STUDY OF WATERFLOODING OIL RECOVERY IN DIFFERENT WETTABILITY CONDITIONS WITH PORE SCALE NETWORK MODEL

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Avignon, France, 8-11 September, 2014

ABSTRACT

In oilfield development, waterflooding is normally characterized as a cheap but efficient process, which leads to a considerable residual oil saturation. The rock wettability condition is an essential parameter in reservoir evaluation, and its effect on waterflooding oil recovery has often been a research focus in the petrophysics field. Characterization of its effect on oil recovery in commercial scale waterflooding processes and their laboratory duplications forms an important component of the waterflooding development and application and the research and development for new EOR methods. In this study, the study of the effect of wettability conditions on waterflooding oil recovery was carried out through pore scale network model. In the article, quasi-static flow rule was applied in the model, which was used in both two intrusive simulation processes corresponding to oil saturating with irreducible water and waterflooding respectively. Inspired by hydrocarbon accumulation mechanism, the factor of wettability conditions was introduced in the model based on contact angle distributions in pores and throats. After a series of numerical simulation experiments, it could be summarized through the analysis of relative permeability curves. Neutral wet condition always corresponded to higher oil recovery than water and oil wet conditions in the waterflooding process. The difference between oil recoveries of water and oil wet conditions didn't have a fixed result, which indicated that the effect of wettability conditions on oil recovery performance may need to be linked with the pore structure characteristic to consider.

INTRODUCTION

The rock wettability is one of fundamental petrophysical properties for the reservoir rock, which reflects interactions between reservoir rock surfaces and fluids. It is also an essential parameter for selecting EOR methods and conducting reservoir simulation [1], and its role becomes even more remarkable, especially in various new inorganic EOR methods, such as low salinity waterflooding and smart waterflooding [2]. It not only affects the fluid distribution in the porous media, but also has an effect upon waterflooding oil recovery. In the 1980s, Anderson et al thought that wettability may be heterogeneous and presented porphyritic wetting, mixed wetting and fractal dimension wetting [3]. Anderson, et al. also discovered that macroscopic neutral wetting index cores always corresponded to higher oil recovery than cores with other conditions in the waterflooding experiment process [4]. Ever since then, the effect of wettability conditions on waterflooding oil recovery has always been a controversial issue. As an effective microscopic percolation simulation tool in the pore scale level, pore scale network model has been used in many fields, such as single-phase flow simulation, multi-phase flow simulation, and chemical flooding simulation [5-6]. In the article, a special network suitable for the study was introduced. The simulation results proved the feasibility of pore scale network model. Its microscopic mechanism has been investigated as well.

METHODOLOGY

Pore Structure Data

Pore scale network model is a statistical model based on pores and throats to conduct fluid flow simulation and characterize various physical and chemical effects. It is necessary to gain pore structure data for two following reasons. On the one hand, fluid flows and various physical and chemical effects occur in pores and throats. On the other hand, it has been proved that fluid flow characteristics are influenced by pore structures. In order to improve the representativeness of the pore scale network, a new method is applied, which combines micro-CT scanning with rate-controlled mercury injection. Representative areas are selected for further testing analyses by medical CT scanning. The selected small area is scanned by micro-CT to obtain pore and throat connectivity data, which include coordination number distribution and pore and throat connectivity relationship. Pore and throat size data are obtained by conducting rate-controlled mercury injection experiment on the other one, which include pore radius distribution and throat radius distribution. Pore structure data are composed with two parts of data above.

Quasi-static Flow Rule

In pore scale network modeling, the void space of the rock is described as a lattice of pores connected by throats. Different rules are developed to determine multiphase fluid configuration and transport in these elements. Quasi-static flow rule is a common rule used in pore scale network modeling. In the rule, it is assumed that multiphase fluid configuration and transport are controlled by both viscous and capillary forces at a moderate flow rate. Based on percolation theory and Poiseuille flow law, it is an optimal path model weighted by throat pressure considering viscous and capillary forces. Figure 1 is a 4×4 two dimensional network guided by quasi-static flow rule. In the displacement process, throats adjacent to the displacement front would become pro-flooding state. It is a state before substituted by the other phase, and then the throat with the highest throat pressure would be selected and updated. After that, pressures in pores also need to be updated at the end of each stage based on flow conservation.

Pore Scale Network Simulation Workflow

In this article, a special pore scale network simulation workflow is established for the study. Similar to a displacement experimental process, there are two intrusive simulation processes in the workflow, oil saturating with irreducible water and waterflooding respectively. When confronted with the throat state marked with a query in Figure 2, the retention effect should be considered. The rules are established here that the query throat will be updated when its radius is greater than or equal to the updated throat radius at this time and it will be permanently enclosed in the reverse condition. The retention effect is applied in both intrusive simulation processes. In Figure 3, several crucial points are set up to make the entire simulation process more reasonable and conformable to the whole displacement process. The termination condition for oil saturating is that no pores and throats can be updated. Relative permeabilities can be calculated by decomposing the whole network into the oil network and the water network at different stages. Different to the oil saturating process, the termination condition for waterflooding includes two parts. Firstly, pores in the outlet boundary of the network are completely occupied by water, and the purpose is to eliminate the end effect. On this basis, oil relative permeability value should be less than 0.01, and the purpose is to ensure a high water cut similar to the experimental process at the end.

Wettability Characterization

During the hydrocarbon accumulation process, the initial state of the rock was strong water wet. Large pores would be invaded by crude oil under the influence of capillary force. At this time, some organics would be deposited and fixed on the large pore surface. The large pore would become oil wet, and the small pore was still strong water wet. In other words, wettability condition could be viewed as property in the pore scale level. Inspired by hydrocarbon accumulation mechanism, the factor of wettability condition was introduced in the model based on contact angle distributions in pores and throats.

RESULTS AND DISCUSSION

In order to carry out horizontal comparison, it is assumed that the initial contact angles of pores and throats are the same during the oil saturating simulation process, which means that the initial network states of three numerical examples of different wettability conditions are exactly the same before the waterflooding simulation process. And then the contact angles of pores and throats are adjusted according to contact angle distributions of different wettability conditions. Since the comprehensive understandings of the waterflooding process can be reflected by analyzing the relative permeability curve, the study is conducted through the analysis of relative permeability curves. After a series of numerical simulation examples, the results can be summarized in Figure 4. Figure 4 includes three most typical numerical simulation results with three sets of relative permeability curves of different wettability conditions.

Observing curves carefully, there are some common characteristics among relative permeability curves of three different wettability conditions. The isotonic point of the relative permeability curve in neutral wet condition is usually the lowest among three situations, and the flow interference with each other fluid is the most remarkable namely. The isotonic point in oil wet condition is always on the right side of that in water wet condition. The water relative permeability curve in neutral wet condition extends longer than other wet conditions at the high water cut stage, which means that it always corresponds to higher oil recovery than water and oil wet conditions. Anderson, et al. indicated that the ultimate recovery would be higher in many experimental results when the preferential wet for one phase fluid was mild. And he explained that this was due to the cutting and trapping oil effects caused by reducing the interfacial tension at the high water cut stage [4], which was consistent with the phenomenon in a series of numerical examples. In Anderson’s work, it had been observed that there was an oil wire connecting two sides of oil droplets separated by water, and it had been summarized as film flow displacement to explain high oil recovery from microscopic perspective [4]. A large number of examples show that oil recovery of water wet condition does not have a fixed relationship with that of oil wet condition. And it was concluded by Anderson that these different results were caused by the influences of heterogeneity, pore geometry, injection rate, specific surface, the end effect and so on [4]. From the single factor analysis method, only difference among numerous numerical examples is the specific pore and throat distribution in the network. So the effect of different wettability conditions on oil recovery performance may need to be linked with the pore structure characteristic to consider from a certain perspective of pore scale network model.

CONCLUSIONS & FUTURE WORK

In this study, the effect of three different wettability conditions on oil recovery performance was investigated by pore scale network model. Both micro-CT scanning and rate-controlled mercury injection were used to gain representative pore structure data. Quasi-static flow rule was established to control fluid flow in the network, which considered capillary and viscous forces reasonably in the displacement process. On the basis, a pore scale network simulation workflow was formed to replace the core flooding experiment. The contact angle distribution was introduced into the model to characterize wettability condition. The simulation results proved that it was feasible to substitute the core flooding experiment with pore scale network modeling. The wettability effect was consistent with previous understandings through other methods basically. The microscopic mechanism for high oil recovery in neutral wet condition was summarized as film flow displacement during the high water cut stage.

From the microscopic view, wettability not only affects capillary force during the flow process, but also has an effect upon fluid distribution in the porous media. In the model, the wettability condition was characterized only from the perspective of capillary force, which mainly reflected the competition between capillary and viscous forces. Besides the competition, differences among numerous numerical examples could only be attributed to pore structure. Obviously this was a narrow sense for wettability, which ignored the advantage of pore scale network model. In the future, it will be necessary to introduce the microscopic mechanism of the wettability effect on fluid distribution in the model to acquire further and comprehensive understandings of its effect on oil recovery performance, such as specific surface and other forces caused by fluid distribution.

ACKNOWLEDGEMENTS

We gratefully acknowledge financial support from PetroChina Research Project (2011A-1003) and National 973 Project (2011CB707302).

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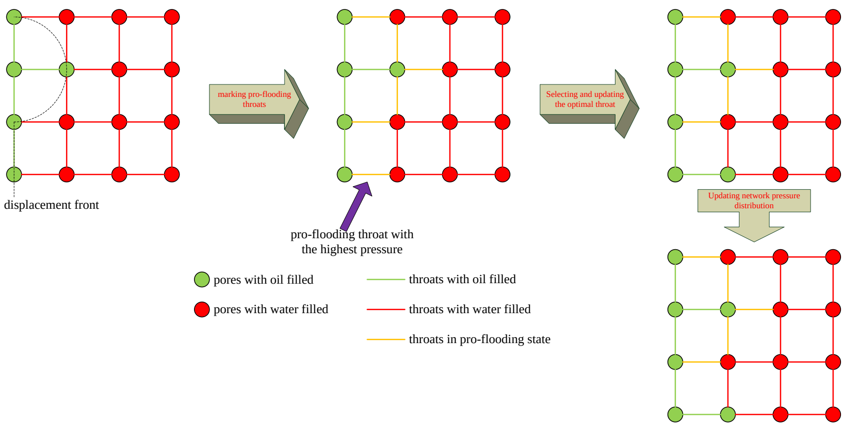

Figure 1. Schematic Diagram for Quasi-static Flow Rule

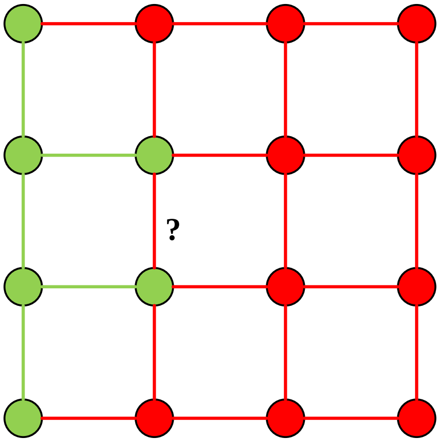

Figure 2. Illustration for Retention Effect

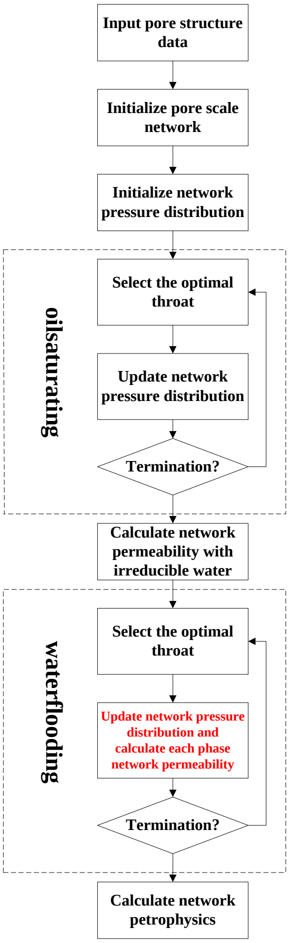

Figure 3. Simulation Workflow

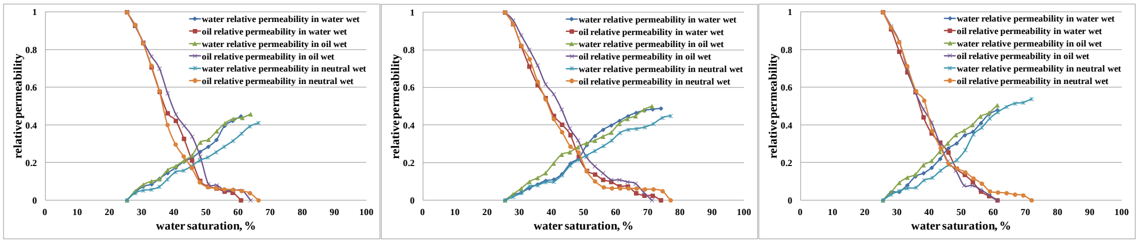

Figure 4. Typical Simulation Relative Permeability Curves of Different Wettability Conditions