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The First Integrated Approach for CO_2 Capture and Enhanced Oil Recovery in China

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Abstract

As the only company which owns the right for coal mines and oil and gas production in China, Yanchang Petroleum Group has the unique advantages to implement integrated CO_2 capture and enhanced oil recovery (EOR) in Ordos Basin. This area is also one of the largest CO_2 emission areas in China. The coal to chemicals plant was built to efficiently co-utilize coal, oil and natural gas. The energy efficiency is about 8.9% higher than the world average level. Two corresponding CO_2 capture plants were built with the capacity of 50,000 and 360,000 tonnes per year. The cost for CO_2 capture is as low as $17.5/tonne, much cheaper than most of the other CO_2 capture project in the world. By optimizing the distance between CO_2 capture plants and EOR sites, the shortest distance, the shortest distance for CO_2 transportation is only 10 kilometers. It is estimated that the cost for CO_2 transportation is $2.58/tonne. Meanwhile, the CO_2 is used for enhanced oil recovery in Yanchang oil fields. Extensive research has been done to investigate the suitable geological conditions for CO_2-EOR. Experiments have also been conducted to study the behaviors of CO_2-crude oil mixture. Two pilot tests including Qiaojiawa 203 block and Wuqi Yougou are now in operation with well production being doubled or tripled. In addition, more than 87% of reservoirs in Yanchang oil field in Ordos Basin are suitable for CO_2-EOR with estimated billions of CO_2 storage capacity.

Introduction

Greenhouse gas emissions are regarded as one of the most important factors resulting in global warming and climate change. In all the greenhouse gases, the proportion of carbon dioxide (CO_2) emitted is the greatest and around 76%, according to the statistics from the Intergovernmental Panel on Climate Change (IPCC) in 2013.

The CO_2 emissions are mainly from the consumption of fossil fuels such as coal, oil and natural gas which provide 85% of worldwide energy needs for human activities (BP, 2017). While in these CO_2 sources from energy consumptions, the burning of coal produces more CO_2 than oil or natural gas at the same equivalent electricity generated. Meanwhile, in 2016, the coal consumption consists of 28% of total world energy, while this number is 62% in China where the coal reserves are the third largest in the world. Table 1 and Fig. 1 are the comparisons of energy consumptions for China, USA and the total world in 2016 (BP, 2017).

Table 1. Comparison of energy consumptions for China, USA and total world in 2016, unit: Million tonnes oil equivalent.

	Oil	Natural gas	Coal	Nuclear energy	Hydro-electricity	Renewables	Total
China	578.7	189.3	1887.6	48.2	263.1	86.1	3053
USA	863.1	716.3	358.4	191.8	59.2	83.8	2272.7
Total world	4418.2	3204.1	3732	592.1	910.3	419.6	13276.3

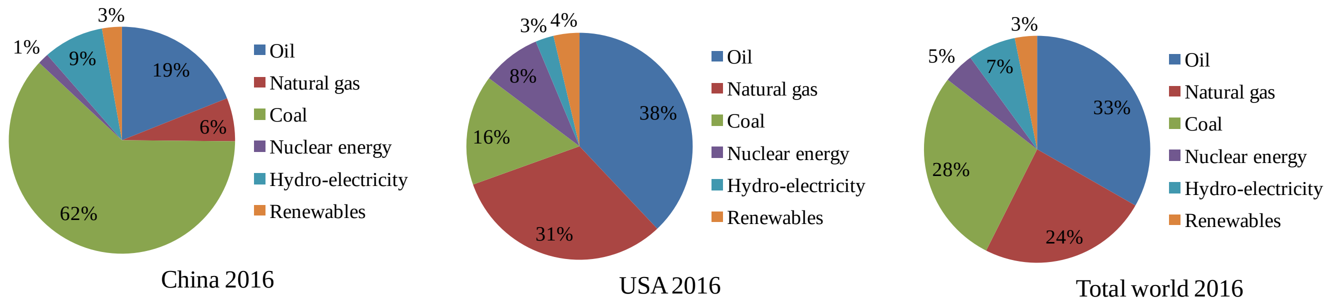


Figure 1. Percentage of energy consumptions for China, USA and total world in 2016.

In 2016, China's carbon emissions are estimated to be 9.1 billion tonnes, while the CO_2 emissions will further increases with the development of economy. Analyzing the CO_2 emission intensity, which is the ratio of CO_2 emitted to gross domestic product (GDP), can help us to find the measures to deal with CO_2 emissions and meanwhile develop the economy. The spatial distribution of CO_2 emission intensity is depicted in Fig. 2 for different provinces in China (Zhao et al., 2014).

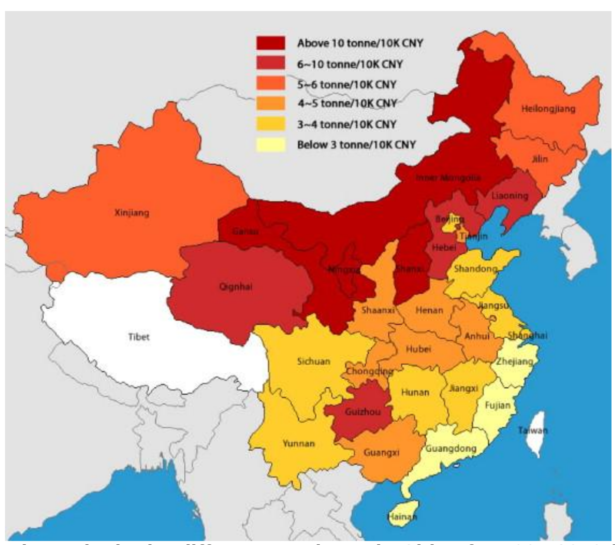


Figure 2. CO_2 emission intensity in the different provinces in China for 1991-2010 (Zhao et al., 2014).

The dark red color means the more intensive CO_2 emitted through human activities as per GDP produces. The areas with the highest CO_2 emission intensity are located in the north part in the Ordos Basin which is ranked as the second largest sedimentary basin in China. It is found that the coal resources are as large as 3.98Tt in this region which accounts for around 39% of China's total coal reserves (Wang et al., 2017). Currently, there are 6 coal mines and this basin is therefore the largest CO_2 emission area in China.

Efforts towards reduction of coal consumptions and improvement of energy efficiency are therefore the key in our pursuit of sustainability excellence. The carbon capture utilization and storage (CCUS) project is an excellent option to greatly reduce CO_2 emissions. Especially for the Ordos Basin, there are great potentials to reduce CO_2 emissions while developing the local economy through the integrated CO_2 capture and enhanced oil recovery approach which is also the next generation of CCUS and CO_2-EOR project.

Overview of integrated approach for CO_2 capture and EOR

Advantages for integrating CCUS and EOR

Previous CCUS project and most of other international projects for CO_2 capture and EOR are usually separated. The distance between CO_2 capture and the CO_2-EOR sites are very long. For example, in the Weyburn project in Canada, the CO_2 is captured in North Dakota in USA and transported through pipelines with the distance around 325 kilometers (Lotz and Brent, 2008). Such long distance between CO_2 source and CO_2-EOR limits the integrated implementation of CCUS and EOR application.

There is a great advantage to implement this integrated approach for Yanchang Petroleum Group in the Ordos Basin in China. In the recent years, several coal to chemical plants were built in this area and an extremely large amount of CO_2 is emitted. Meanwhile, the Ordos Basin not only has China's one-third of coal resources but also is the fourth largest oil and gas basin. The distance between coal to chemical plants and oil fields is very short, ranging from 10 to 140 kilometers, as shown in Fig. 3 (Wang et al., 2017).

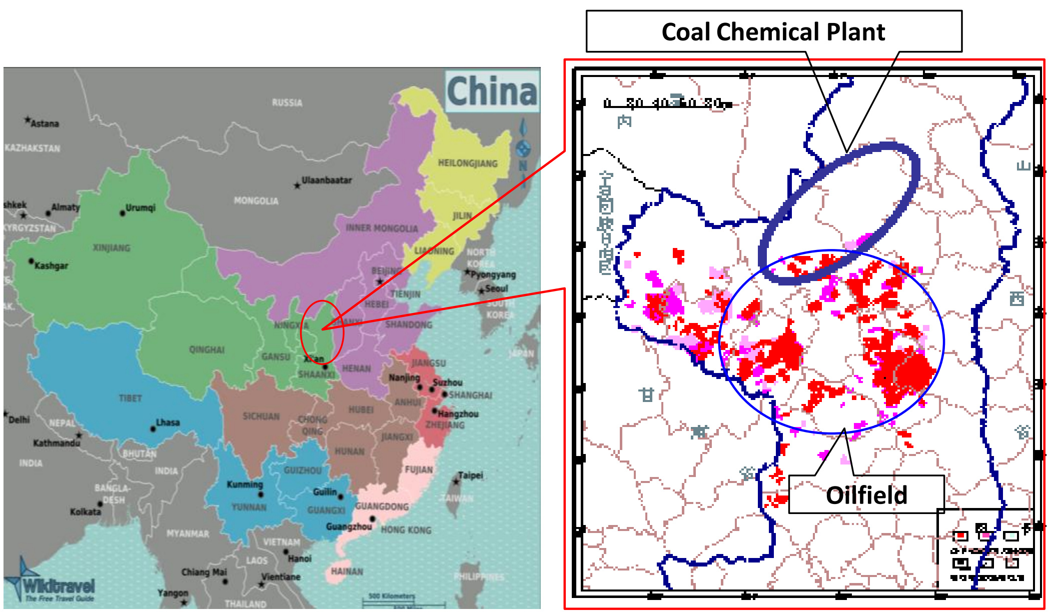


Figure 3. The locations for coal to chemical plants and oil fields.

In addition, because of the low and ultra-low permeability of the oil reservoirs and the lack of water in this area, a large amount of CO_2 is needed for maintaining reservoir pressure and enhancing oil recovery. Most importantly, the Yanchang Petroleum Group has the right for both coal and oil resources in Ordos Basin. The design of CO_2 capture and CCUS project can take full advantage of the CO_2-EOR and therefore implement the integrated approach by sequestrating CO_2 and improving oil recovery at the same time.

Current coal to chemicals plants

The Yanchang Petroleum Group has developed modern coal to chemicals plants by comprehensively co-utilizing coal, oil and gas in Ordos Bain. Through coal gasification and direct liquefaction, the coal is converted to the production such as methanol, gasoline and diesel, acetic acid, olefin, aldehyde, ketone, acid, dimethylether and so on. A diagram of the modern coal to chemicals production line is shown in Fig. 4.

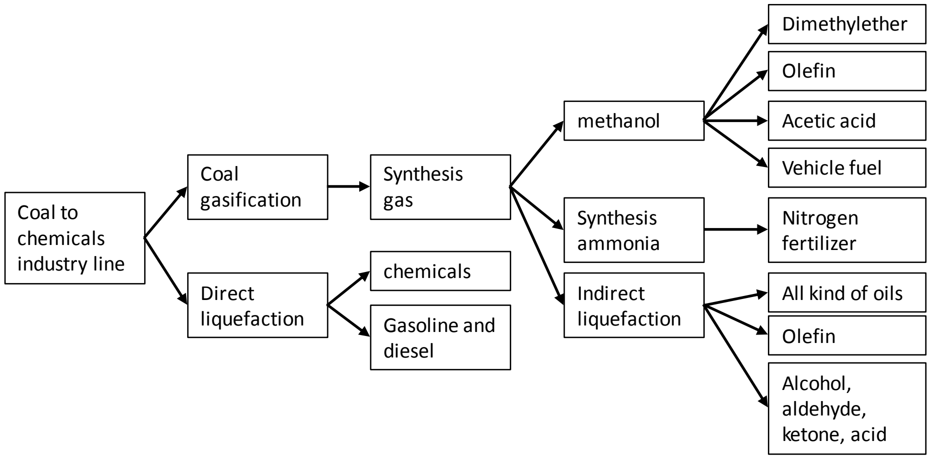


Figure 4. Modern coal to chemicals production line.

Two CO_2 capture plants were built corresponding to two coal to chemicals plants in Yanchang Petroleum Group. The first one has the capacity of 50,000 tonnes/year CO_2 capture. It was built in 2012 in order to reduce the CO_2 emissions from the coal to chemicals plant located in Yulin of Shaanxi province which has the capacity of 30,000 tonnes/year production of acetic acid. The CO_2 is mainly captured from fuel gas which usually has higher concentration of CO_2 in coal to chemicals processes. The 52,000 tonnes of CO_2 were captured in 2015 with 80% of mole fraction captured through low-temperature adsorption in methanol wash process.

Another CO_2 plant is designed to capture 360,000 tonnes/year. The CO_2 source is mainly from the second energy to chemicals plant operated by Yanchang Petroleum Group. The products include 2-ethyl hexanol (0.2 Million tonnes, Mt), polyethylene (0.25 Mt), polypropylene (0.45 Mt), and oils (0.6 Mt).

CO_2-EOR projects

Screen criteria of pilots

The screen criteria have been widely studied for the CO_2-EOR since the first commercial implementation in 1972 (Bachu, 2016). A large number of CO_2-EOR pilot tests were reported (Brock and Bryan, 1989; Enick et al., 2012; Manrique et al., 2010). Technically, the recognized criteria for the successful operations of CO_2-EOR are given as follows.

Table 2. Screen criteria for CO_2-EOR

Factors	CO_2 Miscible flooding (Brashear and Kuuskraa, 1978)	CO_2 immiscible flooding (Klins and Farouq Ali, 1982)
Oil viscosity, mPa.s	<12	100-1000
Oil density, kg/m^3	<876.2	904-1000
Formation depth, m	>900	>700
Reservoir pressure, MPa	>10	>7
Reservoir temperature, ℃	NC	NC
Average permeability, mD	NC	NC
Initial oil saturation, Soi, %	>25	>50
Porosity×Soi, f	>0.04	>0.08
Positive conditions	Thin layer, high dip angle, no bottom or blank water, small Kv	
Negative conditions	High heterogeneity, strong fractures, gas cap, active bottom and blank water	

Based on the previous screening criteria for the successful operations of CO_2-EOR, we established a selection system with 13 major factors. Each factor has a certain range of variations and typical values are used to form a combination of all the possible options. Table 3 lists all the 13 factors and values of them. By conducting sensitive analysis, four major factors are found to be very sensitive to the oil recovery including formation depth, thickness, initial oil saturation and sedimentary rhythm. Several major factors are not sensitive to the oil recovery such as dip angle, reservoir temperature, Ky/Kx and coefficient of variation. Moreover, three large categories are also listed as the first level for geological conditions, reservoir fluid properties and field development. The weight of geological conditions is relatively large. A second level of weight under each category is also given in Table 3. In addition, the main effects of all the factors on final oil recovery are carefully analyzed.

Table 3. Selection criteria of oil reservoirs for CO_2-EOR.

No.	Factors	Values	Sensitivity	Weight level I	Weight level II	Conclusions
1	Sedimentary rhythm	Positive, negative	Strong	0.65	0.16	Positive rhythm is more positive effect on oil recovery
2	Initial oil saturation, Soi, %	30, 40, 50, 60, 65	Strong		0.16	Larger Soi has positive effect on oil recovery
3	Effective thickness of oil formation, m	5, 7.5, 10, 13, 15, 20, 30	Strong		0.16	Negative effect on oil recovery
4	Formation pressure, MPa	3, 5, 7, 9, 12, 18, 25	Strong		0.16	Higher pressure has positive effect on oil recovery
5	Average permeability, mD	0.1, 0.5, 1.5, 10, 50	Yes		0.10	Higher permeability has positive effect at an earlier time but negative effect later
6	Kv/Kh	0.001, 0.01, 0.1, 0.3, 0.5	Yes		0.10	More interlayers have positive effect on oil recovery
7	Coefficient of variation	0.1, 0.2, 0.35, 0.5, 0.7	No		0.10	Larger values have negative effect on oil recovery
8	Dip angle of reservoir, °	5, 10, 15, 20, 25, 35	Minor		0.06	Larger values have positive effect on oil recovery
9	Ky/Kx	5, 10, 20, 50, 100	Minor		0.04	Larger values have slightly positive effect on oil recovery
10	Temperature, ℃	19, 30, 40, 55, 75	No		0.04	Nearly no effect on oil recovery
11	Oil viscosity	calculated by 5 components	Yes	0.25	0.50	Higher values have negative effect on oil recovery
12	Well pattern	5-spot, 7-spot, inverse 7-spot, 9-spot, inverse 9-spot	Yes	0.10	0.50	5-spot, inverse 7-spot and inverse 9-spot can achieve the higher oil recovery
13	Well space, m	100, 200, 300, 400, 500	Yes		0.50	Larger values have negative effect on oil recovery

Not all of the field data can be easily obtained and there may be large uncertainties for the data from fields. In all of the factors which may have impact on oil recovery of CO_2-EOR, six of them are selected and given weight in Table 4.

Table 4. Final weight of different factors.

Factors	Weight	The worse value	The optimal value
Effective thickness of oil formation	0.2592	30	1
Formation depth	0.2304	300	2500
Average permeability	0.1872	0.1	1.5
Temperature	0.0432	75	19
Oil density	0.14	1000	700
Oil viscosity	0.14	1000	1

These six factors are then normalized in terms of their weight. Assume there is l number of reservoirs, each reservoir has m factors. The value of j factor in the k reservoir is $X'_{k,j}$. The normalized value is there,

$$X_{k,j} = \frac{|X'_{k,j} - X^*_{w,j}|}{|X^*_{o,j} - X^*_{w,j}|} \tag{1}$$

Where, $X^*_{o,j}$ is the optimal value and $X^*_{w,j}$ is the worse value. Therefore, the optimal and worse values of all six factors are given in Table 4.

Based on the above analysis and method, we evaluated all the 172 oil reservoirs in Yanchang oil fields for the applicability of CO_2-EOR. It is found that 87% of reservoirs can be used for CO_2-EOR, which accounts for 80% of all reserves in Yanchang Petroleum Group. There is therefore a great potential for CO_2-EOR and CO_2 sequestration.

CO_2-crude oil properties

CO_2-EOR is either miscible or immiscible depending on the properties of mixture at certain reservoir pressure and temperature conditions. The different scenarios have significant influence on field performance and oil recovery. It is therefore necessary to investigate the CO_2-crude oil properties through experiments.

The bubble point pressure is first determined as shown in Fig. 5. With the increase of CO_2 concentration, the bubble pressure increases. The initial bubble point pressure of reservoir is 7.45MPa. It increases slowly when the CO_2 concentration is low, while it increases very fast once the CO_2 concentration is higher than 41%. The bubble point pressure is 25.25 MPa when the CO_2 concentration is 67.13%.

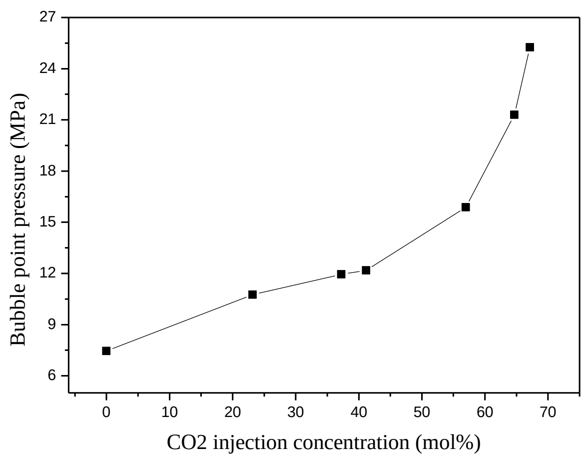


Figure 5. The variations of bubble point pressure with CO_2 concentration.

The density and volume coefficient of CO_2-crude oil mixture are also measured and the results are shown in Fig. 6. At the same CO_2 concentration, the density of fluids decreases as the pressure decreases. Once the reservoir pressure is below bubble point pressure, the density decreases much faster. Moreover, with the increase of CO_2 concentration, the trend of density of the mixture becomes smoothly. At the same reservoir pressure, the fluid density decreases with the increase of CO_2 concentration.

The volume coefficient versus pressure is also tested and shown in Fig. 6. With the increase of CO_2 concentration in the mixture, the volume coefficient increases. The value is 1.12 at reservoir pressure 30 MPa without any CO_2 injected. While when the CO_2 concentration is as high as 67.13%, the volume coefficient is 1.81 at the same pressure. This is therefore beneficial for the improvement of oil recovery in CO_2-EOR processes.

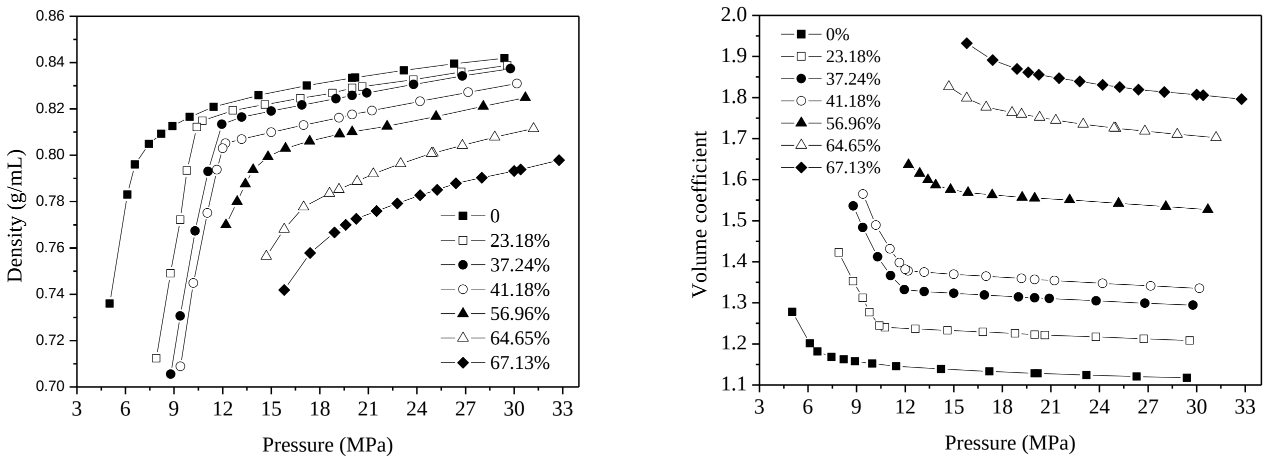
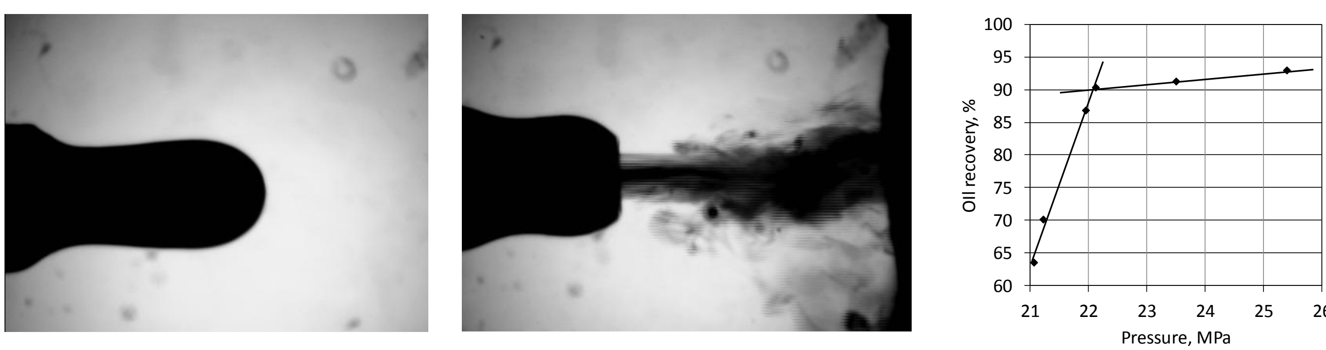


Figure 6. The variations of mixture density and volume coefficient with pressure.

The minimum miscibility pressure (MMP) is one of the most important factors affecting the oil recovery. Once the miscibility between CO_2 and oil is achieved, the surface tension tends to be zero and more CO_2 can dissolve into oil. A miscible displacement process takes place in CO_2-EOR (Yuan and Azaiez, 2015, 2014). The reduction of oil viscosity, improvement of its mobility and swelling effects are all beneficial for enhancing oil recovery (Huang et al., 2017; Or et al., 2016; Seyyedsar et al., 2017; Thomas, 2008; Yuan et al., 2017). A variety of methods have been used to determine the MMP (Wang et al., 2015). The interfacial tension vanish method is used in the present study and the CO_2-oil visualization before and after miscibility is shown in Fig. 7-a and b. Once the miscibility is achieved, there is no clear interface between them and the oil drop cannot keep its shape. The MMP is determined as 23.8 MPa.

In addition, the slim tube method is also used to determine MMP. A tube with 18 meters long which is packed with 80-100 mesh sands is adapted. This method is regarded as more reliable than other methods (Nobakht et al., 2008). The MMP is 22.15 MPa which is slightly less than that measured by interfacial tension vanish method.



a) before achieving miscibility **b) after achieving miscibility** **c) oil recovery versus pressure**

Figure 7. Experimental determination of minimum miscibility pressure.

CO_2-EOR field pilot tests

The first CO_2-EOR pilot test is conducted in Qiaojiawa 203 block from 2012. The average oil production is around 0.2 tonnes/day/well and the water cut is about 63.6%. However, the oil recovery at that time is only 1.72%. To improve oil recovery, this block is chosen as pilot test. There were 5 CO_2 injection wells and 21 oil wells. By the end of 2014, the total CO_2 injection is nearly 34,500 tonnes with the average 20 tonnes/day/well. The injection pressure is around 6-8 MPa. As of February 2016, there were 5 CO_2 injectors and 34 oil production wells. Compared with that of 2014, the total of 24,900 tonnes additional CO_2 were injected, while the average oil production is slightly reduced to about 19 tonnes/day/well. So far, the oil increased by CO_2-EOR is totally 2,200 tonnes, while a negligible amount of CO_2 was produced.

In December 2014, the first well Wu 38-28 in the second field pilot Wuqi Yougou began to injection CO_2 for oil recovery. After the first month CO_2 injection, the oil production of 16 oil wells was found to increase. As to the June 2016, the total amount of CO_2 injected is 9,221.2 tonnes with the average injection rate 19.3 tonnes and injection pressure 10.3 MPa. Currently, there are 5 CO_2 injectors and 18 oil producers in this pilot test. The pilot test also shows that the liquid rate increases by 14.0%, while the oil production rate is improved by 23.32%. Meanwhile, because of the CO_2 injection, the average water cut is reduced by 5.5%. Numerical simulation indicates that the oil recovery with CO_2-EOR can be improved by 11.8% compared with water flooding.

Summary

The Yanchang Petroleum Group provides a great advantage to implement the integrated CO_2 CCUS and oil recovery approach. This is also the first integrated in China by directly capturing CO_2 from coal to chemicals plant and injecting into the nearby reservoirs for enhanced oil recovery.

The development of coal to chemical enables the co-utilization of coal, oil and natural gas. A large amount of useful chemical products have been produced including methanol, acetic acid, olefin, aldehyde, ketone, acid, dimethylether and all kinds of oil. Two coal to chemicals and energy to chemicals plants are now in operation. In addition, two CO_2 capture plants with capacity of 50,000 and 360,000 tonnes per year are now providing the CO_2 sources needed for enhanced oil recovery in the Yanchang oil fields. A series of processes have been optimized through the CO_2 capture project management, location of CO_2 capture plants and EOR onsite as well as connections of different projects. For one thing, the efficiency for energy consumptions is improved to be 8.9% higher than world average level. For another, the cost for CO_2 capture is around $17.5/tonne which is much cheaper than most of the CO_2 capture projects in the world (Wang et al., 2017). The shortest distance for CO_2 transportation is 10 kilometers which is much shorter than the other CCUS projects such as Weyburn project with the distance 325 kilometers. This also greatly reduces the CO_2 transportation cost to be only $2.58/tonne. Meanwhile, it provides very stable CO_2 supply for field EOR projects.

Research shows that around 87% of reservoirs in Yanchang oilfields are suitable for the CO_2-EOR with the estimated geological reserves 1.74×10^9 tonnes. A rough evolution of the cumulative CO_2 storage would be 6.57×10^8 tonnes. If considering the saline aquifer in this area, the amount of CO_2 for sequestration is probably 10 billion tones or even more in the Ordos Basin.

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Reference

Bachu, S., 2016. Identification of Oil Reservoirs Suitable for CO_2-EOR and CO_2 Storage (CCUS) Using Reserves Databases, with Application to Alberta, Canada. Int. J. Greenh. Gas Control 44, 152–165.

BP, 2017. BP Statistical Review of World Energy June 2017.

Brashear, J.P., Kuuskraa, V.A., 1978. The Potential and Economics of Enhanced Oil Recovery. J. Pet. Technol. 30, 1231–1239.

Brock, W., Bryan, L., 1989. Summary Results of CO_2 EOR Field Tests, 1972-1987. In: SPE Joint Rocky Mountain Region/Low Permeability Reservoirs Symposium and Exhibition. Society of Petroleum Engineers, Denver, Colorado, USA.

Enick, R.M., Olsen, D., Ammer, J., Schuller, W., 2012. Mobility and Conformance Control for CO_2 EOR via Thickeners , Foams , and Gels - A Literature Review of 40 Years of Research and Pilot Tests. In: Eighteenth SPE Improved Oil Recovery Symposium. Society of Petroleum Engineers, Tulsa, Oklahoma, USA.

Huang, T., Zhou, X., Yang, H., Liao, G., Zeng, F., 2017. CO_2 Flooding Strategy to Enhance Heavy Oil Recovery. Petroleum 3, 68–78.

Klins, M.A., Farouq Ali, S.M., 1982. Heavy Oil Production By Carbon Dioxide Injection. J. Can. Pet. Technol. 21, 64–72.

Lotz, M., Brent, a C., 2008. A review of Carbon Dioxide Capture and Sequestration and the Kyoto Protocol's Clean Development Mechanism and Prospects for Southern Africa. J. Energy South. Africa 19, 13–24.

Manrique, E., Thomas, C., Ravikiran, R., Izadi, M., Lantz, M., Romero, J., Alvarado, V., 2010. EOR: Current Status and Opportunities. In: SPE Improved Oil Recovery Symposium. Society of Petroleum Engineers, Tulsa, Oklahoma, USA.

Nobakht, M., Moghadam, S., Gu, Y., 2008. Determination of CO_2 Minimum Miscibility Pressure from Measured and Predicted Equilibrium Interfacial Tensions. Ind. Eng. Chem. 47, 8918–8925.

Or, C., Sasaki, K., Sugai, Y., Nakano, M., Imai, M., 2016. Swelling and Viscosity Reduction of Heavy Oil by CO_2-Gas Foaming in Immiscible Condition. SPE Reserv. Eval. Eng. 19, 294–304.

Seyyedsar, S.M., Farzaneh, S.A., Sohrabi, M., 2017. Investigation of Low-Density CO_2 Injection for Enhanced Oil Recovery. Ind. Eng. Chem. Res. 56, 5443–5454.

Thomas, S., 2008. Enhanced Oil Recovery-An Overview. Oil Gas Sci. Technol. 63, 9–19.

Wang, J., Dong, M., Li, Y., Gong, H., 2015. Prediction of Nitrogen Diluted CO_2 Minimum Miscibility Pressure for EOR and Storage in Depleted Oil Reservoirs. Fuel 162, 55–64.

Wang, X., Zeng, F., Gao, R., Zhao, X., Hao, S., Liang, Q., Jiang, S., 2017. Cleaner Coal and Greener Oil Production: An Integrated CCUS Approach in Yanchang Petroleum Group. Int. J. Greenh. Gas Control 62, 13–22.

Yuan, Q., Azaiez, J., 2014. Miscible Displacements in Porous Media with Time-Dependent Injection Velocities. Transp. Porous Media 104, 57–76.

Yuan, Q., Azaiez, J., 2015. Inertial Effects in Cyclic Time-Dependent Displacement Flows in Homogeneous Porous Media. Can. J. Chem. Eng. 93, 1490–1499.

Yuan, Q., Zhou, X., Zeng, F., Knorr, K.D., Imran, M., 2017. Effects of Concentration-Dependent Diffusion on Mass Transfer and Frontal Instability in Solvent-Based Processes. In: SPE Canada Heavy Oil Technical Conference. Society of Petroleum Engineers, Calgary, Alberta, Canada.

Zhao, X., Burnett, J.W., Fletcher, J.J., 2014. Spatial Analysis of China Province-Level CO_2 Emission Intensity. Renew. Sustain. Energy Rev. 33, 1–10.