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Experimental Study on Polymer flooding-assisted CO_2-based Cyclic Solvent Injection Process for Enhancing Oil Recovery in Heavy Oil Reservoirs

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ABSTRACT

CO_2-based cyclic solvent injection (CSI) process is widely applied for enhancing heavy oil recovery in petroleum industry. However, the rapid decrease in oil production after 2 or 3 cycles will be encountered in previous CO_2-based CSI research due to the reduction in oil saturation near the producer. Therefore, five groups of experiments were conducted using a 1D sand-pack model to explore the EOR potential in CO_2-based CSI process via polymer injection assistance to increase oil saturation around the producer. Two polymer flooding assistance modes were investigated, including injection after every cycle and injection after the cycle when oil recovery factor is less than 1%. Two slug size of polymer flooding assistance were evaluated, including volume of 1 PV and the volume of total liquid produced in the previous CO_2-based CSI process. Three different concentration of polymer solution, 0ppm, 250ppm and 1000ppm, were also studied. The experimental results show that the oil recovery factor is significantly improved after polymer flooding assistance during the CO_2-based CSI process. The polymer flooding assistance effectively push the remaining oil toward the producer and form an oil bank for the following CO_2-based CSI section, increasing the oil saturation near the producer. The highest recovery factor (70.72%) is achieved in polymer flooding-assisted CO_2-based CSI process when polymer (1000 ppm concentration) was injected after the cycle that oil recovery factor is less than 1%, and the slug size equals to the volume of total liquid produced in the previous CO_2-based CSI section. The economy evaluation results show the assistance mode of conducting 1000ppm polymer flooding assistance after each cycle has the lowest material cost. Moreover, a field application of this novel technique was designed and implemented in eastern China, and a significant increase in daily oil production and decrease in water cut were achieved. In conclusion, this work innovatively combines the CO_2-based CSI process with polymer flooding, and a polymer flooding-assisted CO_2-based CSI technology for heavy oil reservoirs is proposed. Experimental results in both the laboratory and field reveals the excellent EOR potential and economic benefit of this novel technology for heavy oil reservoirs.

Keywords: CO_2-based cyclic solvent injection, EOR, polymer flooding assistance, field application, economy

1. INTRODUCTION

Heavy oil reservoir is one of the important unconventional crude oil resources in the world, which reserves account for the largest proportion of the world's petroleum resources [1]. However, due to the high viscosity of heavy oil, the development of these reservoirs faces the challenge of poor flowability of crude oil under reservoir condition. This development difficulty has led to low oil recovery factors during primary or secondary development, such as natural energy drive or water flooding processes. The oil recovery factor of heavy oil reservoirs is estimated at 11% on average after primary or secondary development, which lefts much possibility for future EOR process [2-4]. To enhance heavy oil recovery factor, various development methods for heavy oil reservoirs have been developed through years of research, such as steam-assisted gravity drainage (SAGD) [5, 6],chemical flooding [7, 8], and in-

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situ combustion (ISC) [9, 10] and cyclic solvent injection (CSI) [11, 12].

There are some limitations regarding the steam-assisted gravity method, chemical flooding, and in-situ combustion method, such as huge energy consumption [6] and greenhouse gas emissions [13] during SAGD process, environment pollution potential during chemical flooding process [14, 15] and high risk due to lose control during ISC process [9, 10, 16]. The CSI process involves circulating a specific solvent into the reservoir to displace the oil and improve the recovery factor [3]. Compared with the previous mentioned three development methods, CSI process effectively overcomes the above-mentioned shortcomings, and has the following advantages: 1) Many previous studies have proven that the CSI process has excellent ability to improve oil recovery because of foamy oil flow [17-19]. 2) The efficiency of the CSI process is not significantly affected by the wormholes generated by solvent injection. The reason is the existence of wormholes can increase the contact area between solvent and crude oil and provide channels for diluted oil to flow back to wellbore [20]. 3) The generation of steam is not required during CSI process, and the energy consumption in CSI process is effectively reduced, resulting in less greenhouse gas emission [21].

Many kind of gases can be employed as solvents during CSI process, such as methane [22, 23], ethane [24, 25], propane [17, 26], and CO_2 [27, 28]. Compared to hydrocarbon solvents, CO_2 has drawn more attention to the oil and gas industry as solvent in CSI process for the following reasons: 1) With the increasing focus on environmental protection in recent years, countries around the world are emphasizing the utilization and sequestration of CO_2. CO_2-based CSI process can sequester a certain amount of CO_2 in underground reservoirs, which can reduce CO_2 emissions and protect the environment [29]. 2) CO_2 can effectively diffuse into heavy oil, and enhance oil recovery factor by oil swelling, viscosity reduction and foamy oil flow [30, 31].

Therefore, lots of factors that affect CO_2-based CSI process had been comprehensively studied, such as injection pressure [32], injection rate [33] and soaking time [34]. Abedini in 2013 conducted 12 groups of CSI experiment using core samples. Experiment results showed longer soaking time would intensify the process of interaction between CO_2 and oil phase, and more CO_2 could diffuse into oil phase for better oil swelling and interfacial tension reduction [35]. Du in 2014 studied the effect of pressure depletion rate (PDR) on cyclic solvent injection process. The findings in this research illustrate that oil recovery factor of each cycle increased with the increasing PDR. However, total experimental time decreased with the increasing PDR, and the increment of oil recovery factor decreased with the decrease rate of pressure decline [20]. Ma, Wang [36] conducted core flooding experiments to evaluate the primary parameter effects on the process performance. The effects of soaking time and injection rate were examined during the experimental study. This work indicates that the optimal injection velocity should be determined based on the reservoir boundary and permeability. The experimental results also suggeste that longer soaking resulted in a more significant oil production increment in the third cycle during the process. Qian, Yang [37] investigated the microscopic residual oil distribution during the CO_2 Huff-and-Puff processes under different injection pressures, cycle numbers and soaking times. The results of this work suggest that a higher ultimate oil recovery factor could be achieved under a higher injection pressure and fewer cycle numbers. Zhou, Yuan [38] conducted a series of long core CO_2 Huff-and-Puff experiments to study the effect of soaking time. This research found that the recovery factor increased with increasing soaking time, but the final recovery factor increment is limited. This finding is supported in the following study from other research work [39].

One difficulty during the application of CSI process, which is the sharp oil production decrease after several cycles, has been reported by many scholars [36, 40] and limits the field application. The main reason for this phenomenon is the reduction of oil saturation in reservoir near the wellbore. Many methods to improve the performance of CSI process has been researched and proposed in recent years. Jia in 2014 proposed gas flooding-assisted cyclic solvent injection (GA-CSI), which a gas flooding was conducted after production process of CSI to produce diluted foamy oil in reservoir. The results shows the GA-CSI process could increase the oil production rate by over 3 times compared with conventional CSI process [41]. Zhang in 2019 compared cyclic hot solvent injection (CHSI) with N-Solv method [42]. The mechanism of CHSI is to injection hot solvent into reservoir and heat the solvent chamber to greatly reduce the oil viscosity. The results show the oil recovery factor of CHSI is 10 percent higher than that of N-Solv method. However, tremendous volume of free gas is trapped in the solvent chamber, thus CHSI process is also recognized as one solvent-consuming method. Zeng conducted experimental work to evaluate the possibility of chemical blended with CO_2 to enhance oil recovery. The results suggest that surfactant could lower interfacial tension and oil-wettability while CO_2 could make oil swelling, and further improve oil recovery [43].

Among the previous proposed researches in improving the performance of the CSI process, polymer has not been introduced into the CO_2-based CSI process. Polymer flooding is famous for its excellent ability to increase viscosity and reduce relative permeability of displacing phase, further enlarge swept area and enhancing oil recovery factor [15, 44-46]. Thus, polymer flooding has been applied for the reservoir development for the past several decades. Many laboratory and field application studies have been conduction on feasibility and EOR ability of polymer flooding, and the plenty of research results have suggested that polymer flooding is one of mature, efficient, and cost-effective EOR techniques [47-50].

Therefore, combining previous studies on improving CO_2-based CSI with characteristic of polymer flooding, this study innovatively designed a polymer flooding assistance method during CO_2-based CSI process to establish an oil bank and increase the oil saturation in CO_2 swept zone when the efficiency of CO_2-based CSI process was relatively low. Therefore, high efficiency and oil production could be obtained in the following cycles of the CO_2-based CSI process. To investigate the mechanism of this novel polymer flooding-assisted CO_2-based CSI technique, five groups of experiments were implemented using the 100×2.5 cm 1D sand-pack model. Two polymer assistance flooding modes (polymer flooding assistance after the last cycle of CO_2-based CSI process or after each cycle), two polymer flooding assistance slug size (the PV volume of produced liquid in previous CO_2-based CSI process or constant 1PV) and three polymer concentration (1000ppm, 250ppm and 0ppm) were considered during experimental studies. Different experimental combinations would result in varying oil recovery factor and material usage, thus a basic economic evaluation was conducted to determine the material cost for producing one barrel of crude oil using different combination methods in this new technical idea. Furthermore, a single well pilot test in field using this novel technology was conducted and validated the field operability and EOR ability. The research results on this innovative polymer flooding-assisted CO_2-based CSI technology would provide new technical ideas for the field development of heavy oil reservoirs.

2. EXPERIMENTS

2.1 Materials

The reservoir condition in this study is simulated by packed silicon sands which was flited in range of 80 to 100 mesh to reduce heterogeneity. Heavy oil sample has viscosity of 1348cP under 58°C. Polymer agent (BHHP-112), which is widely used during polymer flooding process for field development [51, 52], is provided by Tianjin Dagang Oilfield Binggang Petroleum Technology Group Co., Ltd. Polymer solution with different concentration was prepared with distilled water. Relationship between viscosity and concentration is measured and shown in the following Fig. 1. Other features of the polymer agent can be obtained from the official website of Tianjin Dagang Oilfield Binggang Petroleum Technology Group Co., Ltd. and some of the published literatures [53, 54].

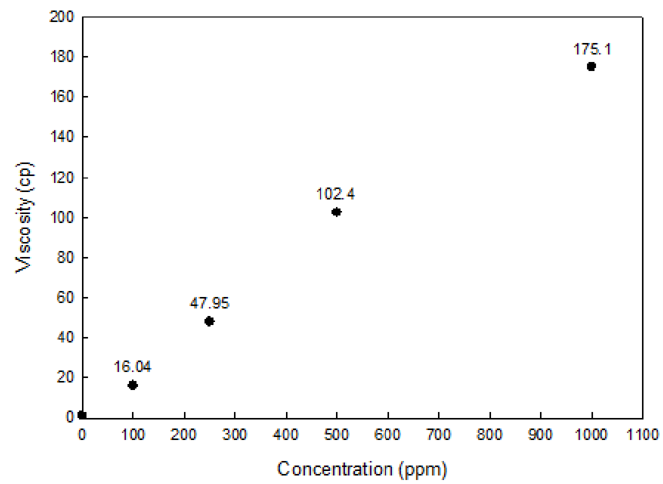
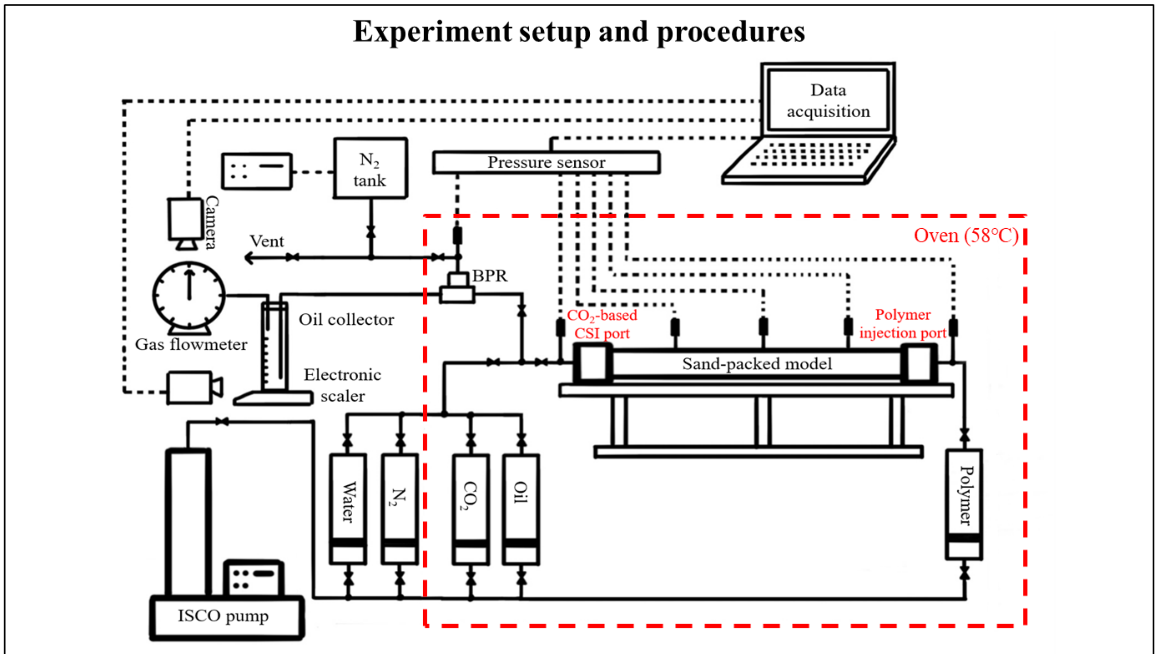


Fig. 1. Relation between polymer concentration and viscosity

2.2 Experiment setup and Equipment

The schematic of experiment setup is divided into three regions and shown in Fig. 2: vacuum region, injection region and production region.

Vacuum region mainly contains a vacuum pump for porosity measurement of the sand pack model. Injection region includes an ISCO pump connected with five transfer cylinders (including N_2, water, crude oil, CO_2 and polymer) for leaking test, permeability measurement, initial oil saturation creation, CO_2-based CSI process and polymer injection. The most essential equipment in production region is back pressure regulator (BPR) to control the depletion of the model pressure and simulate CO_2-based CSI process. Besides, there are three pressure transducers located at both ends and middle of the model to record the inner pressure change. Cameras were connected with a computer to record oil and gas production.



Group	Injection mode	Injection volume	Polymer concentration
1	Start with CO_2-based CSI section. After the last cycle (R_o<1%), turn to polymer injection section.	The volume of produced liquid in previous CO_2-based CSI section	1000 ppm
2	Start with 1 cycle of CO_2-based CSI, and turn to polymer injection.	The volume of produced liquid in previous cycle	1000 ppm
3		1 pore volume	1000 ppm
4	Start with CO_2-based CSI section. After the last cycle(R_o<1%), turn to polymer injection.	The volume of produced liquid in previous CO_2-based CSI section	250 ppm
5		The volume of produced liquid in previous CO_2-based CSI section	0 ppm

Fig. 2. Experimental setup and scheme

2.3 Experiment scheme

In this study, one experimental period includes two sections: one CO_2-based CSI section and one polymer flooding assistance section. CO_2-based CSI section include three stages (injection, soaking and production), and polymer flooding assistance section was conducted followed the CO_2-based CSI section at polymer injection port. Experimental periods could be implemented multi-times, and experiment was terminated until the oil recovery is less than 1% in the first two cycles of CO_2-based CSI section after last polymer flooding assistance section.

Two polymer flooding assistance modes were considered: polymer flooding after last cycle of CO_2-based CSI section (oil recovery factor<1%) and polymer flooding after each cycle of CO_2-based CSI section. Two slug size of polymer flooding assistance were considered: the volume of produced liquid in previous CO_2-based CSI section and constant 1 pore volume (PV). In addition, the effect of polymer concentration on polymer flooding assistance was also considered, including decreasing the concentration of 1000 ppm, 250 ppm and 0 ppm. The detail experiment scheme can be found in Fig. 2.

3. RESULTS

As shown in previous experiment scheme, Group 1, 3, 4 and 5 firstly started CO_2-based CSI section until the oil recovery factor in last cycle is less than 1%. For Group 1, 3, 4, and 5, the average oil recovery factor of the CO_2-based CSI section is 15.25%. This average oil recovery factor obtained is taken as the reference oil recovery factor when no improvement methods are involved in the CO_2-based CSI process under the current experimental conditions.

Compared to reference oil recovery factor (15.25%) of CO_2-based CSI section, all the oil recovery factor in five groups of experiment is much higher, which proves that polymer flooding assistance can significantly boost development performance of CO_2-based CSI process, as shown in Fig. 3. The oil recovery factor in each group is different due to different polymer flooding assistance mode, slug size and concentration. The reasons for the difference will be discussed in following section.

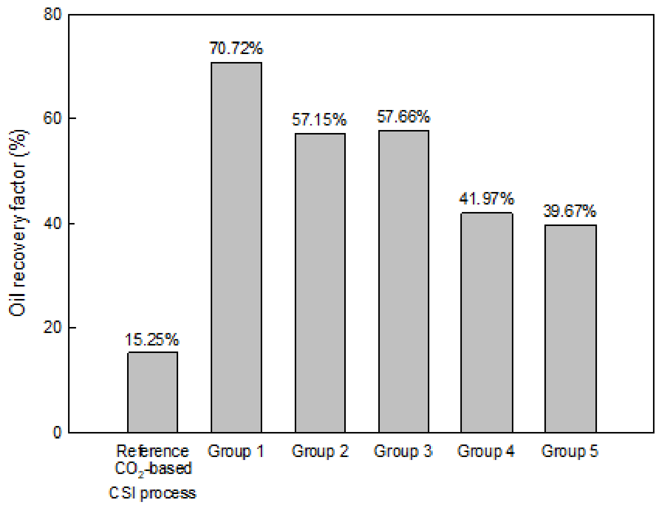


Fig. 3. Oil recovery factors in five groups

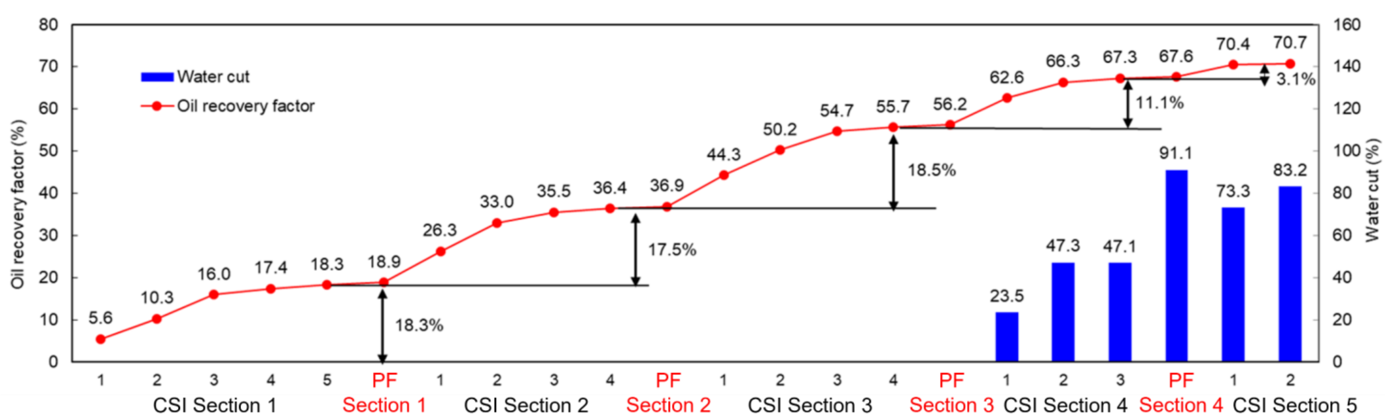
3.1 *Research on difference polymer flooding assistance modes*

Based on experiment procedures, two polymer flooding assistance modes were designed and compared in Group 1 and 2. The oil recovery factor and water cut profile in Group 1 and 2 are shown in Fig. 4 and Fig. 5.

There is total five experimental periods conducted in Group 1. The oil recovery factor of CO_2-based CSI section in the first three periods is at the similarly high level (around 18%), while the oil recovery factor of CO_2-based CSI section in the following experiment period 4 and 5 decreases to 11.1% and 3.1%, respectively. In every CO_2-based CSI section, the change of oil recovery factor with cycle number is consistent with the previous finding that oil recovery is higher in the beginning cycles and gradually decrease with cycle number increasing [55].

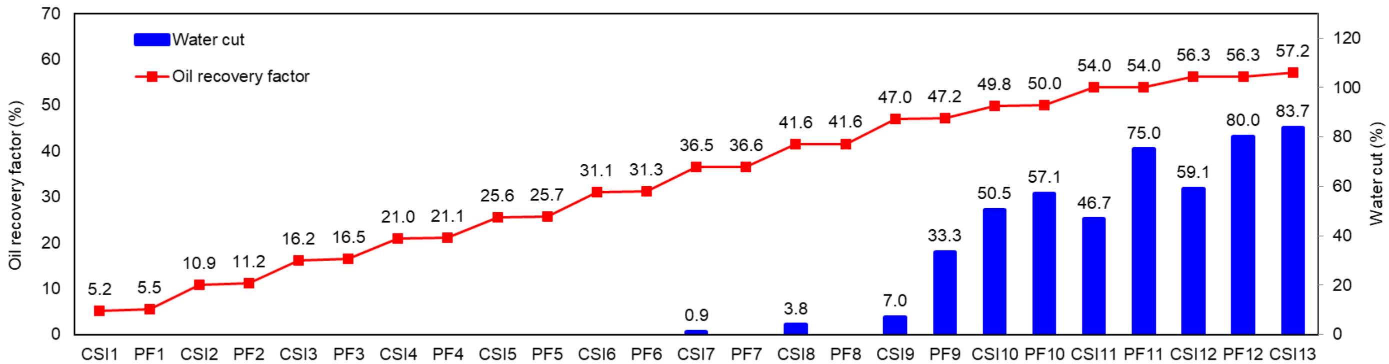
In this work, the experiments were designed to be terminated until the oil recovery is less than 1% in the first two cycles of the CO_2-based CSI process after the last polymer flooding assistance section. Therefore, there is no polymer flooding assistance section in the last experiment period 5 (take the Group1 as an example) because the oil recovery factor in the second cycle of fifth CO_2-based CSI section is only 0.3% and experiment ends. The oil recovery factor of four polymer flooding assistance sections is 0.43% on average, which is much lower than the oil recovery of CO_2-based CSI section. The reason for this phenomenon is that the polymer flooding assistance, which is carried out after the CO_2-based CSI section in each experimental period, has the ability to effectively push the oil that is outside the CO_2-swept area closer to the producer. The slug size of the polymer flooding assistance is equal to the volume of the produced fluid during the previous CO_2-based CSI section, and the polymer flooding assistance section will end before the polymer solution pushes the oil out. Then, during the first three polymer flooding assistance sections, the fluid produced from reservoir is mainly composed of carbon dioxide, with a very small amount of crude oil. As a result, the oil saturation near the producer experiences a significant increase, and the CO_2-based CSI section in the next experimental period can achieve a high oil recovery condition, similar to conducting CO_2-based CSI in an undeveloped reservoir.

However, due to viscous fingering during polymer flooding assistance section [56], polymer solution begins in the first cycle of fourth CO_2-based CSI section (when 0.49PV polymer solution has been injected). The water cut of CO_2-based CSI section in experiment period 4 increases from 23.5% to 47%, and reaches 91.1% in the



Note: PF Section denote the polymer flooding assistance section.

Fig. 4. Oil recovery factor and water cut profile in Group 1



Note: PF denote the polymer flooding assistance section.

Fig. 5. Oil recovery factor and water cut profile in Group 2

following fourth polymer flooding assistance section. In the next experiment period 5, there is a significant decrease of water cut in produced liquid. The water cut of two cycles is 73.3% and 83.2% respectively, which proves the excellent ability to reduce water production of CO_2-based CSI section. The reason for the sharp decrease of water cut is mainly because the emulsion between oil and injected polymer solution is formed with the reaction of CO_2. Many previous studies have proved that CO_2 has ability to lower the interfacial tension between oil and water phase. In the later stages of the experiment, when the water saturation within the reservoir is relatively high, the oil and water form an oil-water emulsion under the influence of the trapped carbon dioxide.

The microscopic photograph of the emulsion is shown in Fig. 6. Many small oil drops are suspended in water phase to form an oil-in-water emulsion. Therefore, compared with the high viscosity of heavy oil, the emulsion has a much lower viscosity and better deliverability, and more oil can be produced from reservoir. The emulsion is unstable system, and the distinct interface between oil and water phase will appear under high temperature heating, which provides convenience for demulsifying.

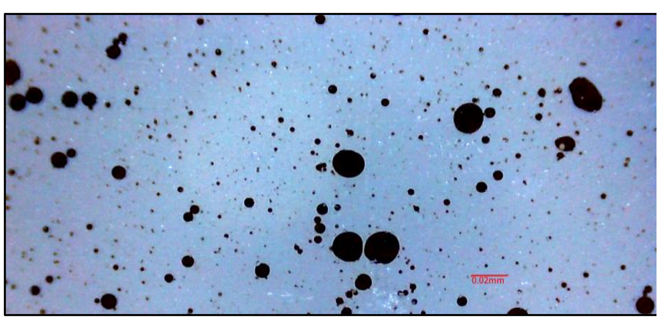


Fig. 6. Produced oil-water emulsion

The oil recovery factor in Group 1 is the highest (70.72%) among five groups of experiment with the cumulative volume 0.65PV polymer solution injected. The cycle number is also the most (18 cycles), which represents the development time of Group 1 will be longer than other groups.

In Group 2, due to different polymer flooding assistance mode with Group 1, each experiment period only includes one cycle of CO_2-based CSI section, followed by one polymer flooding assistance section. The injection volume is the same as the volume of produced liquid in previous CO_2-based CSI cycle. Therefore, there are total 13 experiment periods in Group 2, as presented in Fig. 5. And the oil recovery factor experiences a significant increase in this group, as each experimental period is primarily influenced by the single cycle of CO_2-based CSI section, which contributes the most to oil pro duction. In the first nine experiment periods, the oil recovery of every cycle has little decline and maintains at relative high level (5%). This phenomenon, together with the oil recovery factor after each polymer flooding assistance section in the first group of experiments, provides evidence for the ability of polymer flooding assistance to establish an oil bank and increase oil saturation around the producer. Therefore, the oil recovery factor and cycle number are significantly improved and extended, respectively. After experiment period 9, the water cut of both CO_2-based CSI and polymer flooding assistance sections is higher than 50%, and the oil recovery efficiency gradual decreases.

For Group 2, the total slug volume of polymer flooding assistance is 0.6PV. Polymer solution is firstly produced and recorded from reservoir at seventh CO_2-based CSI section, and polymer solution breakthroughs at polymer flooding assistance section 9. Before polymer injection section 9, 0.38PV polymer solution has been injected into reservoir, which is 0.11PV less than Group 1 (0.49PV). This represents multiple injection of a small amount of polymer solution will result in a shorter breakthrough time. Therefore, the final oil recovery rate is 57.2%, which is 13.5% lower than oil recovery in Group 1 (70.7%).

The change of polymer solution injection pressure at polymer injection port in Group 1 is shown in Fig. 7. The polymer flooding assistance section 1 has the highest injection pressure peak of 3.9MPa, because the oil slug to be pushed during polymer flooding assistance section 1 is larger than other three polymer flooding assistance sections. As the experiment proceed of Group 1, the size of oil slug to be driven by polymer flooding decrease, resulting in a significant decrease in the injection pressure peak during the polymer flooding assistance section. Thus, the injection pressure peak decrease from 3.9MPa to 1.89MPa from the polymer flooding assistance section 1 to the polymer flooding assistance section 4.

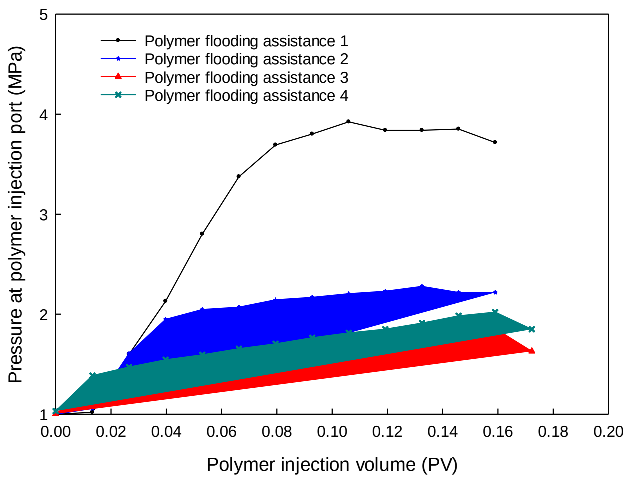


Fig. 7. Relation between polymer injection pressure and polymer injection volume at the polymer injected port during each polymer flooding assistance section (Group 1)

Fig. 8 presents the injection pressure peak during each polymer flooding assistance section in Group 2. The injection pressure peak at first five cycles are similar at about 2.7MPa and much less than the injection pressure peak of polymer flooding assistance section 1 in Group 1 (3.9MPa). This is because the experimental setup of Group 2 is to conduct polymer flooding assistance after each cycle of CSI process, and the slug size of each polymer flooding in Group 2 is less than the slug size of polymer flooding assistance in Group 1. Therefore, the polymer injection time is short, and the polymer flooding assistance section in Group 2 ends before the polymer injection pressure reach 3.9 MPa as in Group 1. Between cycle 5 and 9, the injection pressure peak has a continuous decrease. This is because 1) more oil has been produced from reservoir, and less resistance will be encountered during polymer flooding assistance section. 2) viscous fingering during polymer flooding due to viscosity difference between crude oil and polymer solution will causes early breakthrough and further reduce the injection pressure [56]. After cycle 9, water cut has a significant increase which represents the breakthrough of polymer solution. Therefore, the polymer injection pressure peak keeps stable at about 1.9MPa.

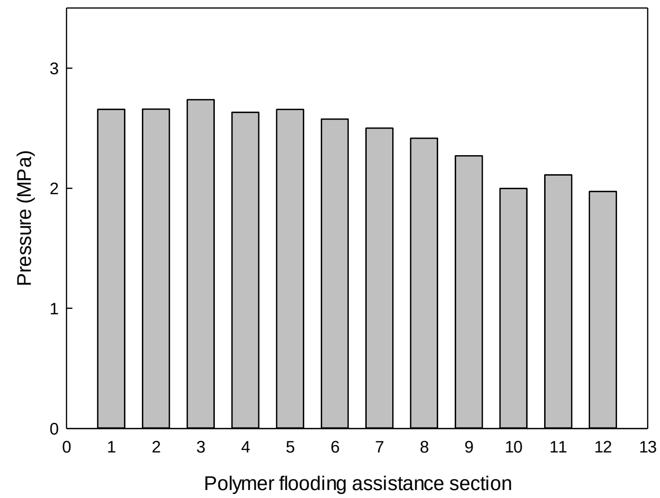
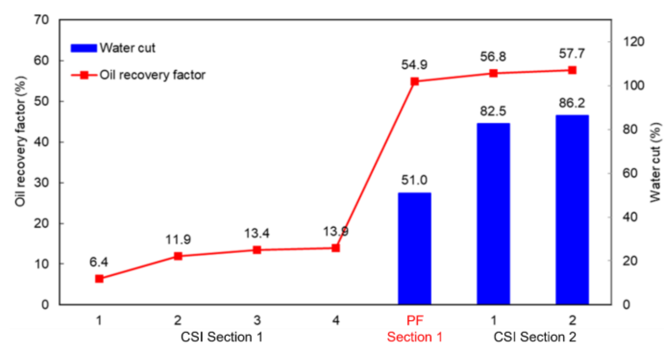


Fig. 8. Polymer injection pressure peak at the polymer injected port during each polymer flooding assistance section (Group 2)



Note: PF denote the polymer flooding assistance section.
Fig. 9. Oil recovery factor and water cut profile in Group 3

3.2 Research on slug size of polymer flooding assistance

Group 1 and 3 were conducted to investigate the effect of polymer flooding slug size on oil recovery factor. Group 3 has a largest polymer flooding assistance volume (1PV) after CO_2-based CSI section around all groups of tests. The production profile of Group 3 is shown in Fig. 9. From the Fig. 9, it is obvious that there are only two experimental periods in this group. The oil recovery factor of CO_2-based CSI section in experiment period 1 is 13.9%, while the following 1PV polymer flooding assistance section contributes oil recovery factor of 40.96%. In experiment period 2, two cycles of CO_2-based CSI only contribute 2.77% recovery factor.

Therefore, the oil recovery factor in Group 3 is l3.09% lower than Group 1 because 1PV polymer flooding assistance section pushes most of residual oil out of the system, and the main EOR mechanisms transfers from CO_2-based CSI to polymer flooding.

In reservoir displacement development, mobility ratio is one of the essential parameters and defined as mobility of displacing phase divided by mobility of displaced phase.

$$M = \frac{\lambda_D}{\lambda_d} \qquad \text{Equation 1}$$

$$\lambda = \frac{k}{\mu} \qquad \text{Equation 2}$$

In these two equations, the subscripts D and d represent displacing water and displaced oil respectively. M is mobility ratio between two phases, and λ is mobility. k and μ represent effective permeability and viscosity, respectively.

Higher mobility ratio can bring a wider swept area and a higher oil recovery factor. Conventional single polymer flooding can enhance oil recovery by increasing viscosity of displacement phase to control mobility ratio only from displacing phase aspect. Compared with traditional polymer flooding, Group 3 realizes mobility ratio from two aspects, which can be called dual mobility ratio control: decreasing displacement phase mobility by increase the viscosity of polymer solution and increasing displaced phase mobility by CO_2-based CSI process to decrease the viscosity of the oil.

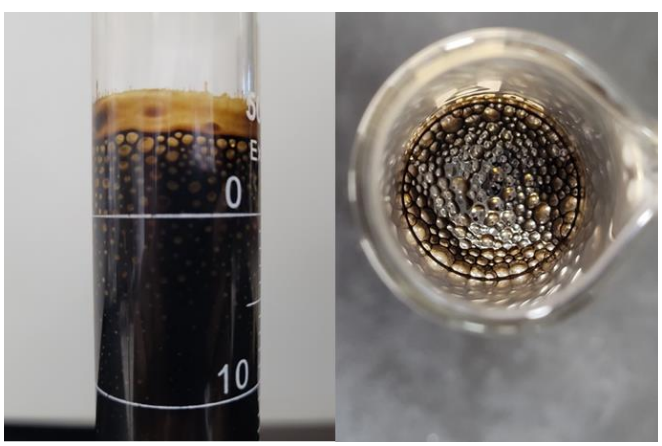
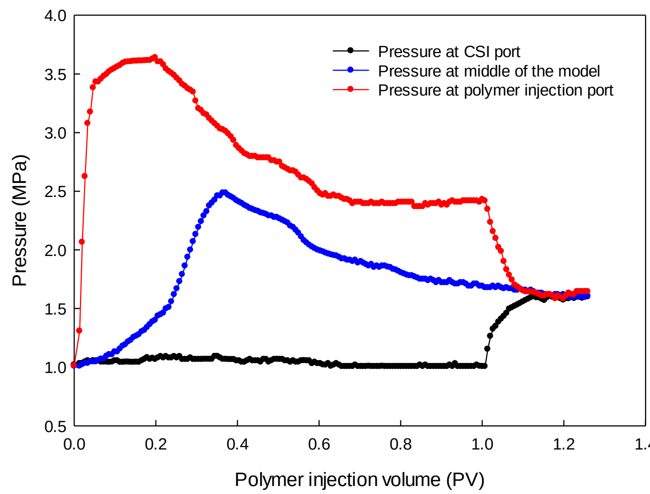


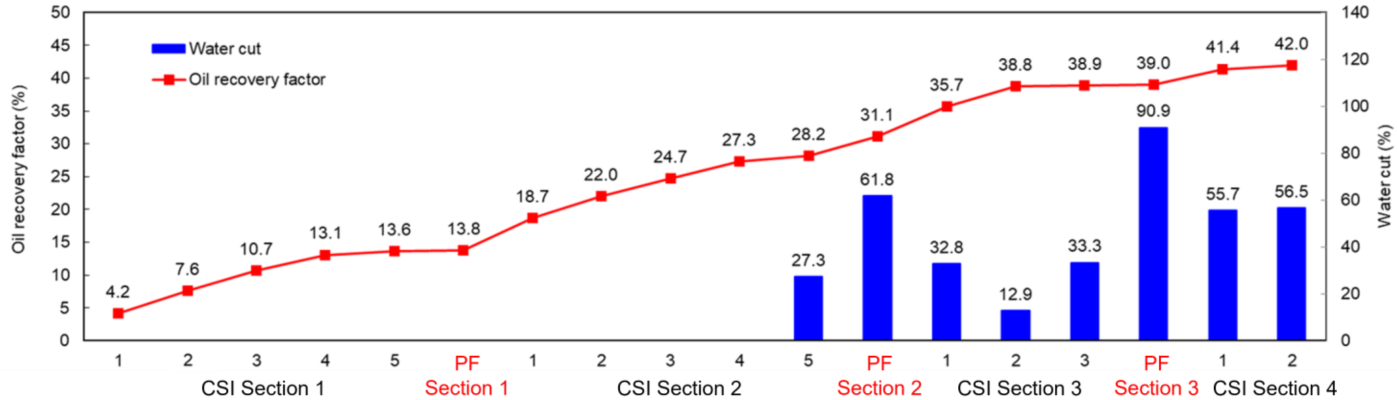
Fig. 10. CO_2 release from produced oil phase during polymer flooding after heating

The realization of dual mobility ratio control in Group 3 is supported by the volume change of oil produced from polymer flooding assistance section after heating. Before polymer flooding assistance section, some of CO_2 is dissolved in oil phase in reservoir. During oil production from a reservoir, CO_2 has a tendency to release from the oil phase. However, due to the high viscosity of the oil, a portion of the CO_2 becomes trapped in the oil phase. Therefore, the produced oil is placed in oven for heating under higher temperature, and CO_2 release process from oil phase is shown in Fig. 10. During the heating process, the viscosity of the oil decreases significantly, allowing the CO_2 to release from the oil phase, further resulting in the formation of many CO_2 bubbles. As a result, there is a significant decrease in the volume of oil produced.



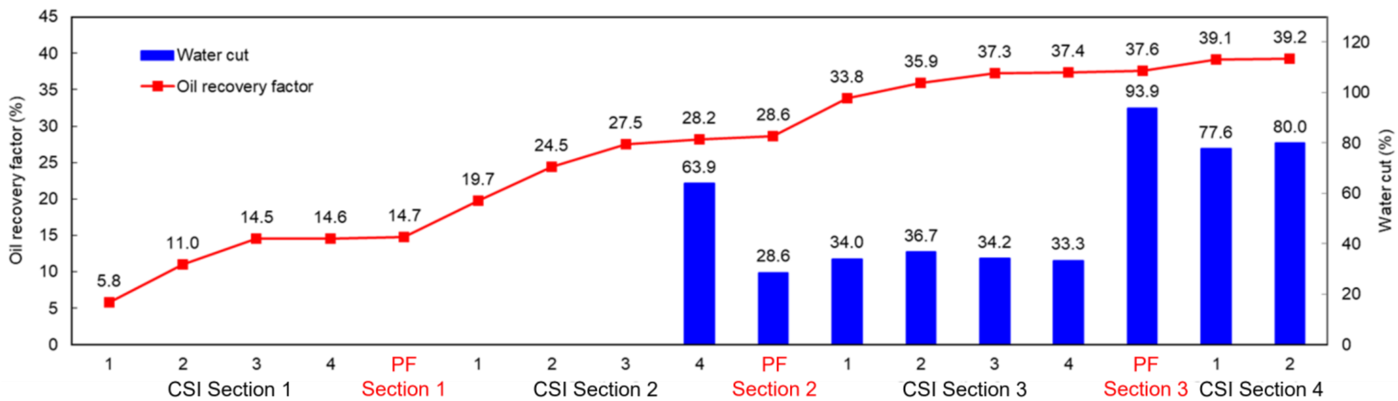
Note: PF denote the polymer flooding assistance section.
Fig. 11. Pressure change during 1PV polymer assistance injection section in Group 3

The realization of dual mobility ratio control in Group 3 not only effectively enhance oil recovery but also lower the injection pressure of polymer solution. Ordinary polymer flooding with large slug is considered not suitable for heavy oil reservoirs because of excessive polymer injection pressure. In Group 3, because some heavy oil has been produced and some CO_2 diffuses into oil phase to lower residual oil viscosity through CO_2-based CSI process, the highest injection pressure is lower than single polymer flooding under the same experiment condition. The pressure change of two ends and middle of the model is shown in Fig. 11and can be used to describe the displacement front. As the polymer injection begin, the pressure at polymer injection port rapidly increases to the highest pressure (3.62MPa) at 0.2PV, which represents the highest displacement pressure difference is 2.62MPa (0.34MPa lower than single polymer flooding under similar experimental condition). After 0.2PV, the pressure at polymer injection port has a decrease trend while the pressure at middle of the model has a significant increase. With the pressure at middle of the model increasing, the highest pressure 2.46MPa is encountered at about 0.38PV. After this point, the pressure at injection point and middle of the



Note: PF Section denote the polymer flooding assistance section.

Fig. 12. Oil recovery factor and water cut profile in Group 4



Note: PF Section denote the polymer flooding assistance section.

Fig. 13. Oil recovery factor and water cut profile in Group 5

model both gradual drop until polymer flooding assistance section ends.

3.3 Research on difference polymer concentration

Previous three groups of experiment explore the different polymer flooding assistance mode and slug size. However, polymer concentration, one of the important parameters for influencing the viscosity of polymer solution, should also been considered. Therefore, in Group 4 and 5, two different polymer concentration, 250ppm and 0ppm (pure water), is selected to research the effect of polymer concentration on polymer flooding-assisted CO_2-based CSI technique.

The production profiled in Group 4 and 5 are shown in Fig. 12 and Fig. 13.The overall oil recovery factor trend of both Group 4 and 5 is similar with Group 1 because of the same polymer flooding assistance mode and similar slug size. However, due to different concentration and different viscosity of displacing phase, the recovery factors have a significant decrease, which are 42.0% and 39.2% for Group 4 and 5 respectively. The reason for the decrease of oil recovery factor is the less viscosity of displacing fluid will cause a more unstable displacement due to larger mobility ratio and more viscous fingers. Therefore, the displacement during polymer flooding assistance is not stable as Group 1 and polymer solution can be observed more quickly at production well. In Group 1, the polymer solution is produced and observed in cycle 13 for the first time. When lower polymer concentration to 250ppm, the polymer is firstly observed in cycle 9, and the first cycle recording polymer from producer is 7 when the polymer concentration goes down to zero (water).

For polymer injection pressure, because polymer concentration decreases from 250 ppm to 0 ppm in Group 4 and 5, the highest polymer injection pressure decreases due to less viscosity of the displacing phase, shown in the following Tab. 1. When the polymer concentration gradually decreases to 0 (water flooding assistance), the polymer injection pressure peak during water flooding assistance section 1 in Group 5 is only 3MPa. Besides, because the earlier breakthrough is encountered due to the viscosity decrease in displacing phase, there is a significant decrease of the polymer injection pressure peak during the polymer flooding assistance section 2 in Group 4 and water flooding assistance section 2 in Group 5.

Tab. 1. Summary of polymer concentration and polymer injection pressure peak in Group 1, 4 and 5

	Group 1	Group 4	Group 5
Concentration	1000ppm	250ppm	0ppm
P section No.	The polymer injection pressure peak		
1	3.9	3.3	3.0
2	2.3	1.6	1.3
3	2.0	1.4	1.2
4	1.9	/	/

The production gas-oil ratio (GOR) of each cycle in all five groups of experiment are calculated and presented in the Fig. 14. For the CO_2-based CSI section of every experiment period in Group 1, 3, 4 and 5, the production GOR has a significant increase because the gas production increases while the oil production decreases as cycle number increasing. A dramatic decrease of the production GOR could be observed in the first cycle of the CO_2-based CSI section after each polymer flooding assistance section in Group 1, 3, 4 and 5, which suggests that the concentration and injection volume of polymer solution have little effect on the trend of production GOR. The main reasons for this GOR decrease include 1) after each polymer flooding assistance section, most of the CO_2 trapped in reservoir (free gas form) could be pushed out of the system. Therefore, less CO_2 injection is needed during the first cycle of CO_2-based CSI process, which causes less gas production in the first cycle of CO_2-based CSI process after the polymer flooding assistance section. 2) The system pressure increases after the polymer flooding assistance section and therefore reduce the required injected CO_2 volume to raise the

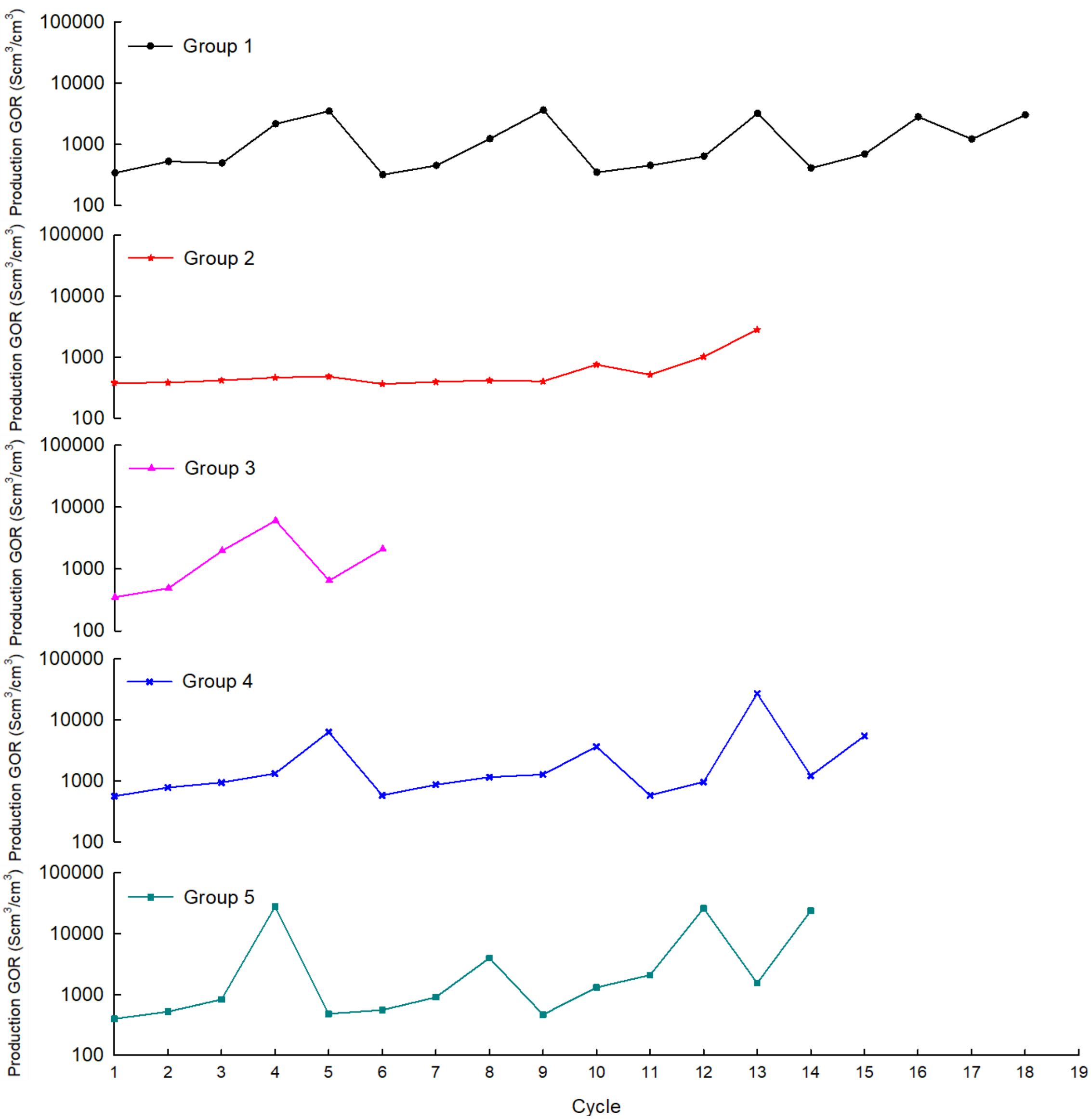


Fig. 14. Production GOR at each cycle during the CSI process for all groups

system to 5MPa at the first cycle of the CO_2-based CSI process.

For Group 2, the overall trend of production GOR is different compared with other four groups, as presented in Fig. 14. The production GOR of the Group 2 is stable first, followed by a significant increase after cycle 9. The main reason for this trend is that most of the trapped CO_2 (free gas form) during one cycle CO_2-based CSI section is replaced by polymer solution in each experiment period. Therefore, the injected CO_2 volume and the produced CO_2 volume for every cycle of CO_2-based CSI section after varies little. Moreover, previous experiment results of oil recovery factor shows that oil recovery in each experiment period also remains high level and has little difference because polymer flooding assistance effectively increases the oil saturation near the producer and creates oil bank for CO_2-based CSI section. Therefore, both stable trends of CO_2 production volume and oil recovery factor bring a stable production GOR trend at beginning cycles. After cycle 9, the production GOR has a significant increase, and the reason is the oil production decrease after polymer solution breakthrough.

3.4 Economy evaluation

To evaluate the economy of polymer flooding-assisted CO_2-based CSI process with different parameters, a basic economic evaluation (only including CO_2 gas fee, polymer agent fee and confecting polymer water fee) was conducted. The cost of materials is obtained through the investigation of real material cost in eastern China. The cost per ton of carbon dioxide and polymer agent are 70.66 and 2100 US dollar, respectively. The cost of confecting polymer water per cubic meter is 1.13 US dollar.

Based on experiment results, the CO_2 usage is shown in the following Tab. 2. The CO_2 usage of reference CO_2-based CSI section was calculated by the average CO_2 usage in Group 1, 3, 4 and 5. Therefore, assuming 88.185 US dollars per barrel based on current oil price, the material cost in each group is calculated and shown in Tab. 3.

The analysis results of above table suggest that polymer flooding-assisted CO_2-based CSI technology has significantly lower cost than reference CO_2-based CSI only process, regardless of polymer flooding assistance mode, slug size and polymer concentration. The reason is the ultimate oil recovery factor is significantly enhanced by polymer flooding assistance, while the CO_2 usage between polymer flooding-assisted CO_2-based CSI process and reference CO_2-based CSI process has little difference. The increased material cost comes from the cost of polymer agents and confecting water, but this part of the cost is relatively small.

In five groups of experiment, Group 2 has the lowest cost ($1.5696) because of the usage of CO_2 is the lowest, and the cost of CO_2 is also the lowest. With the polymer concentration decrease, the cost of polymer agent decreases. Due to the fact that oil recovery factor decreases with the decrease of polymer concentration, the total cost shows an increasing trend as polymer concentration decrease. Group 3 has the highest material cost ($2.3573) because of low CO_2 utilization and excessive polymer flooding injection volume.

3.5 Field polit test

Based on this experiment study and results, a single-well pilot test to evaluate the EOR potential and accessibility of polymer flooding-assisted CO_2-based CSI process during field development was conducted in eastern China. The test well selected for pilot test is J49-10, which is in a heavy oil block with two corresponding polymer injectors, as shown in Fig. 15. The reason for the selection at this well includes 1) well condition is good which can guarantee the continuity of the pilot test. 2) there is a good correlation between injector and producer through previous conductivity test. 3) the viscosity of the crude oil under reservoir condition is about 720cP, which provides enough space for CO_2 viscosity reduction. 4) reservoir physical property is

Tab. 2. CO_2 usage in each group

	CSI only	Group 1	Group 2	Group 3	Group 4	Group 5
CO_2 usage (L)	6.5187	6.3629	4.7931	6.8137	6.3847	6.5134

Tab. 3. Calculated Material Cost in Each Group

Cost, $	CSI only	Group 1	Group 2	Group 3	Group 4	Group 5
CO_2 gas	5.1122	1.0761	0.9825	1.3376	1.8398	1.9418
Polymer agent	/	0.3875	0.3984	0.6921	0.0889	/
Water	/	0.1835	0.1886	0.3276	0.1683	0.1841
Total	5.1122	1.6471	1.5696	2.3573	2.0971	2.1259

suitable for polymer flooding-assisted CO_2-based CSI process, and the permeability and porosity of the reservoir are 210mD and 21%, respectively.

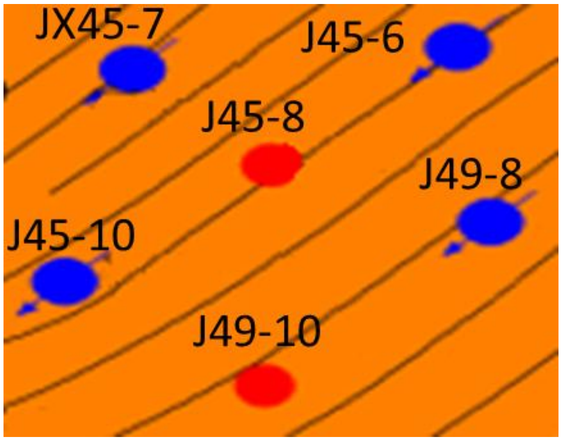


Fig. 15. Well position of the pilot test

The oil production history of this well is shown in the following Fig. 16. Polymer solution is injected into reservoir through injectors J45-10 and J49-8. The viscosity of polymer solution at wellhead is between 40cP and 70cP, and the daily injection volume for J45-10 and J49-8 is 60m^3 and 50m^3, respectively. Due to high viscosity of oil, the oil production of J49-10 under single polymer flooding is only 0.8 tons per day with water cut of 92.15%.

Therefore, the development technology of this well is transferred from single polymer flooding to polymer flooding-assisted CO_2-based CSI process. During pilot test, total 252t CO_2 was injected, followed by one month soaking. Polymer solution was continuously injected into reservoir during CSI section to achieve higher oil recovery rate at high oil price of that time. Therefore, during production of polymer flooding-assisted CO_2-based CSI process, the oil production has a dramatical increase from 0.8 to about 5 tons per day, and the highest daily oil production reaches 5.9t. Besides, there is a significant decrease of water cut from about 92% to 73%. Therefore, the results of this pilot test strongly prove the feasibility and great EOR potential of polymer flooding-assisted CO_2-based CSI technology.

4. CONCLUSION

Five groups of experiment were conducted using 1D sand-pack model to investigate the influential factors of the novel polymer flooding-assisted CO_2-based CSI process.

1) The experimental results illustrate the polymer flooding assistance approach can effectively create an oil bank for the following CO_2-based CSI process.
2) The highest recovery rate of 70.7% is achieved when performing polymer flooding assistance after the last cycle of previous CO_2-based CSI section and using a displacement slug equal to the total volume of produced liquid from CSI section.
3) The oil recovery rate of CO_2-based CSI process with polymer flooding assistance after each cycle (Group 2）is lower than previous experiment results. But the economy evaluation results show the material cost per barrel of oil using this polymer flooding assistance mode and polymer injection volume is the lowest.
4) When increases the slug size of polymer flooding assistance to 1PV, the oil recovery factor is 57.66%. The cycle number of this experiment is the least because most oil is produced in the polymer flooding assistance section. Dual mobility ratio control theory is realized by simultaneously increasing the mobility of crude oil while reducing the mobility of water.

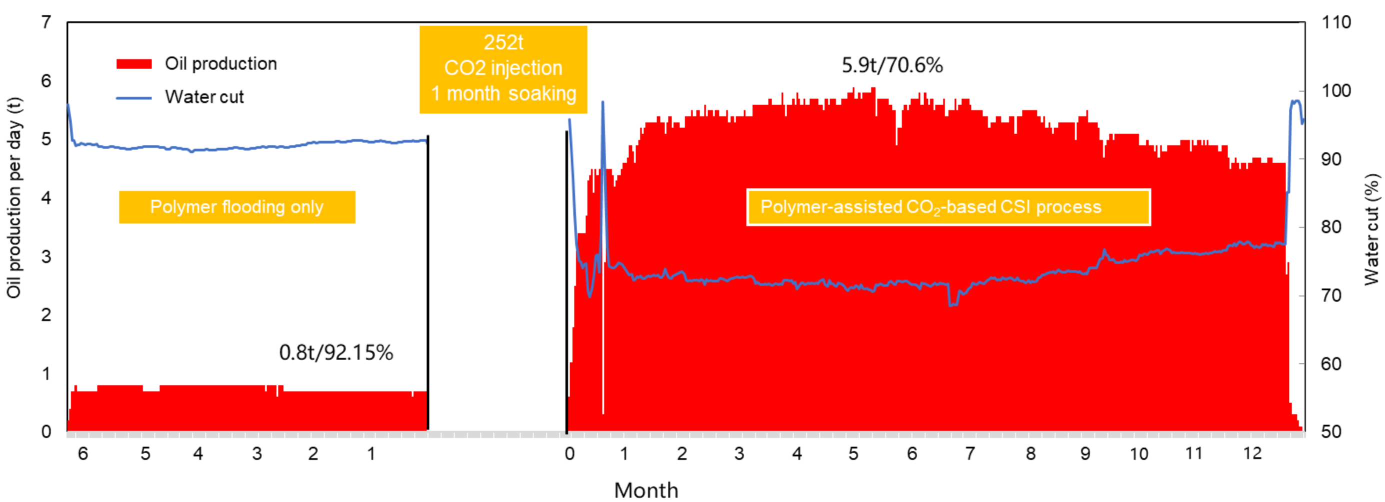


Fig. 16. J49-10 production profile

5) While decreasing the polymer concentration, the oil production has a great decrease, and the material cost per barrel of oil with lower concentration polymer flooding assistance section is higher.
6) A single well field pilot test was designed and conducted in eastern China using polymer flooding-assisted CO_2-based CSI process. The daily oil production has an increase from 0.8 to 5 tons after applied the polymer flooding-assisted CO_2-based CSI process. The success of the field pilot test demonstrates the excellent field operability and enhanced oil recovery ability of polymer flooding-assisted CO_2-based CSI technique.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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