frontiers | Frontiers in Earth Science

TYPE Opinion
PUBLISHED 09 January 2023
DOI 10.3389/feart.2022.1035771

OPEN ACCESS

EDITED BY
Zhilin Cheng,
Xi'an Shiyou University, China

REVIEWED BY
Dong Xiong,
China University of Petroleum, China
Qinglin Shan,
Shandong University of Science and Technology, China

*CORRESPONDENCE
Qiao Deng,
dengqiao2008@163.com

SPECIALTY SECTION
This article was submitted to Geochemistry,
a section of the journal Frontiers in Earth Science

RECEIVED 03 September 2022
ACCEPTED 13 September 2022
PUBLISHED 09 January 2023

CITATION
Xia X, Deng Q, Sang P, Tan L, Yan L, Bao J and Li W (2023), Low-carbon oil exploitation: Carbon dioxide flooding technology.
Front. Earth Sci. 10:1035771.
doi: 10.3389/feart.2022.1035771

Low-carbon oil exploitation: Carbon dioxide flooding technology

Xueqin Xia[1,2], Qiao Deng[1,2,3]*, Pengfei Sang[4], Leichuan Tan[5], Liangzhu Yan[1,2,3], Jingwen Bao[1,2] and Wenlong Li[6]

[1]Cooperative Innovation Center of Unconventional Oil and Gas, Yangtze University (Ministry of Education and Hubei Province), Wuhan, Hubei, China, [2]Hubei Key Laboratory of Drilling and Production Engineering for Oil and Gas, Yangtze University, Wuhan, Hubei, China, [3]Carbon Hydrogen Epoch Technology Co. Ltd., Wuhan, Hubei, China, [4]Engineering Technology Research Institute of PetroChina Southwest Oil and Gas Field Company, Chengdu, Sichuan, China, [5]CNPC Chuanqing Drilling Engineering Co. Ltd., Chengdu, Sichuan, China, [6]Tianjin Branch of CNOOC Ltd., Tianjin, China

KEYWORDS

low carbon, CO_2 flooding, flooding mechanism, carbon capture utilization and storage, enhanced oil recovery

Introduction

It is well known that there are many technical methods for improving oil recovery, including gas miscible flooding, thermal oil recovery, chemical flooding, and microbial oil recovery. Among these, CO_2 flooding is one of the key technologies for improving oil recovery that achieves the goal of reducing carbon emissions (Jia et al., 2019). Given the increasing awareness regarding human environmental protection, the development of a low-carbon economy is an irresistible global trend. The concepts of "carbon peak" and "carbon neutrality" have gradually gained popularity. Carbon neutrality has also spawned the carbon capture, utilization, and storage (CCUS) industry (Zou et al., 2021). CO_2 flooding is one of the main carbon utilization technologies that makes full use of carbon resources to enhance oil recovery while promoting the development of a low-carbon economy. This paper reviews and summarizes the developments regarding CO_2 flooding in domestic and foreign scenarios, discusses the mechanism and process of CO_2 flooding, analyzes the technological challenges, and provides some corresponding solutions.

Research status

CO_2 flooding has been used globally to enhance oil recovery for more than 30 years and is becoming more popular. Therefore, an increasing number of researchers are engaged in research on CO_2 flooding (Chen et al., 2015). There are many reported CCUS-EOR projects from domestic and foreign investigators, as shown in Table 1. Research on CO_2 flooding began in the 1950s (Whorton et al., 1952), and some European countries had earlier used CO_2 flooding to enhance oil recovery. The former Soviet Union first began studying CO_2 injection enhanced oil recovery (EOR) technology in 1952. In 1968, CO_2 flooding tests were carried out in the Tuimajin Oilfield, which achieved a 15% increase in the final crude oil recovery (Qin et al., 2015). CO_2 flooding developed the

TABLE 1 International CCUS-EOR projects [modified according to Xiang et al. (2022)].

	Project name	Capture quantity million tons/year	Trapping mode	Utilization
International	Val Verde Natural Gas Plant	1.3	Natural gas processing	EOR
	LaBarge Gas Plant	7		
	Lost Cabin Gas Plant	0.8–1.0		
	Central Plant	8.4		
	Enid Fertilizer CO_2-EOR Project	0.7	Industrial separation	
	Great Plain Synfuel Plant and Weyburn-Midale Project	3	Precombustion capture	
	Air Products Steam Methane Reformer EOR Project	1	Hydrogen production from natural gas	
China	Research and Demonstration of CO_2-EOR in Jilin Oilfield	0.6	Chemical and physical absorption	
	Daqing Oilfield CO_2-EOR Demonstration Project			
	Shengli Oilfield CO_2-EOR Project	0.04	Chemical absorption	
	CO_2-EOR Project in Zhongyuan Oilfield	0.1		
	Karamay Dunhua Oil and Xinjiang Oilfield CO_2-EOR Project	0.1		
	CO_2-EOR Project in Changqing Oilfield	0.05	Low-temperature methanol wash	

fastest in the United States, which has the largest number of CO_2 flooding projects accounting for more than 90% of the global total. CO_2 flooding affords good economic benefits, with an annual oil production of about 1,500 × 104 t for five consecutive years and oil recovery increase of 7–15% (Hitesh et al., 2008; British Petroleum Company, 2017; British Petroleum Company, 2018). In the 21st century, greenhouse gas emission reductions have further promoted rapid development of CO_2 flooding technology (Shen and Liao, 2009; Koottungal, 2014).

Since the 1960s, China has started paying attention to CO_2 flooding technology and has successively carried out indoor research on CO_2 flooding. In 1963, the first study on CO_2 flooding was carried out in the Daqing Oilfield in China. From 1991 to 1993, immiscible displacement tests of CO_2 by alternating gas and water injection were carried out in the eastern Sanan Oilfield. In 1995, Jilin Oilfield carried out the CO_2 single-well huff and puff test and obtained 1420 t of increased crude oil through multiple tests. In 1998, Shengli Oilfield carried out the CO_2 single-well huff and puff test to obtain increased crude oil outputs by more than 200 t. Subsequently, China has continued to strengthen research on CO_2 flooding technology. At present, research on CO_2 flooding for EOR in the Jilin Oilfield is relatively mature (Chen et al., 2012).

Carbon dioxide flooding mechanisms, methods, and processes

CO_2 flooding has been increasingly used in recent times. Understanding and mastering the oil displacement mechanism can therefore promote technological progress.

Carbon dioxide flooding mechanisms

There are nine mechanisms of CO_2 flooding:

1) Viscosity reduction: Carbon dioxide and crude oil have good mutual solubilities. Temperature and pressure also affect the solubility of CO_2 in crude oil, and extremely high temperatures are not conducive to viscosity reduction (Li et al., 2008).
2) Improve oil–water mobility ratio: CO_2 increases the viscosity of water and decreases the viscosity of crude oil. These two viscosities tend towards each other, thus improving the mobility ratio of crude oil to water and expanding the swept volume (Luo et al., 2012).
3) Expansion effect: The dissolution of CO_2 in crude oil greatly expands the volume of the oil. The greater the degree of expansion, the stronger is the ability to flow and easier it is to replace (Gu et al., 2007).
4) Extraction and gasification of light hydrocarbons in crude oil: CO_2 can be used to extract and gasify light components in crude oil, thereby reducing the relative density of crude oil and enhancing recovery (Roper et al., 1992).
5) Miscible effect: When the pressure reaches the miscible pressure, CO_2 mixes with the light hydrocarbons in crude oil to form an oil zone, which greatly improves oil recovery during the oil displacement process (Grigg and Siagian, 1998).
6) Molecular diffusion: The water phase hinders diffusion of carbon dioxide molecules into the oil phase, completely inhibiting the release of the light hydrocarbons from the oil phase to carbon dioxide. Therefore, sufficient time is required for the carbon dioxide molecules to fully diffuse into the oil phase.

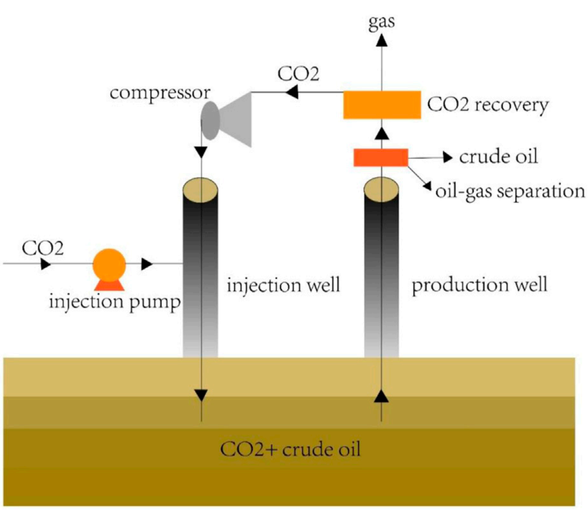

FIGURE 1
CO_2 enhanced oil recovery (EOR) process flowchart.

7) Reduce interfacial tension: In the process of CO_2 flooding, mixing CO_2 and the light components in crude oil (C2–C6) effectively reduces the oil–water two-phase interfacial tension, reduces the resistance of CO_2 in the displacement process, and enhances oil recovery (Desch et al., 1984).
8) Dissolved gas flooding: CO_2 injected into the oil layer increases its pressure, but in the displacement process, the pressure reduction causes CO_2 to escape from the crude oil and occupy the pore spaces, thereby allowing dissolved gas flooding that is conducive to flooding (Gu et al., 2007).
9) Acidizing plugging improves permeability: CO_2 dissolved in water generates carbonic acid and renders the aqueous solution acidic. To a certain extent, massive injection of CO_2 can flush out blockages, dredge oil circulation, and restore the production capacity of a single well (Rao et al., 2004).

Carbon dioxide flooding methods

CO_2 flooding can be divided into two types: CO_2 immiscible and CO_2 miscible flooding. Expansion viscosity reduction is the main mode of CO_2 immiscible flooding. For reservoirs with low pressures, high temperatures, and heavier components, the surface tension between CO_2 and crude oil is large. CO_2 can be used to extract some light components of crude oil, thereby expanding the crude oil, reducing its viscosity, and improving recovery. The essence of CO_2 huff and puff is immiscible flooding, and the mechanism involves expanding the volume of crude oil continuously so that the tension and viscosity of the crude oil interface can be reduced. This method allows injection of carbon dioxide into the bottom of the production well. After shutting down, the carbon dioxide penetrates the reservoir, which is ultimately conducive to continued production from the well. When the formation pressure is greater than the CO_2 miscible pressure and less than the formation fracture pressure, CO_2 miscible flooding occurs. The injection methods may be continuous or simple, among others. Studies have shown that miscible flooding enables greater recovery than immiscible flooding.

Carbon dioxide flooding processes

The flooding processes include primary, secondary, and tertiary flooding. Primary flooding is the method of extracting crude oil using only natural energy. Secondary flooding is the method of increasing the reservoir pressure by injecting gas or water. EOR technology involves the use of high pressures to inject supercritical/dense-phase CO_2 into the reservoir, which allows the CO_2 to drive the flow of crude oil to the production well, thereby increasing oil recovery. The CO_2-EOR process flow chart is as shown in Figure 1. After the CO_2 is compressed, it is injected into the injection well. Then, the production well produces the oil–gas mixture, which further helps separation of the crude oil.

Prospects

In recent years, with increasing awareness regarding environmental protection, CO_2-EOR technology has developed gradually. This not only eases the pressure on environmental pollution but also enhances oil recovery. However, there are still some problems and challenges: 1) it is necessary to strengthen measures to tackle the problem of low CO_2 oil recovery; 2) the economic issues with regard to use of CO_2, such as the fact that CO_2 is corrosive to the pipeline during gathering and transportation, accelerate the costs from pipeline damage; 3) gas source of CO_2 flooding: owing to the increased distance between the oilfield and the city, the costs of gathering and transportation are high, which limit the development of CO_2 flooding technologies.

This paper therefore suggests two areas of improvement: 1) China should continue to strengthen technical research on improving oil recovery; 2) China needs to develop breakthrough carbon dioxide capture technologies and provide inexpensive natural gas sources.

Author contributions

All authors conceived and designed the study. Write the first draft, XX and QD; Writing review and editing, PS and LT; Format modification, LY, JB, and WL.

Funding

This work was supported by the Open Foundation of Cooperative Innovation Center of Unconventional Oil and Gas, Yangtze University (Ministry of Education and Hubei Province, No. UOG 2022-03), Open Fund of Hubei Key Laboratory of Drilling and Production Engineering for Oil and Gas (Yangtze University, No. YQZC202206), and Hubei Provincial Natural Science Foundation Youth Project of 2022 (No. ZRMS2022000846).

Conflict of interest

PS was employed by the company Engineering Technology Research Institute of PetroChina Southwest Oil and Gas Field Company, LT was employed by the company Chuanxi Drilling Company, CNPC Chuanqing Drilling Engineering Co. Ltd.; QD and LY were employed by the company Carbon Hydrogen Epoch Technology Co. Ltd. WL was employed by the company CNOOC Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

British Petroleum Company (2017). *BP statistical review of world energy*. London: BP Company.

British Petroleum Company (2018). *BP statistical review of world energy[R]*. London: BP Company.

Chen, Huanqing, Hu, yongle, and Tian, Changbing (2012). Research progress of CO2 flooding and storage [J]. *Oilfield Chem.* 29 (01), 116–121+127.

Chen, Huanqing, Hu, Yongle, and Tian, Changbing (2015). Researches on CO2 flooding and sequestration and its significance in low carbon economy [J]. *J. Southwest Petroleum Univ. Soc. Sci. Ed.* 17 (5), 7. doi:10.11885/j.issn.1674-5094.2015.01.29.01

Desch, J. B., Larsen, W. K., Lindsay, R. F., and Nettle, R. L. (1984). Enhanced oil recovery by CO2 miscible displacement in the little knife field, billings county, North Dakota. *J. Pet. Technol.* 36 (09), 1592–1602. doi:10.2118/10696-PA

Grigg, R. B., and Siagian, U. W. R. (1998). *Understanding and exploiting four-phase flow in low temperature CO2 floods*. Midland, Texas: SPE Permian Basin Oil and Gas Recovery.

Gu, Libing, Li, Zhiping, and Jin, Ou (2007). The existing state of enhanced oil recovery by utilizing carbon dioxide[J]. *China Min.* 16 (10), 66–68. doi:10.3969/j.issn.1004-4051.2007.10.020

Hitesh, M., Marshall, C., and Khosrow, B. (2008). *The potential for additional carbon dioxide flooding projects in the United States[R]*. Tulsa, Oklahoma, USA: SPE Symposium on Improved Oil Recovery.

Jia, Kaifeng, Ji, Dongchao, and Gao, Jindong (2019). The existing state of enhanced oil recovery by CO2 flooding in low permeability reservoirs [J]. *Unconv. oil gas* 6 (1), 9.

Koottungal, Leena (2014). 2014 world EOR survey[J]. *Oil Gas J.* 112 (4), 79–91.

Li, Yongtai, Liu, Yifei, and Tang, Changjiu (2008). *Principle and method of enhanced oil recovery [M]*. Beijing: Petroleum Industry Press, 180–188.

Luo, Zhongwei, Fang, Mengxiang, and Li, Mingyuan (2012). *Carbon dioxide capture, storage and utilization technology [M]*. Beijing: China Electric Power Press, 208–231.

Qin, Jishun, Han, Haishui, and Liu, Xiaolei (2015). Application and enlightenment of carbon dioxide flooding in the United States of America [J]. *Petroleum Explor. Dev.* 42 (02), 209–216. doi:10.11698/PED.2015.02.10

Rao, D. N., Ayirala, S. C., Kulkarni, M. M., and Sharma, A. P. (2004). *Development of gas assisted gravity drainage (GAGD) process for improved light oil recovery*. USA: SPE/DOE Symposium on Improved Oil Recovery.

Roper, M. K., Pope, G. A., and Sepehrnoori, Kamy (1992). *Analysis of tertiary injectivity of carbon dioxide*. Midland, Texas: Permian Basin Oil and Gas Recovery.

Shen, Pingping, and Liao, Xinwei (2009). *Carbon dioxide geological storage and enhanced oil recovery technology [M]*. Beijing: Petroleum Industry Press.

Whorton, L. P., Brownscombe, E. R., and Dyes, A. B. (1952). *Method for producing oil by means of carbon dioxide*. USA: U. S. Patent.

Xiang, Yong, Hou, Li, Du, Meng, Jia, Ninghong, and Lv, Weifeng (2022). Research progress and development prospect of CCUS-EOR technologies in China [J]. *Oil gas Geol. recovery* 5, 1–17. doi:10.13673/j.cnki.cn37-1359/te.202112048

Zou, Caineng, Xue, Huaqing, and Xiong, Bo (2021). Connotation, innovation and vision of "carbon neutral. *J. Nat. Gas. ind.* 41 (8), 12. doi:10.3787/j.issn.1000-0976.2021.08.005