Research Progress in Carbon Dioxide Storage and Enhanced Oil Recovery

Keliang Wang, Gang Wang, Chunjing Lu
MOE Key Laboratory of EOR Technology, Northeast Petroleum University, Daqing 163318, China
wg_0459@163.com

Abstract. With the rapid development of global economy, human beings have become highly dependent upon fossil fuel such as coal and petroleum. Much fossil fuel is consumed in industrial production and human life. As a result, carbon dioxide emissions have been increasing, and the greenhouse effects thereby generated are posing serious threats to environment of the earth. These years, increasing average global temperature, frequent extreme weather events and climatic changes cause material disasters to the world. After scientists’ long-term research, ample evidences have proven that emissions of greenhouse gas like carbon dioxide have brought about tremendous changes to global climate. To really reduce carbon dioxide emissions, governments of different countries and international organizations have invested much money and human resources in performing research related to carbon dioxide emissions. Manual underground carbon dioxide storage and carbon dioxide-enhanced oil recovery are schemes with great potential and prospect for reducing carbon dioxide emissions. Compared with other schemes for reducing carbon dioxide emissions, aforementioned two schemes exhibit high storage capacity and yield considerable economic benefits, so they have become research focuses for reducing carbon dioxide emissions. This paper introduces the research progress in underground carbon dioxide storage and enhanced oil recovery, pointing out the significance and necessity of carbon dioxide-driven enhanced oil recovery.

1. Introduction
The huge impacts of considerable greenhouse gas (carbon dioxide) emissions upon global climate and environment have aroused widespread concerns of the world. It is inevitable for human beings to achieve sustainable development by intensively reducing carbon dioxide emissions. Manual carbon dioxide storage in strata and carbon dioxide-enhanced oil recovery are two options for intensively reducing carbon dioxide emissions. On the premise that mature technical solutions and appropriate venues for storage are available, underground carbon dioxide storage is the most promising scheme for reducing carbon dioxide emissions with the highest storage capacity. Carbon dioxide-enhanced oil recovery is not only helpful for storing carbon dioxide, but also effective for increasing recoverable oil reserves. It is a scheme for reducing carbon dioxide emissions which can yield social and economic benefits.

Over the past one century, the average global temperature has increased by 0.74°C. The increasing global temperature results in changes to global climate and thereby causes many major disasters such as coastal flooding, changes to ocean current, frequent hurricane, El Nino, La Nina and frequent extreme weather events (including drought and storm). Besides, climatic changes cause a range of problems such as vegetation deterioration, grain yield reduction, extinction of species and disease
spreading. In addition, they result in thawing of polar glacier and ice sheets, which contributes to
global sea level rise. The global sea level annually rose by 1.8 mm and 3.1 mm on average after 1961
and 1993 respectively. Chinese warming trends are generally the same as overall global warming
trends. As a whole, the average temperature has increased year by year in both China and the world.
Owing to climatic changes, more and more disasters have taken place. These years, a series of signs
such as annual increase in sea level in coastal areas of China, declined sea ice grade in the north of
Bohai Sea and Yellow Sea, decreased area of northwestern glaciers and thinner permafrosts in Tibet
have suggested that China has been heavily impacted by climatic changes. Since the last century, it has
been always warm in winter in China, where significant changes have occurred to precipitation. As
extreme weather events like high temperature, drought and heavy rainfall occurred more and more
frequently, the affected area by drought has increased year by year in northern China. As a result,
severe agricultural losses, aggravated flooding of southern China and huge losses to people’s life and
property have been caused. Plenty of abnormal climatic phenomena and disasters have attracted
extensive attention of people.

2. Carbon Dioxide driven Enhanced Oil Recovery

With the swift development of national economy in China, the contradictions between petroleum
supply and demand have become increasingly more conspicuous in this country. In 2010, the import
of crude petroleum was unprecedentedly high and reached 0.23 billion tons in China, in which the
dependence on foreign oil was up to 53.8%. According to estimates, china will have an annual demand
for 0.4 billion tons of oil and the degree of dependence on import will be over 60% by 2020. By that
time, there will be more serious contradictions between oil supply and demand. In China, the new
 crude oil reserves can’t satisfy needs for oil during national economic development. To increase crude
 oil reserves, it has become more and more important to increase recovery of demonstrated geological
reserves. In China, oilfields are mostly continental sedimentary strata, which are characterized by
severe heterogeneity, high viscosity of crude oil and relatively low water-driven recovery. According
to statistics, the average recovery of oilfields put into production is almost 32% in China, which
suggests that approximately 10 billion tons of demonstrated geological reserves are still left
undergrounds after water-driven oil recovery. By further improving recovery, there will be a
considerable potential for resources. Hence, it is urgent for China to improve its recovery technologies
by oil recovery.

Pursuant to the findings of “Evaluation of Secondary Potential for Increasing Recovery of Oilfields
Developed on Lands of China and Research of Development Strategies”, among the sole 10.13 billion
tons of reserves in conventional rare oilfields, the recovery of about 123,000,000 t crude oil reserves
can be driven by carbon dioxide. To increase the recovery by 12.7% through carbon dioxide, the
recoverable reserves can be approximately increased by 0.16 billion tons. There will be a greater
increase in the recoverable reserves if special CO2-EOR technologies are utilized. In addition, 6.32
billion tons of crude oil reserves in low-permeability reservoirs have been proven in China. In
particular, carbon dioxide-driven recovery technologically outperforms water-driven recovery a lot
among about 50% of unused reserves. Apart from increasing recovery, this storage scheme can store
more than 0.2 billion carbon dioxide, generating enormous social and economic benefits. Therefore,
carbon dioxide flooding technology is not only effective for increasing crude oil recovery, but also
favorable for storing carbon dioxide undergrounds.

It is a technology for increasing recovery of oilfields by injecting carbon dioxide into oil reservoirs.
Under standard temperature and pressure, carbon dioxide is a kind of colorless and odorless gas with a
density of 1.97 g/L, which is heavier than air. When the temperature and pressure go beyond their
critical points, carbon dioxide will change in terms of its properties and look like liquids. It is as
viscous as gas and its diffusion coefficient is 100 times higher than that of liquids. Under this
circumstance, carbon dioxide is a type of excellent solvent. It is more soluble and permeable than
organic solvents such as water, ethanol and ethyl ether. In the process of CO2-enhanced oil recovery, it
is the most important to mix phases of carbon dioxide and crude oil. During the displacement,
supercritical fluids will extract relatively heavy hydrocarbons from crude oil and constantly have pre-
displaced gas concentrated. Thus, carbon dioxide and crude oil turned into miscible liquid with a
single liquid phase, in order to effectively displace crude oil of reservoirs into producing wells.
Multiphase flow of carbon dioxide, water and oil in the process of displacing crude oil with carbon
dioxide is another important research topic. To find out the flow mechanism for enhancing oil
recovery with carbon dioxide, many researchers have performed related experimental and theoretical
research. For instance, lots of researchers have explored monophasic or multiphase flow through
porous media. During carbon dioxide flooding, some carbon dioxide is still left undergrounds, while
certain carbon dioxide is recovered together with crude oil as associated gas, which can be recycled
through separation or direct injection back to reservoirs. In general, carbon dioxide flooding can
increase crude oil recovery rate by 7% to 17% and prolong the service life of oil wells by 15 to 20
years. Hence, carbon dioxide flooding technology is effective for comprehensive utilization and
storage of carbon dioxide. Over the past 20 years, domestic and foreign academic and industrial
research and practices have suggested that it is one of the best ways for gradually solving problems
concerning carbon dioxide emissions by developing integrated technologies for comprehensive
utilization and storage of carbon dioxide.

3. Research Progress in Carbon Dioxide Storage and Enhanced Oil Recovery

With the swift development of national economy in China, After a comprehensive analysis of data
about oilfield production, it is discovered that CO₂-enhanced oil recovery can greatly increase the
yield per well, achieve an input to output ratio of 1:3 to 1:13 and generate remarkable economic
benefits. This recovery technology has been widely used in many countries of the world such as the
United States and Canada. In 2012, 119 miscible carbon dioxide flooding projects and 16 non-miscible
flooding projects were implemented all over the world, including 112 miscible flooding projects and 8
non-miscible flooding projects in the United States. In 2011, a total amount of about 20,000,000 t oil
was recovered by carbon dioxide in the United States, where almost 60,000,000 t carbon dioxide was
used for oil recovery. In the same year, 3 commercial projects and 3 industrial experimental projects
were carried out in Canada. In Trinidad, 5 miscible projects and 1 non-miscible project were
implemented in 2011. At present, the United States is the world’s largest country of oil recovery by
carbon dioxide. According to the 2009 research report of the United States Department of Energy,
1,111 oil reservoirs out of main American reservoirs were suitable for carbon dioxide enhanced oil
recovery and accounted for 55% of total oil reservoirs.

In addition to the United States, there has been also lots of research and practices about carbon
dioxide enhanced oil recovery in Canada. From 1990 to 2005, 43 projects were carried out to recover
oil by injecting carbon dioxide into wells, including the large-scale project of Weyburn Oilfield for
recovering oil through carbon dioxide injection. On 15th September 2000, the Canadian company
EnCana organized a carbon dioxide flooding experiment in the Weyburn Oilfield and injected 5,000 t
carbon dioxide with a purity of 95%. The carbon dioxide was supplied by coal gas factories of Beulah
in the United States and transported over 320 km. In the area where the test was performed, there were
210 oil wells, which daily produced 9,000 bbl crude oil. By March 2005, the Canadian Weyburn
Oilfield had cumulatively injected about 70,000,000 t carbon dioxide, and the oil recovery is projected to be increased by 9.89% in 15 years. In China, there has been very little research and practices about carbon dioxide enhanced oil recovery. This oil recovery technology wasn’t employed until 2000 when the China National Petroleum Corporation (CNPC) invested RMB0.2 billion in implementing a key industrial carbon dioxide flooding project in the Jilin Oilfield. At present, experimental research about carbon dioxide enhanced oil recovery is being performed in many oilfields of China, including Daqing, Jilin, Liaohe, Jidong, Shengli and Jiangsu oilfields, where good results have been achieved.

In China, gas enhanced oil recovery technologies were researched and used in a relatively late period, whereas initial successes have been achieved over the past few years. In 1960s, indoor experimental research on carbon dioxide was performed in Daqing Oilfield. In 1965, this oilfield specially and firstly carried out a pilot study for increasing oil recovery via small well spacing, where the oil recovery increased by 10% or so. This indoor experiment suggested that carbon dioxide and water could make lyophile rock cores hydrophile in terms of surface properties.

By 1970s, carbon dioxide enhanced oil recovery technology hadn’t been studied more intensively owing to limited sources of carbon dioxide. Only some measurements on miscibility pressure and miscibility mechanism were performed in the Shengli Oilfield. In 1984, work about miscible and non-miscible carbon dioxide flooding was conducted over again. Related experiments were performed in some oilfields of China, including Zhongyuan Oilfield, Daqing Oilfield and Huabei Oilfield. Daqing Oilfield cooperated with France to conduct field non-miscible carbon dioxide flooding tests in Sanan with exhausts of hydrogenation workshops in Daqing Petrochemical Refinery. In addition, it carried out two field tests in the east fault of the No.1 Northern Zone and in the east of the No.2 Northern Zone. Water and gas were alternately injected in the tests. Thereafter, some natural reservoirs of carbon dioxide were successively discovered in the Yellow Bridge of northern Jiangsu Province, Wanjin Tower of Jilin and Da Gang.

Since 1994, Jilin Oilfield has been performing experiments about carbon dioxide huff, puff and foam fracturing with liquid carbon dioxide of Wanjinta Carbon Dioxide Gas Field. The results suggested that the average yield per well increased by 75.5 t and 144.3 t respectively. In 1996, carbon dioxide huff and puff tests were performed in 48 wells of Jiangsu Oilfield and Fumin Oilfield, in which oilfield have cumulatively increased by 1,500 t. Besides, desirable outcomes have been achieved in 7 tested wells. Apart from field studies of Daqing, Jilin and Jiangsu oilfields, some feasibility studies have been also performed in other fields. However, field tests have been carried out at an industrial scale.

Concerning carbon dioxide enhanced oil recovery, several kinds of processes and technologies have been studied and tested on sites. Meanwhile, appropriate reservoir conditions for carbon dioxide enhanced oil recovery and physical properties of crude oil are summarized. Various oil products have been tested through numerical simulations and elaborate parametric design. Ideal outcomes have been gained in these tests.

The recovery ratio is so high in developing oil-gas reservoirs by gas injection that considerable economic benefits can be created. By recycling the carbon dioxide produced during magnesite smelting and included in industrial waste gas, atmospheric pollution is prevented to protect environment and create good social benefits. In addition, gas enhanced oil recovery technology can be widely applied in several kinds of oil-gas reservoirs to supplement stratum energy fast. In utilizing this technology, phases of carbon dioxide may be easily mixed with those of crude oil, and viscosity can be reduced. Thus, this recovery technology will inevitably become an alternative for oilfield exploitation with widespread applications in the future.

4. Significance and Necessity of Research on Carbon Dioxide Oil Recovery Technology

In China, reservoirs of most oilfields are continental, sedimentary and extremely heterogeneous. In these reservoirs, crude oil is relatively viscous and its water content increases increasingly faster. Furthermore, plenty of oilfields are in the middle and late stage of their development. Although they have taken a range of measures such as water and steam injection, the oil recovery ratio is still a little
low. Almost more than 60% geological reserves of crude oil can be hardly exploited and even can’t be mined. What’s worse, the crude oil recovery rate is even lower in low-permeability heavy oil and condensate gas reservoirs. To better accommodate growing demands for petroleum during industrial development of China, it has become rather urgent to look for an effective and economical oil recovery technology.

Gas injection has been demonstrated by conclusions of much theoretical research and practices to be more effective than water injection for increasing oil recovery rate. In foreign countries like the United States and Canada, gas enhanced oil recovery technologies have been studied earlier and more in-depth studies on gas enhanced oil recovery have been performed. Moreover, much oil has been industrially recovered by injecting carbon dioxide to increase the oil recovery rate. As a result, productivity and economic benefits have been improved.

On one hand, there are abundant sources of gas in China: Oilfields of East China are rich in carbon dioxide, which is even as much as 1 X 1,011 m³ in the natural reserves, so plenty of materials are available in these oilfields. As per preliminary statistics, more than 10.5×10⁸ t geological reserves are suitable for recovering oil through gas injection. Compared with water-driven oil recovery, gas injection can increase the oil recovery rate by 16.4% on average, which suggests that there is huge economic potential for recovering oil with carbon dioxide. On the other hand, it is fairly urgent and necessary to explore how to recover oil with carbon dioxide in China as soon as possible, because this recovery technology has developed late and slowly in this country, where both field tests and indoor theoretical research are not quite mature.

In Liaohe Oilfield, it has become inevitable to examine the technologies for recovering oil with carbon dioxide. On one hand, water and steam injections for oil recovery have fallen into dire plights due to complex geological structures of the Liaohe Reservoir and existence of much heavy and highly condense oil, so it is urgent to explore new ways for oil recovery. On the other hand, there is the world’s largest magnesite in Yingkou near the oilfield, where oil has been heavily recovered over the past years. During the production of magnesium, numerous byproducts of high-purity carbon dioxide are generated. The yield of carbon dioxide has been even as high as about 3×10⁶ t per year over the past three years. Thus, gas sources have been made available for miscible carbon dioxide-enhanced oil recovery. In addition, air pollution will be absolutely caused if so much carbon dioxide is not recycled but completely released to the air, which is not in line with the current prevalent idea which strongly advocates environmental protection. Under this situation, we have to perform indoor research and field tests on how to recover oil by injecting carbon dioxide. It is not only necessary, but also of great significance for promoting and applying this technology as soon as possible.

5. Conclusion
At present, the carbon emissions are the second highest in China, which is second only to the United States. Effective CO₂ capturing and application have become new development trends under the impacts of greenhouse effects as there were increasingly greater demands for environmental protection. CO₂ injection technology is receiving growing concerns of different countries in the world. In spite of some technical problems, they have been gradually solved. Nowadays, methods for oil recovery are developing into some circular economical models such as capturing, storage and flooding. It is inevitable for development of CO₂ flooding by creating harmony between energy and environment.

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