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RESEARCH PAPER

Application and enlightenment of carbon dioxide flooding in the United States of America

QIN Jishun[1,2,3,*], HAN Haishui[1,2], LIU Xiaolei[2,4]

1. PetroChina Research Institute of Petroleum Exploration & Development, Beijing 100083, China;
2. State Key Laboratory of Enhanced Oil Recovery, Beijing 100083, China;
3. National Energy (Experiment) Research Centre of CCUS, Beijing 100083, China;
4. Institue of Porous Flow & Fluid Mechanics, Chinese Academy of Sciences, Langfang 065007, China

Abstract: The application and characteristics of CO_2 flooding in the USA were analyzed and summarized. Supporting techniques of CO_2 flooding were generalized, and then the enlightenment was expounded for CO_2 flooding in China. The development process and forming reasons of CO_2 flooding technology were analyzed and summarized based on systematic tracking of EOR survey data all over the world and sufficient investigation of CO_2-EOR technology application. With the number of CO_2 flooding projects, scale and annual production as indicators, the current situation of American CO_2-EOR technology was evaluated. The characteristics of the projects and development-driving force of CO2 flooding in America were also summed up. The characteristics of formation properties, crude oil properties and project timings of American CO_2 miscible flooding projects were outlined emphatically. Meanwhile, the application scale and reservoir adaptability differences between American CO_2 miscible and immiscible flooding were comparatively analyzed. A series of supporting techniques were illuminated with the SACROC CO_2 flooding project as an example. The challenges, technical bottlenecks and suggestions were analyzed and proposed for the promotion of CO_2 miscible flooding technology in China.

Key words: CO_2 flooding; miscible flooding; immiscible flooding; gas driving; enhanced oil recovery

Introduction

Carbon dioxide flooding is a flooding technology with carbon dioxide as the displacing media. CO_2 flooding technology involves reservoir engineering design, CO_2 injection technology, dynamic monitoring and adjustment technology, and processing technology of produced fluid[1–5].

In the middle of the 20th century, carbon dioxide, a by-product of hydrogen production, was found to be able to improve the mobility of oil by the Atlantic Refining Company. Subsequent research shows that inter-phase mass transfer, oil volume expansion, decrease of oil viscosity and interfacial tension, and miscibility of oil and CO_2 are the main mechanisms of CO_2 flooding. Based on this discovery, the first patent of CO_2 flooding was born[6], marking the beginning of CO_2 flooding technique.

In 1958, the first CO_2 flooding test of well group scale was implemented by Shell Company in a Permian reservoir. The test shows that injecting CO_2 into the reservoir can replenish formation energy and enhance oil production[7–9]. In 1972, the first commercial project of CO_2 flooding in the world in SACROC block of Kelly-Snyder oilfield in Texas, USA was put put into production by Chevron Company, in which the average well production enhanced more than 3 times at the initial stage[10]. The success of this project marked the maturity of CO_2 flooding technology.

The three oil crises happened from 1970 to 1990 make the oil production and consumption countries worldwide realize the importance of petroleum self-sufficiency and petroleum security for national economy. In order to increase domestic oil production and decrease oil dependence on other countries, countries represented by the USA, have been adjusting and renewing energy policies and laws continually to encourage native oil companies and private capital making investment in EOR technical research and related infrastructure construction. For example, the law on petroleum excess profit tax passed by USA government in 1979 includes regulation of tax reduction on profit obtained by using EOR methods (such as CO_2 flooding), which promoted the development of CO_2 flooding technique and related industries. Thanks to this tax law, several CO_2 gas fields including MK Elmo Domo, Sheep Mountain were put into development in large scale in USA, and gas transportation pipelines between CO_2 gas field and oil field

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*** Corresponding author.** E-mail: qinjs@petrochina.com.cn
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such as Bravo Dome Pipeline were constructed[11–12]. All these guarantee gas source for CO_2 flooding projects. At the end of 1986, CO_2 flooding projects in operation and under construction had reached 40.

In the over ten years after 1990, economy in the Asia-Pacific region had been developing rapidly with demand for fossil fuels soaring and CO_2 emission increasing year by year. Reasonable development and utilization of fossil fuels became a new challenge, the concept of integrated CO_2 capture, flooding and storage came into being. Under the response of the petroleum producing countries, oil companies and research institutions, the development and practice of CO_2 flooding and storage technique formed a new industry hotspot[13–17].

Since the beginning of 2000, crude oil price has been continually increasing, making CO_2 flooding projects profitable. As a result, new projects have been continually increasing. According to the data of 2014, there are 152 CO_2 flooding projects under operation in the world, with annual EOR oil production of $1\ 470\times10^4$ t[18].

After more than 60 years of attempt and practice, CO_2 flooding technique has gradually taken shape and become mature. The USA is the largest use of CO_2 flooding technology in the world. According to the data of 2014, the annual oil production of CO_2–EOR had reached $1\ 371\times10^4$ t, accounting for 93% of the world CO_2–EOR oil production. China can learn the successful experience of the USA in applying and developing CO_2 flooding technique, and consider our own conditions and reservoir characteristics.

1. Overview of CO_2-EOR application in the USA

The USA is one of the countries developing and applying EOR technique early. Because of related laws of federal and state government, resource conditions and production cost, EOR techniques of USA include mostly thermal production technology and gas flooding.

In the middle of the 20th century, during the development of native oilfields in the US, large amounts of natural gas was produced associated with crude oil production, exceeding the market demand. Storage of natural gas not only needs large facilities and devices but also faces the safety issue. Therefore, the US government unveiled acts on gas pipeline construction and safety, and federal gas company operation, which on one hand, promoted the construction of gas pipeline and equipment, ruled the usage of pipeline and equipment, on the other hand, adjusted the benefit distribution during pipeline transportation, encouraged all companies to invest in gas pipeline construction and utilization. This is an important incentive for developing and promoting natural hydrocarbon gas flooding by oil companies.

To cope with the world's oil crisis in 1972, the USA government passed the emergency energy security act, promoting the increase of oil production in the USA greatly and the research on EOR technologies by oil companies.

Since 1980, with the increase of oil and gas demand, the price of oil and gas has been going up constantly, the US government has adjusted the energy policy, As a new rising force, CO_2-EOR has been gradually promoted, the number of projects increased year by year, oil production also increased, but both the number and production of thermal recovery projects declined in the same period, in 2006, the oil production of gas flooding EOR exceed that of thermal oil recovery for the first time (Fig. 1 and Fig. 2)[18–23].

The development of gas flooding in the USA experienced two leaps because of the specific time and energy policy adjustment. The first leap happened from 1980 to 1992, during which to cope with oil crisis, the USA unveiled laws and regulations stimulating investment into the energy field, consequently the enthusiasm of oil companies and civil capital was aroused, CO_2 source was expanded, promoting the quick development of CO_2-EOR technology. In this period, the number of CO_2 projects increased from 17 to 54 (Fig. 1), EOR annual output increased from 10×10^4 t to 783×10^4 t (Fig. 2). The second leap came after 2002, when the oil price soared over 100 $/bbl, which gave CO_2 flooding considerable profit margin. In this period, the number of CO_2 projects increased from 67 to 137 (Fig. 1), EOR annual output increased from 963×10^4 t to 1371×10^4 t (Fig. 2). At this time, miscible CO_2 flooding in the US had been relatively mature, so the scale of CO_2-EOR projects was further enlarged.

As CO_2-EOR technology gets more and more mature in USA, people realize that CO_2 flooding is an effective way to enhance oil recovery. Taking CO_2 flooding project in SACROC block of Chevron Company as an example, after 40

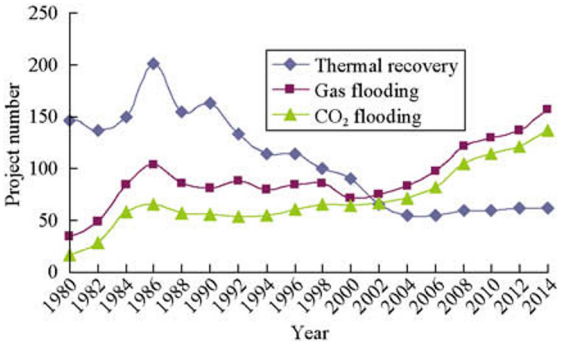

Fig. 1. Numbers of thermal recovery, gas flooding, CO_2 flooding projects in the USA.

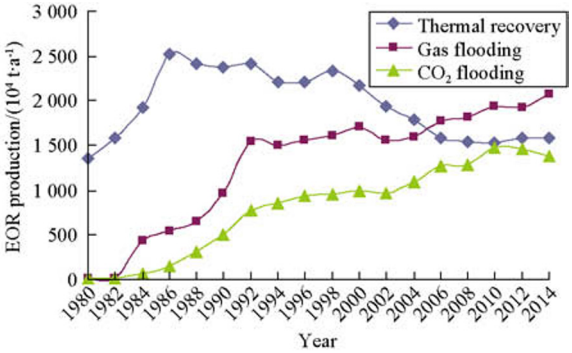

Fig. 2. EOR production of thermal recovery, gas flooding, CO_2 flooding in the USA.

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