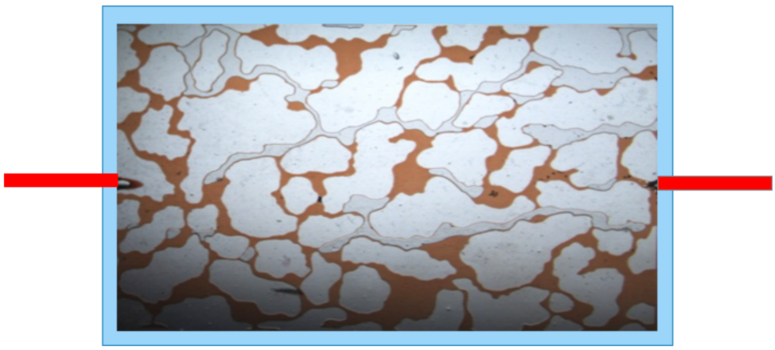


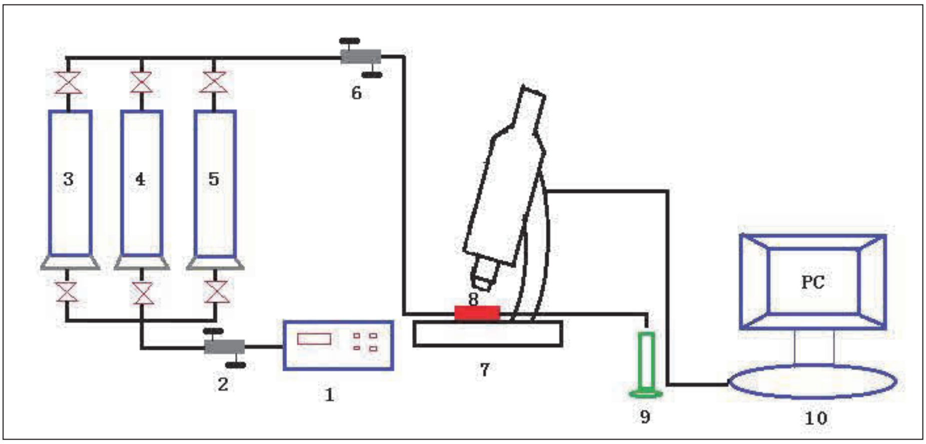
Figure 1: Etched Glass Micro-model

2.2 Setup

The setup is composed of three parts involving power system; monitor system and processing system (see Fig.2). The power is from a micro-syringe pump by injecting fluid and the real-time can be observed from the pressure transducer which is used to measure the pressure drop across the model; the main component of monitor systerm is the microscopy, which is equipped with a video recording camera to record flow procedure. Micro-models are fixed on the holder, which is placed on the microscope platform and can be moved horizontally with hand adjuster. The processing systerm includes high-speed computer and technical image-processing software. All experiments were conducted at a room temperature.

2.3 Fluids & Equipments

Synthetic reservoir brine was used as the water phase and simulated oil with a viscosity of 1.78 cp at room temperature was used as the oil phase. A red oil-soluble dying was dissolved in the oil phase to elevate visibility, and polymer solution, with a dose of polymer, whose average molecurer mass 400×10^4, dissolved in the



1—High Pressure Syringe Pump 2、6—Triple Valve 3、4、5—Intermediate Container

7—ZEISS Microscopy 8—micro-model 9—Mesuring Meter 10—Monitor Computer

Figure 2: Experimental Setup

water phase to increase viscosity and optimize the flow rario between oil and water phrase.

The microscopy is Stemi 2000-C from ZEISS Com. and the pump is LSP01-1BH, from Longer Precision Pump Ltd Cor., with the minute linear rate 5μm/m, it can insure our precise injection and vedio quality. In this study, all viscosity is tested by Brook-field viscos-valve.

2.4 Procedure

The dry models were first vacuumed for more 2 hours to remove air inside the pore spaces. It was then saturated with water and keeped 2 days before it was subjected to oil injection. After oil injection, model was aged for 3 days. Thereafter, the water injection was initiated at a designed injection rate, after certain period and the model was strongly-water swepted, the distribution and type of residual oil were investigated in 4 models to probe how the PTR/CN affect watering efficiency. Then change injection fluid to exam the influence about PTR/CN on polymer flooding, and study their effect on oil recovery and the EOR ability of polymer.

3 Results and Discussions

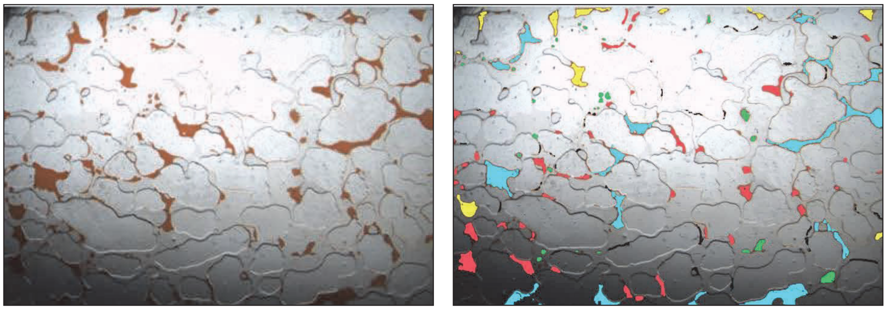
3.1 Distribution and Type Definition of Residual Oil

Each oil- saturated model was displaced by water at a constant rate of 2μl/min, which is adhere to the field trial. Figure 3 (a) shows the distribution of residual oil after water flooding and (b) definite 5 types on one model. In the left figure, red represents oil phase, while various color means different type oil by using techical image-processing software in the right figure.Since Z-dimension is very short, the glass micro-model is pseudo 3-dimensional, oil recovery can be calculated by saturation in X-Y dimension and the content of different type oil was shown in fig.3 (c).

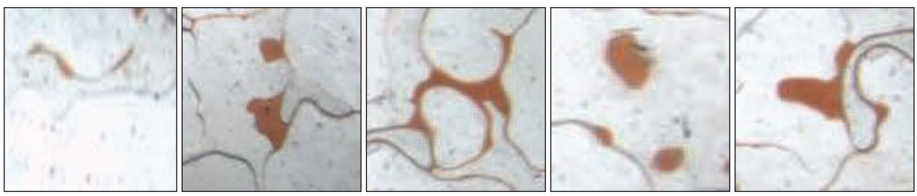
3.2 Effect of Pore Structure on Waterflooding

After saturated with oil for 3 days, water injection was initiated on each model. The water injection rate was calculated based on space data measured in the field. Certain PV watering, with the injection pressure increased, the distribution of residual oil formed on 4 models (see Fig.4) to study the effect of pore structure on oil recovery. We can see that most of the water is driving along the less resistant channel direction, namely middle zone of the model, and flooding efficiency is higher in the axis area than other part else.Water fingering from large pores was observed for all the models tested, and much oil left behind water swept is in the macro-hole sieged by thin throats because of the "macro hole surrounded by keyhole" mechanism, and the cluster and blind-ending type occupied large proportion in them.

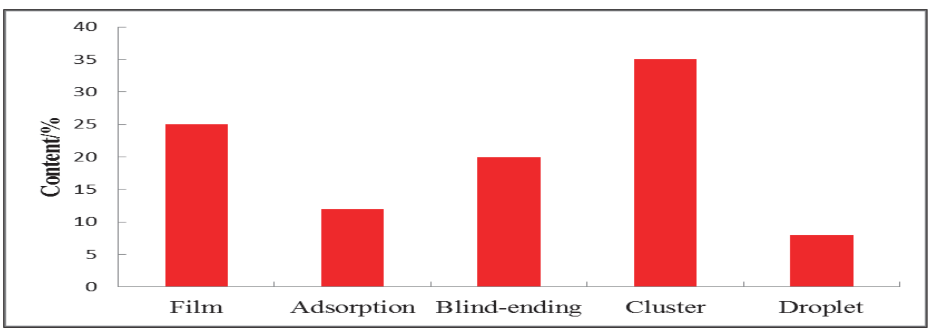
We can see directly from fig.4 that pore throat ratio (PTR) and coordination number (CN) have significant effect on water flooding effiviency in 4 micro-models. On one side, the bigger value of PTR (eg. K9), meaning the average diameter ratio of big channel with thin throat, the bigger the capillary force exists in thin throats that resit water coming inside to drive oil. As a result, the recovery of oil is low, for example, the oil recovery is 38% and 25% on model K9P3and K9P5, respectively. On the other side, the modest value of PTR (eg. K4), the modest capillary force exists, that is not too big to prohibit water coming. Hence, water coming from throat path would flow direct to the big channels with less resistance to displace oil in them, and increase the efficiency of water flooding. For example, the oil recovery is 45% and 60% on model K4P3and K4P5 respectively. What's more, if one pore is connected by several thin throats, namely the so-called coordination number (CN) is bigger (eg. P5), the oil in big channel can be driven completely from several throat directions under the condition of modest PTR, for example, the oil recovery on model K4P5 is 60% and the highest in 4 models; with same CN, while bigger PTR (eg. K9P5), since water cannot breakthrough in thin throat because of high



a) Distribution of Residual Oil



b) Defination of Residual Oil Type



c) Content Contrast of Residual Oil

Figure 3: Distribution & Type Defination & Content Contrast of Residual oil after Water Flooding

capillary force, the oil in throat can not flow, and the oil in big hole surrownded by these thin throat cannot move consequently, leading to a less watering efficiency. For example, the oil recovery is 25% on model K9P5, that's how the PTR and CN effect water flooding. Clear to say it is the heterogeneity of reservoir media that induce low recovery for water-development reservoir.

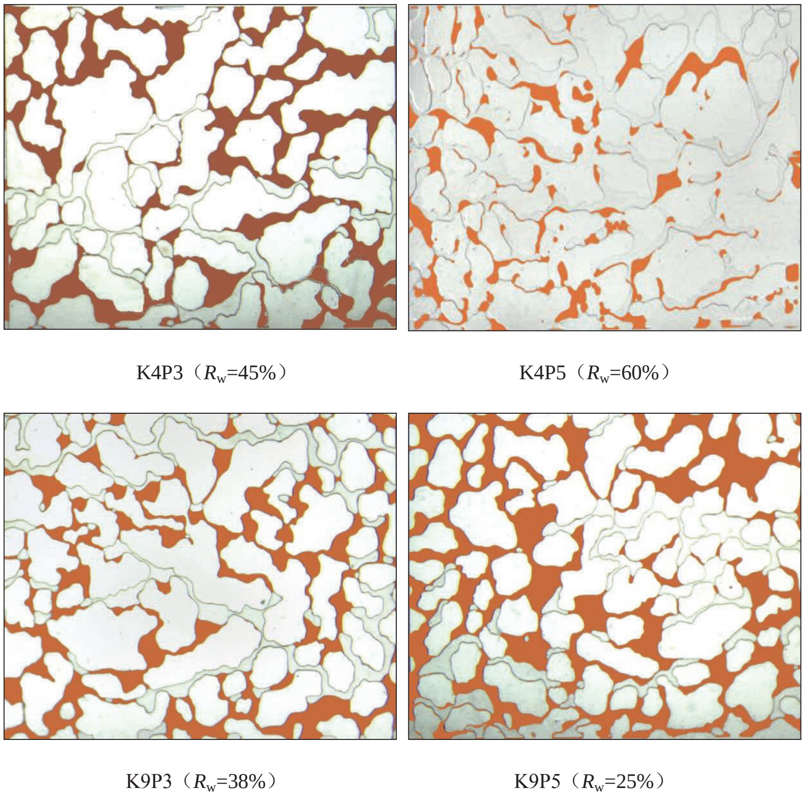
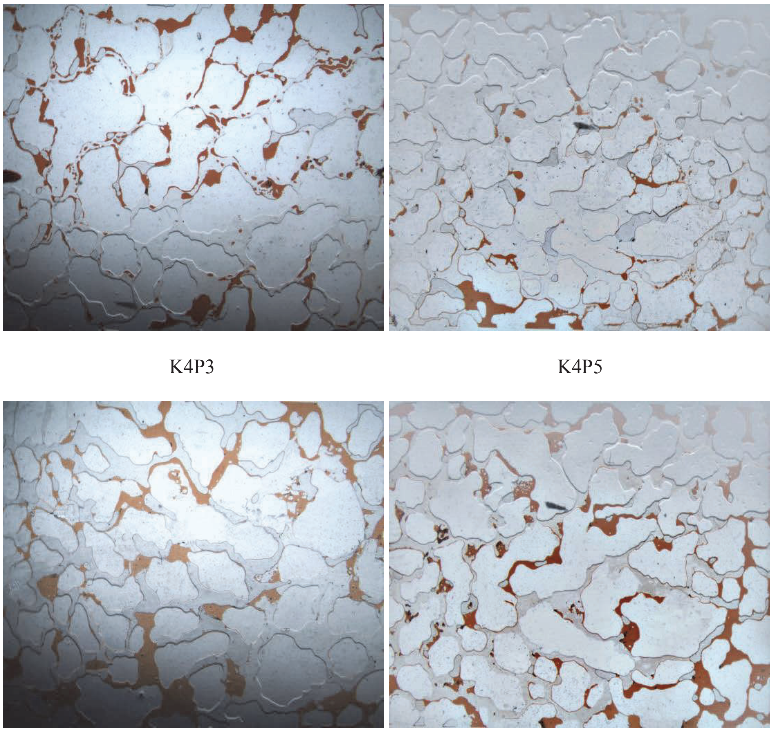


Figure 4: Influence of Pore Structure (PTR & CN) on Water Displacement Efficiency.

3.3 Effect of Pore Structure on Polymer Flooding

Polymer injection was initiated on each model after water displacement. The injection rate and PV was constant, the distribution of residual oil can be seen in fig.5. From mentioned above, we know that water is hard to breakthrough in K9 models. In order to creat the same water flooding degree to match the field situation, more water PV was consumed on K9 models. Since the volume of polymer molecure is bigger than that of wate, with higher viscosity, higher pressure was produced during polymer injection. Residual oil was displaced by high pressure from viscous force, showing an increase amount of droplet oil in flooding procedure. When CN is bigger, meaning more paths to get big hole to driving the oil left behind watering, and the recovery can be bigger than small CN models. The enhaced oil recovery on each model can be checked out in fig. 6.



K4P3 K4P5

K9P3 K9P5

Figure 5: Effect of Pore Structure (PTR & CN) on Polymer Displacement.

Figure 6 shows that all models with different types of pore structure can enhance oil recovery by polymer flooding. The maximum increment of oil recovery ratio is 16% in K4P5 model, and the minimum value is 8% in K9P3 model. The reason is that the CN of P5 model is bigger that of others and there are more throats connected with macro pores. Due to the lipophilicity of model, polymer solution moves in the middle of pores and breaks to a large stretch of oil into oil droplets. Then oil drops are flooded by following solutions, causing reduction of remaining oil. As a result, residual oil after polymer flooding in this type of pore structure is least and oil displacement efficiency is higher than that of P3 models. Under the same coordination number, the smaller the pore-throat ratio is, the higher the efficiency of polymer flooding is. Compared four models, whatever the coordination number is, the increment of oil recovery ratio of K4 model is bigger than that of K9 model, which shows that the influence of pore-throat ratio on polymer flooding is greater than that of coordination number.

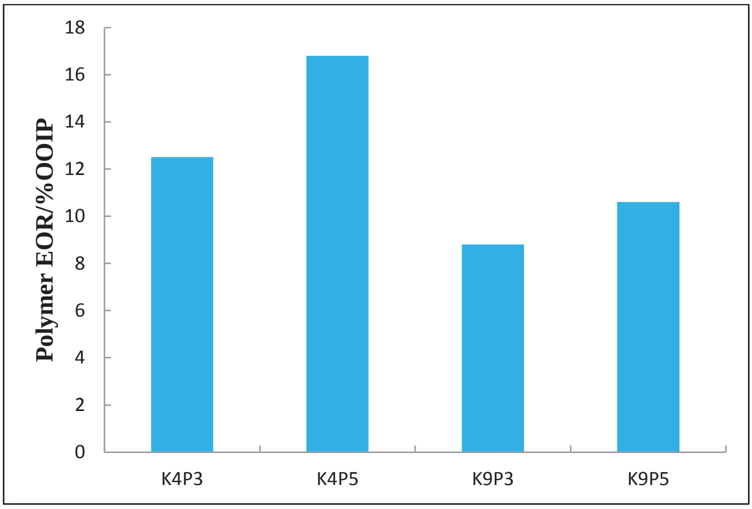


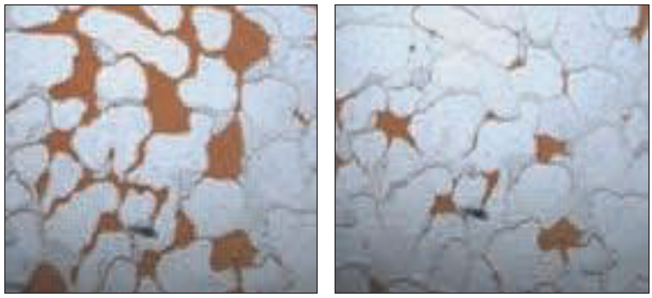
Figure 6: Effect of Pore Structure (PTR & CN) on Polymer EOR.

3.4 Principles of Enhanced Oil Recovery by Polymer Flooding

In regard to the same model, the sweep efficiency is enhanced by injecting high viscoelastic polymers. The remaining oil after water flooding is replaced by polymer solutions that contact with it. The polymers move in the middle of pores, and the oil flows along the wall. The results of water and polymer flooding are shown in fig.7.

The experiment also shows that the pressure of polymer flooding is much higher than that of water flooding at the same injecting speed, and the greater the model heterogeneity is, the higher the pressure of polymer flooding is. The reason is that the polymer with a complex structure, which is much bigger than that of water molecular, can cause higher pressure in small pores. Besides, shear stress between polymer and oil is larger than that of water. With high pressure and high shear stress, oil films can be peeled off easily and carrying ability of solutions is improved. The content change of remaining oil is shown in fig.8.

Fig.8 shows that all types of oil, including oil film, blind-ending oil and clustered or tufted oil, are reduced. The reason is that water viscosity is enhanced and water-oil mobility is reduced in the process of polymer flooding, and the ability to carrying remaining oil by injecting solutions is improved. Besides, polymer solutions are able to break apart tufted oil and wash off oil film. Then oil can get together and be brought out by following fluids.



R_w=40% R_{total}=80%

Figure 7: Displacement Effect of Different Systerm.

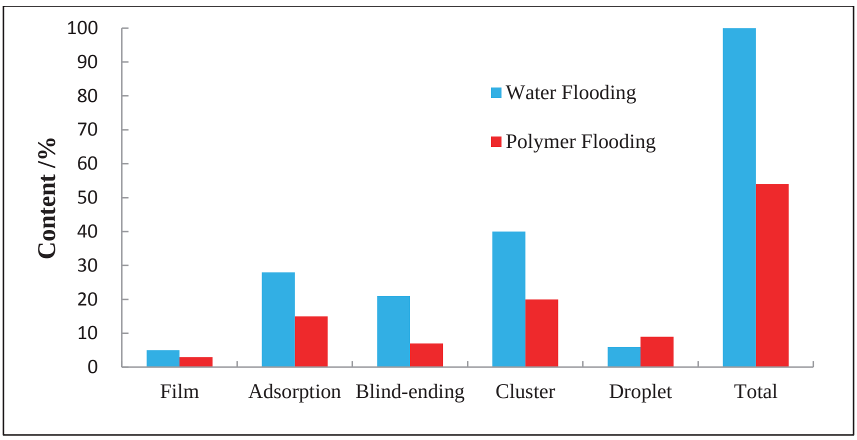


Figure 8: Content Change of Different Types Oil in Water-Polymer Flooding.

4 Conclusions

Etched glass micro-models were invented, with oil-wet and pore structures strictly following target layer VI in Shuanghe Oil field, the displacemnet experiment shows that both water and polymer solution move in the middle of pores, and the oil flows along the wall because of lipophilicity. No considering permeability, the influence of pore-throat ratio (PTR) on polymer flooding is greater than that of coordination number (CN). The more heterogeneity of the model (namely bigger PTR, smaller CN) is, the lower oil recovery both water and polymer can get. Residual oil after water flooding can be reduced by injecting high viscoelastic polymers while sweep efficiency increasing on each model. Compared with other type oil, the content changes about blind-ending and clustered oil are reduced significantly. Since all 4 models with different types of pore structure can be enhanced oil recovery by polymer flooding, polymer injection has great application on EOR in Shuanghe Oil field.

Acknowledgement: This work is conducted at the Micro-model Displacement laboratory of Enhanced Oil Recovery Institute, China University of Petroleum, Beijing. Many students from this institute joined the experimental work. We appreciate their great support.

References

Abrams, A. (1975): The Influence of Fluid Viscosity, Interfacial Tension, and Flow Velocity on Residual Oil Saturation Left by Waterflood. *SPE Journal,* vol. 15, no. 5, pp. 437-447.

Bora, R.; Maini, B. B. (2000): Flow Visualization Studies of Solution Gas Drive Process in Heavy Oil Reservoirs Using a Glass Micromodel. *Speree,* June, pp. 224-229.

Bora, R.; Chakma, A.; Maini, B. B. (2003): Experimental Investigation of Foamy Oil Flow Using a High Pressure Etched Glass Micromodel. SPE paper 84033, presented at the SPE Annual Technical Conference and Exhibition held in Denver, CO., 5-8, Oct., 2003.

Clemens, T.; Tsikouris, K.; Buchgraber, M. (2012): Pore-Scale Evaluation of Polymers Displacing Viscous Oil – Computational Fluid Dynamics Simulation of Micromodel Experiments. SPE paper 154169, presented at the Eighteenth SPE Improved Oil Recovery Symposium held in Tulsa, Oklahoma, USA, 14–18, April 2012.

Forth, R.; Slevinsky, B.; Lee, D.; Fedenczuk, L. (1996): Application of Statistical Analysis to Optimize Reservoir Performance. *Journal of Canadian Petroleum Technology,* vol. 35, no. 8, pp. 36-42.

Haghighi, M.; Yortsos, Y. C. (1997): Visualization of Steam Injection in Fractured Systems Using Micromodels. SPE paper 37520 presented at the International Thermal Operations and Heavy Oil Symposium held in Baskerfield, CA., 10-12, February, 1997.

Hendraningrat, L.; Shidong, L. (2012): A Glass Micromodel Experimental Study of Hydrophilic Nanoparticles Retention for EOR Project. SPE paper 159161, presented at the SPE Russian Oil & Gas Exploration & Production Technical Conference and Exhibition held in Moscow, Russia, 16–18, October 2012.

Mei, S.; Bryan, J.; Kantzas, A. (2012): Experimental Study of the Mechanisms in Heavy Oil Waterflooding Using Etched Glass Micromodel. SPE paper 157998, presented at the SPE Heavy Oil Conference Canada held in Calgary, Alberta, Canada, 12–14, June 2012.

Nguyen, Q. P.; Thissen, M. H. G.; Zitha, P. L. J. (2002): Effect of Trapped Foam on Gas Tracer Diffusion in a Visual Microflow Model. SPE paper 75208, presented at the 2002 SPE/DOE Improved Oil Recovery Symposium held in Tulsa, OK, 13-17, April 2002.

Pentland, C. H.; Tanino, Y.; Iglauer, S.; Blunt, M. (2010): Capillary Trapping in Water-Wet Sandstones: Coreflooding Experiments and Pore-Network Modeling. SPE paper 133798, presented at the SPE Annual Technical Meeting and Exhibition, Florence, Italy, 19-22 September 2010.

Qu, Z.; Sun, W.; Ni, F.; Tang, G.; Chen, Z. (1991): A Study of Oil Displacement by Water Imbibition Using a Visual Micromodel for Andesite Reservoir in Fenghuadian Oilfield, Huanghua Basin. *Acta Petrolei Sinica,* no.3, pp.52-61.

Romero-Zerón, L. B. (2004): The Role of Porous Media Wettability on Foamed Gel Propagation and Fluid Diverting Performance. Ph.D. thesis, University of Calgary, 2004.

Sohrabi, M.; Tehrani, D. H.; Danesh, A.; Henderson, G. D. (2004): Visualization of Oil Recovery by Water-Alternating-Gas Injection Using High-Pressure Micromodels. SPE 89000, 2004.

Sun, W.; Qu, Z. (2004): Characterization of Water Injection in Low Permeable Rock Using Sandstone Micro-Model. SPE paper 86964 presented at the SPE International Thermal Operations and Heavy Oil Symposium and Western Regional Meeting held in Bakersfield, California, U.S.A.,16–18, March 2004.

Van Meurs, P.; van der Poel, C. (1958): A Theoretical Description of Water-Drive Processes Involving Viscous Fingering. *Petroleum Transactions, AIME,* vol. 213, pp. 103-112.

Wassmuth, F. R.; Arnold, W.; Green, K.; Cameron, N. (2009): Polymer Flood Application to Improve Heavy Oil Recovery at East Bodo. *Journal of Canadian Petroleum Technology,* vol. 48, no. 2, pp. 55-61.