Laboratory Evaluation of CO_2 Flooding: A Strategic Technology for Sustainable Development of Oil Companies

Hao Kang[1,2], Jian Gao[3,4] and Gang Hui[5,*]

[1]*Polytechnic College, Hebei Normal University, Shijiazhuang 050024, China*
[2]*College of Engineering, Hebei Normal University, Shijiazhuang 050024, China*
[3]*Research Institute of Petroleum Exploration and Development, PetroChina, Beijing 100083, China*
[4]*State Key Laboratory of Enhanced Oil Recovery, Beijing, 100083, China*
[5]*Unconventional Petroleum Research Institute, China University of Petroleum (Beijing), Beijing 102249, China*
E-mail: haokang@hotmail.com
[*]*Corresponding Author*

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Abstract

With the development of humankind, energy demand and climate change have both faced with serious situations now. In order to find new technologies for solving these problems, long core displacement experiment concerning CO_2 flooding is conducted with 11 different core samples from N formation in M oilfield. Results show that oil production rate will be greatly improved and the oil recovery can reach nearly 25% by the CO_2 huff and puff process using 3 rounds which is much higher than the real recovery factor in M oilfield. Considering the enhanced oil recovery and carbon storage effects generated by this technique at the same time, CO_2 flooding is definitely a promising technique with great potential both for sustainable development of oil companies and humankind. For large scale field application, it is

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suggested that oil companies and governments should provide corresponding support policy concerning further study of this technology. Particularly, further studies should focus on the application of CO_2 flooding with other EOR technologies, optimal CO_2 injection mode, optimal CO_2 injection rate, optimal CO_2 injection pressure and so on.

Keywords: Sustainable development, carbon dioxide, sustainable strategy, carbon storage, carbon capture.

1 Introduction

With the development of human society in all aspect, the energy consumption has always been on the increasing trend and the carbon emission in the world is of giant quantity now [1–3]. This has led to many serious environmental problems which is of great threatening to the future survival of humankind [4–6].

In order to realize the harmony between man and nature through sustainable development, technology innovation has been viewed as one of the choice for moving ahead. Many studies are conducted concerning new technologies application for sustainable development and positive results are obtained in various areas: Hong et al. studied the application of bamboo materials for making biofilm reactor fillers which can provide technical support for the remediation of polluted river water quality [7]; Wang et al. constructed a Stackelberg game model to explore the subsidy mode for effectively promoting the biofuel ethanol industry in China, and they finally found out the main influential elements for the optimal subsidy mode which can be a good reference for policy making [8]; Zhou studied the generation of hydrogen through biomass under conditions of solar energy, and different catalysts are compared with the Fe-Ce catalyst be viewed as the optimal choice [9]; Cai et al. prepared and tested the Pd-Co-Ti catalyst, and their study can be good support for CO oxidation in flue gas generated thus air pollution can be better controlled [10]. All these studies adequately proves that new technologies application can be a good choice with bright prospects to realize sustainable development.

As a technique of great potential, CO_2 flooding can increase the oil recovery greatly in the oilfield [11–15]. This process can also lead to the storage of CO_2 into the underground formation [16–19]. Particularly, CO_2 flooding technique can lead to two positive effects for petroleum industries:

On one hand, it can directly lead to the emission decrease of greenhouse gases from oil companies, and this is positive to meet the demand from governments for carbon emission reduction. On the other hand, many scholars have proved that CO_2 flooding can be especially effective to increase the oil recovery of low permeable reservoirs which will be of better economic benefits for oil companies [20–23]. In fact, the oil reserve in low permeable reservoir shares a large portion of oil reserves in the total world. CO_2 flooding can supplement the formation energy effectively and increase the production of single well. The total benefit can be very significant.

This paper firstly reviews the carbon dioxide emissions in a brief manner and explains the urgency for reduction the carbon emission. Then, laboratory experiment is conducted concerning the detailed characteristics of CO_2 flooding. Finally, some useful conclusions are obtained concerning the application of this technique.

2 Carbon Dioxide Emissions

Based on data collected by BP from various resources [24], CO_2 emissions are analyzed to illustrate the situation and the necessity for emission reduction.

Figure 1 below shows the CO_2 emissions of the total world since the year 1965. The vertical coordinate uses a unit of million tonnes. From the curve, it is obvious to see that the trend is generally always in an increasing pattern. In the past 55 years, the absolute value of world CO_2 emission has increased from about 11000 to 32000. There are only 3 short decreasing periods: during the year 1979 to 1982, the year 2008 to 2009, and the year 2019 to 2020.

Specifically, since 2019, due to the influence of the Corona Virus Disease 2019, the carbon emissions showed a relatively big decrease all over the world. However, based on statistic data collected, there are still countries where carbon emission remains in the increasing pattern: China and Iran. In order to make more detailed analysis, the CO_2 emissions in these two countries are illustrated in Figures 2 and 3 respectively.

Figure 2 shows the CO_2 emissions in China since the year 1965. From the curve, it is obvious that the emission trend has always been in an increasing pattern without any decline. In the past 55 years, the absolute value of CO_2 emission in China has increased from about 500 to 10000.

Figure 3 shows the CO_2 emissions in Iran since the year 1965. From the curve, it is obvious that the emission trend is generally in an increasing pattern

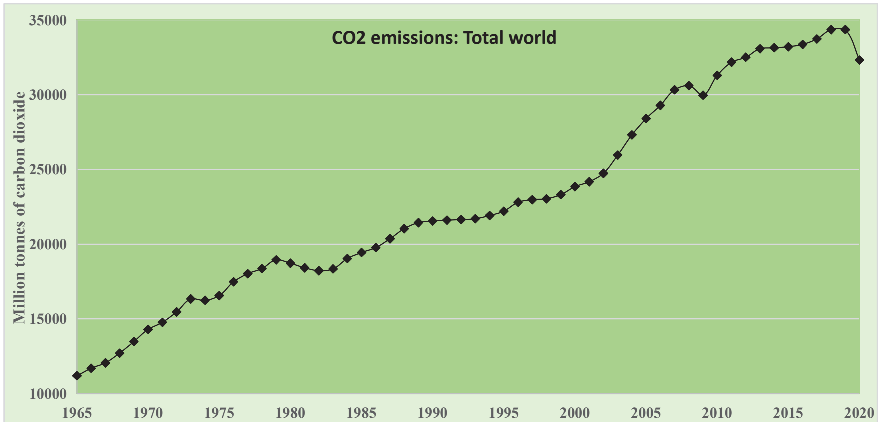

Figure 1 CO_2 emissions of total world from year 1965 to 2020.

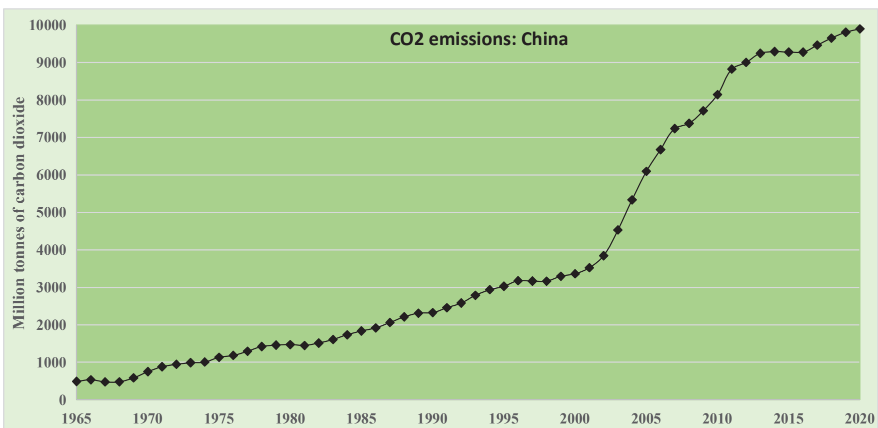

Figure 2 CO_2 emissions of China from year 1965 to 2020.

with some small decline occasionally. In the past 55 years, the absolute value of CO_2 emission in Iran has increased from about 20 to 680.

Although the general increasing pattern is the same between China and Iran, there is actually great difference between the emission level. Take year 2020 as an example, the total emission in Iran only accounts for 6.8% of the emission in China. Therefore, the situation in China is much more challenging than other countries in the world.

In fact, there is also countries whose CO_2 emissions have already been in the declining pattern in recent years. Figure 4 illustrated the emission in US

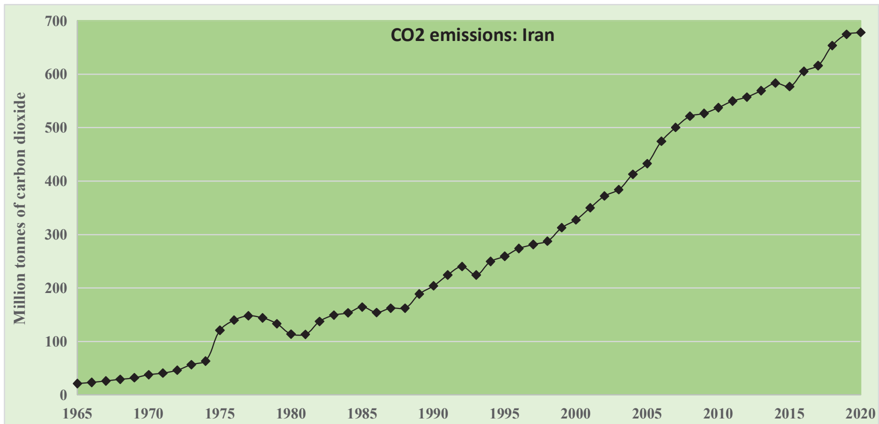

Figure 3 CO_2 emissions of Iran from year 1965 to 2020.

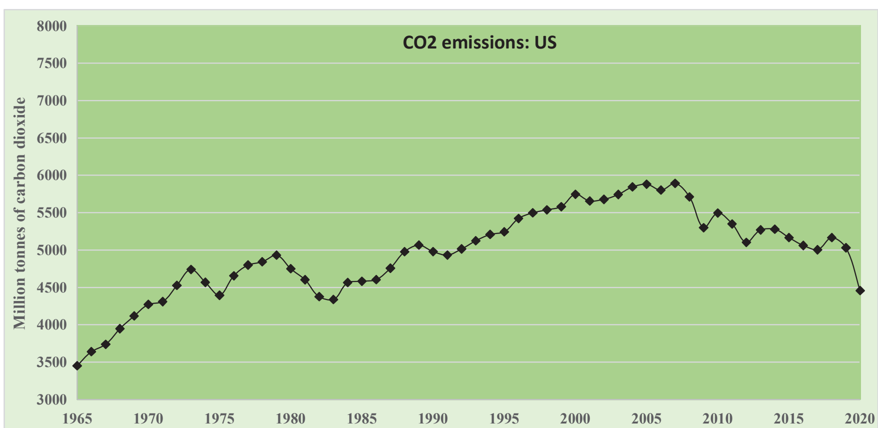

Figure 4 CO_2 emissions of total North America from year 1965 to 2020.

since year 1965. From the curve, it is obvious that the emission is actually not always in an increasing pattern at all. There are much more decreasing periods than that in Iran of China. Especially, after year 2006, the emission is generally in a single decrease pattern. This is mainly due to the innovation of technology in US: the development of shale gas has achieved great success in US and many industrial projects once flaring coal starts to flaring gas from then on, so the CO_2 emissions can be greatly reduced by using natural gas as a clean energy.

3 Enhanced Oil Recovery Experiment by CO_2 Flooding

3.1 Experiment Preparation

In the development process of tight oil, reservoir pressure and productivity usually drop quickly, and it is difficult to inject adequate water into the reservoir for energy supplement purpose. Therefore, there is great challenge to improve the recovery of tight oil reservoir. Based on field experiences and laboratory experiments, CO_2 flooding is regarded as an important way for enhanced oil recovery. In the CO_2 flooding process, the oil will expand and its viscosity will decrease, and the formation energy can be supplemented. Finally, the recovery of tight oil reservoir will be increased.

Currently, there have been many studies concerning the huff and puff of CO_2. Man-made or ordinary core has been usually used in the laboratory experiment tests. However, since the tight oil reservoir is of great heterogeneity, the ordinary core cannot model this characteristic adequately. Therefore, in this study, the long core is used to evaluate the huff and puff process of CO_2, and this can be good reference for enhanced oil recovery in tight oil reservoir by huff and puff of gases.

To carry on the experiment, eleven cores are selected from the N formation in M oilfield and the total length of cores is 95.93cm. The cores are selected with permeability of different range and the heterogeneity of formation can be better characterized.

The average permeability of long core is calculated as Formula (1) below. In this formula, L stands for the length and K stands for the permeability of each core. The specific detailed parameters of cores are as illustrated in Table 1.

$$\bar{K} = \frac{L_1 + L_2 + L_3 + \cdots + L_n}{\frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{L_3}{K_3} + \cdots + \frac{L_n}{K_n}} \tag{1}$$

Table 1 Fundamental parameters of long core

Core No.	1	2	3	4	5	6	7	8	9	10	11
Length/cm	8.8	8.6	8.9	8.3	8.8	9.2	8.7	8.8	8.7	8.4	8.8
Diameter/cm	2.50	2.51	2.50	2.48	2.48	2.50	2.49	2.49	2.49	2.50	2.50
Permeability/ $\times 10^{-3} \mu m^2$	6.5	0.23	0.24	0.17	0.14	0.33	0.13	0.36	0.12	0.40	0.69
Porosity/%	14.1	12.1	10.6	10.3	6.6	11.3	9.3	11.2	9.9	12.1	12.6

The apparatus used in this experiment is the displacement apparatus large enough which can model the displacement experiments in the long core under high pressure (up to 70 MPa) and high temperature (up to 200°C) conditions. The apparatus is composed of five systems: injection system, modelling system, production system, data collection system, and supplementary system. It can model the production process of water flooding, gas flooding, chemical flooding and so on. Since the core permeability in this experiment is extremely low, the pressure difference has to be high enough for effectively driving the fluids. Therefore, the back pressure is set to be relatively lower so that the inlet pressure does not need to be very high.

3.2 Experiment Procedure

The experiment procedure of CO_2 huff and puff is as follows:

(1) Put the core into the vacuum apparatus and using the vacuum pump to suck at least 48 hours to create vacuum. After that, saturate the core with standard salt water.
(2) Put the core into the core holding unit. Increase the surrounding pressure to above 1.5∼2.0 MPa than the injection pressure and increase the back pressure accordingly. Increase the temperature to the experimental set temperature at 60°C. After the pressure and temperature are in steady state for enough time, saturate the core by injecting oil into it.
(3) The huff and puff process are set to happen without miscibility of CO_2 with the oil. In the huff process, the CO_2 is generally intended to be injected by 0.3 pore volume. Then, the injection process will be ceased and the system will stay for about 1 hour. After that, the puff process will be started with oil production. Cumulative oil production, cumulative gas production and so on will be recorded promptly for following data analysis purpose. One thing to be paid special attention: in the puff process, micro flow-rate control valve is used for flow and pressure control, thus fast pressure decrease can be avoided.
(4) After the CO_2 huff and puff process above, ethyl ether will be consistently injected into the core until there is no oil produced from the end. Therefore, the core can be cleaned by this process.
(5) Nitrogen will be injected after the above process, and the residual ethyl ether will be swept out from the core.
(6) Data analysis or the next round of experiment can be carried on.

4 Results and Discussion

After getting data from the experiment, the data are illustrated in figures below to clearly show the results.

Figure 5 shows the procedure of the whole experiment: the relationship between the injection volume and injection time. In periods 0–56 min, 118–188 min, and 248–308 min, CO_2 injection is conducted. In other periods between 0 to 448 min, injection is ceased and oil production is conducted after the soak period. Actually, there has been adequate study concerning the soak time of CO_2 huff and puff [25]. Zhan et al. conducted reservoir simulation on basis of a single well model, the multiple linear regression method is applied to find the relationship between soak time and 5 influencing factors. These factors include reservoir permeability, CO_2 injection volume, reservoir porosity, formation oil saturation, and CO_2 injection rate. Their study results show good fit towards the real CO_2 huff and puff case of Yushulin oilfield. In fact, the management of soak process is a crucial and complicated process. The management system should be established based on the characteristics of oil reservoir reaction during this process. In this view, further studies should be conducted concerning the soak time towards specific reservoirs to realize highly efficient production management.

To further investigate the oil production process, Figure 6 illustrates the relationship between oil production and injection time. From Figure 6, it is easy to see that the oil production can reach 2.2 mL in the first round of

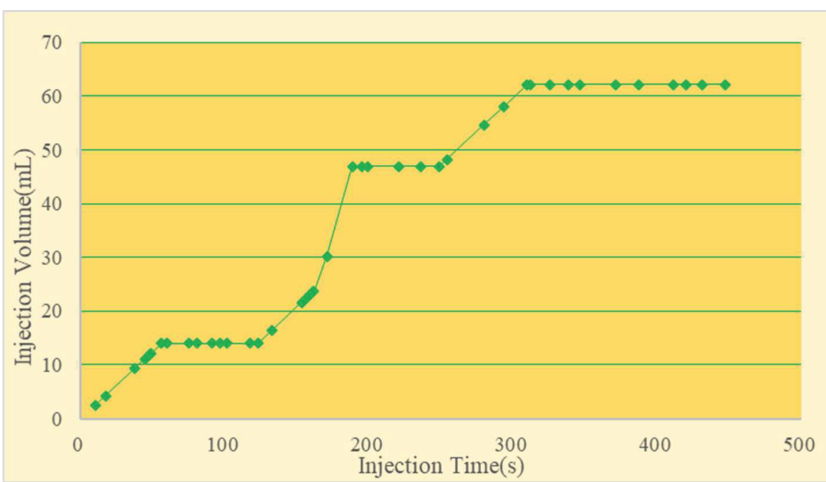

Figure 5 Relationship between injection volume and injection time.

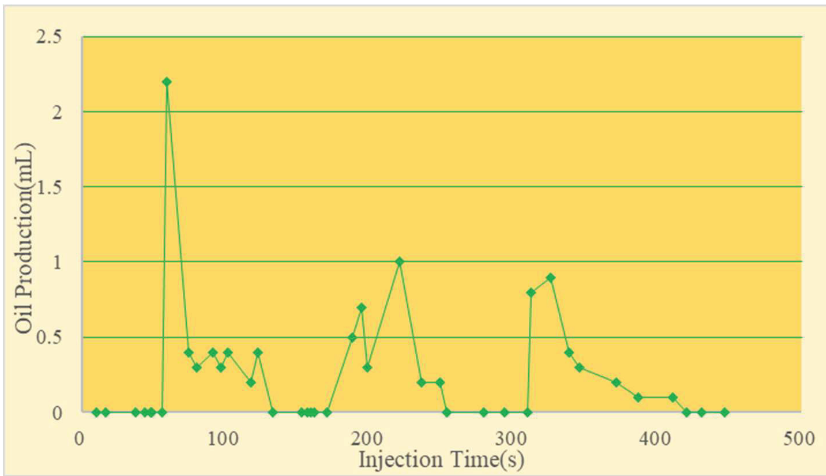

Figure 6 Relationship between oil production and injection time.

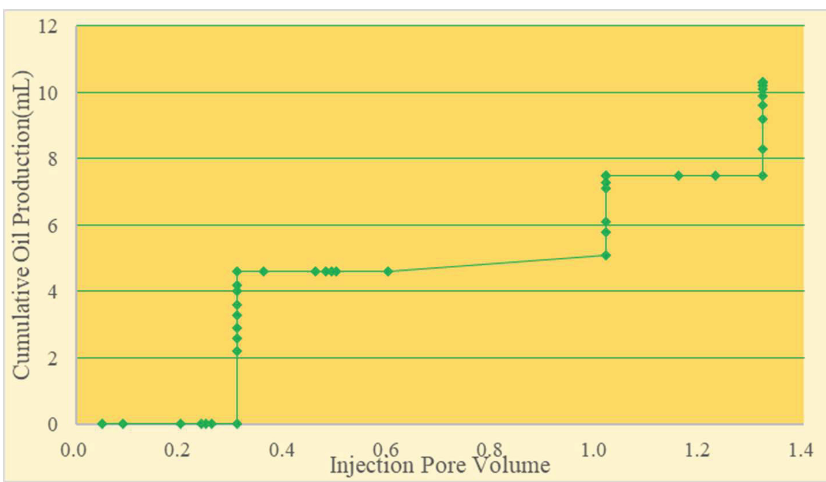

Figure 7 Relationship between cumulative oil production and injection pore volume.

puff process. The oil production can reach 1.0 mL in the second round of puff process and the oil production is lower than 1.0 mL in the third round of puff process. This trend shows that the oil production diminishes with the huff and puff process going on.

Figure 7 illustrates the relationship between cumulative oil production and injection pore volume. In the first round of huff and puff process,

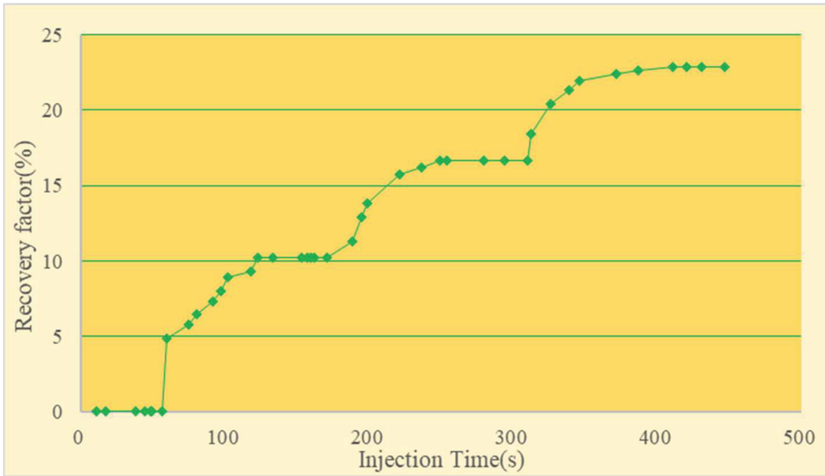

Figure 8 Relationship between recovery factor and injection time.

the cumulative oil production reaches 4.6 mL while the injection pore volume is only 0.3. In the second round, the injection pore volume is 0.7, while the cumulative oil production increases only by 2.5 mL. In the third round, the injection pore volume is set as 0.3, and the cumulative oil production increases by 2.5 mL again at the same level with that in the second round.

Figure 8 illustrates the relationship between recovery factor and injection time. In the first round of puff process, the recovery factor reaches a relatively high level. In the second and third round of oil production, the recovery factor decreases to a relatively low level. Actually, this result can also be deducted or calculated from results above.

Actually, Qi et al. conducted research on CO_2 huff and puff in low permeability reservoir of the Ordos Basin[21]. Both laboratory experiments and pilot tests are conducted concerning this technology. After the injection period, there are great increase concerning liquid production rate and oil production rate on site. The oil recovery factor are greatly enhanced by this technology. This pilot test shows great prospect for the large-scale application of CO_2 flooding in Yanchang oilfield and will definitely promote the stable production of this oilfield to finally realize the goal of sustainable development for local economy in the Shanxi Province of China.

In all, the first round of huff and puff process showed better results in oil production rate, recovery factor and so on. The second and third rounds show relatively poorer results, whereas, there is not very sharp difference between the last two rounds. At the end of the three rounds, the total recovery factor can reach as high as about 25% which proves the great potential of CO_2 flooding technique for enhanced oil recovery and sustainable development.

Actually, Liu et al. studied the application of CO_2 huff and puff into untra-high water-cut reservoir [26]. In-depth profile control technique is firstly used to plug the predominant flow channels and very good results with enhanced oil recovery are obtained after the CO_2 huff and puff process. This study also indicates that CO_2 flooding technology has good adaptability and can be applied together with other EOR techniques to achieve improved oil recovery. Oil companies can provide more support for research on this area in future. For example, the study on CO_2 injection alternating with water should also be a technology with good prospect. Li et al. conducted pilot test in the Changqing oilfield and the oil production is greatly improved with lower water cut [27]. However, due to the whole complicated process, many parameters can actually be optimized further, such as the injection pressure, the injection rate, the injection mode and so on. Accordingly, oil companies will find new opportunities for technical breakthrough in these related studies by near future.

5 Conclusion

The world CO_2 emissions are in serious situation nowadays and it is urgent to find out effective strategies to change this trend. At the same time, the demand for oil and other energy resources has also been in a very high level and many oilfield companies face the problem of extreme low production with little profit. CO_2 flooding can achieve enhanced oil recovery and carbon underground storage effectively at the same time, it is a technique with great potential for sustainable development of oil companies and the humankind. Long core displacement experiment is conducted in this study with core samples of different porosity and permeability from low permeable reservoir. On the laboratory test scale, oil recovery can reach nearly 25% by the CO_2 huff and puff process in 3 rounds, and this is much higher than the current recovery factor in the M oilfield studied which shows the real potential of CO_2 flooding technology. At the same time, only a few parameters are actually considered in this study. In future, it is suggested that oil companies should provide more support concerning the study of more aspects of CO_2 flooding, such as the application of CO_2 flooding with other EOR technologies, the CO_2 injection mode, the CO_2 injection rate, the CO_2 injection pressure and so on. In this way, this technology will be further developed and sustainable development both for companies and humankind will be more easily to be achieved.

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Conflict of interest

The authors all declare that they have no conflict of interests regarding the publication of this paper.

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Biographies

Hao Kang received the bachelor's degree in Petroleum Engineering from China University of Petroleum in 2008, and the philosophy of doctorate degree in Petroleum Geology from Peking University in 2014, respectively. He is currently working at the College of Engineering, Hebei Normal University. His research areas include exploitation and utilization of energy resources.

Jian Gao received the bachelor's degree in Petroleum Engineering from Southwest Petroleum University in 1998, and the philosophy of doctorate degree in Petroleum and Natural Gas Engineering from China University of Petroleum in 2007, respectively. He is currently working at the Research Institute of Petroleum Exploration and Development, PetroChina. His research areas include exploitation and utilization of energy resources.

Gang Hui, corresponding author of this paper, received the bachelor's degree in Petroleum Engineering from China University of Geosciences in 2008, and the philosophy of doctorate degree in Petroleum Engineering from University of Calgary in 2021, respectively. He is currently working at Unconventional Petroleum Research Institute, China University of Petroleum. His research areas include exploitation of unconventional oil and gas resources.