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Potential evaluation of CO_2 storage and enhanced oil recovery of tight oil reservoir in the Ordos Basin, China

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Abstract

Carbon -di-oxide (CO_2) is regarded as the most important greenhouse gas to accelerate climate change and ocean acidification. The Chinese government is seeking methods to reduce anthropogenic CO_2 gas emission. CO_2 capture and geological storage is one of the main methods. In addition, injecting CO_2 is also an effective method to replenish formation energy in developing tight oil reservoirs. However, exiting methods to estimate CO_2 storage capacity are all based on the material balance theory. This was absolutely correct for normal reservoirs. However, as natural fractures widely exist in tight oil reservoirs and majority of them are vertical ones, tight oil reservoirs are not close. Therefore, material balance theory is not adaptive. In the present study, a new method to calculate CO_2 storage capacity is presented. The CO_2 effective storage capacity, in this new method, consisted of free CO_2, CO_2 dissolved in oil and CO_2 dissolved in water. Case studies of tight oil reservoir from Ordos Basin was conducted and it was found that due to far lower viscosity of CO_2 and larger solubility in oil, CO_2 could flow in tight oil reservoirs more easily. As a result, injecting CO_2 in tight oil reservoirs could obviously enhance sweep efficiency by 24.5% and oil recovery efficiency by 7.5%. CO_2 effective storage capacity of Chang 7 tight oil reservoir in Longdong area was 1.88×10^{7} t. The Chang 7 tight oil reservoir in Ordos Basin was estimated to be 6.38×10^{11} t. As tight oil reservoirs were widely distributed in Songliao Basin, Sichuan Basin and so on, geological storage capacity of CO_2 in China is potential.

Key words

Co_2 Effective storage capacity, Enhance oil recovery, Tight oil reservoirs

Introduction

It is an essential to reduce anthropogenic carbon dioxide (CO_2) emission in order to alleviate the impact of climate change and ocean acidification (The Royal Society, 2005; Intergovernmental Panel on Climate Change (IPCC), 2007; Hoegh-Guldberg and Bruno, 2010). CO_2 is regarded as the most important greenhouse gas due to dependence of the world economies on fossil fuels as primary energy source is increasing so that its relative abundance in the atmosphere is larger than other green house gases (IPCC, 2005). It is estimated that global CO_2 emission will be more than double by 2050 (IEA and OECD, 2008; IEA, 2010). Therefore, it is increasing pressure on the governments to seek new solution to mitigate CO_2 impact. Indeed, many countries have committed to reduce CO_2 emission within stringent timeframes (pledged emission reductions by 2020: EU member states, 20–30% relative to 2005 levels; USA, 17% relative to 2005; Russia) aiming to limit global temperature rise and ocean acidification (Stern and Taylor, 2010; Flannery *et al.*, 2012). However, stabilization scenarios of the International Energy Agency (450 ppm CO_2 equivalents or 2 degree scenario) will require a reduction of global CO_2 emission at least 50% by 2050, compared to 2000 level (IEA, 2010; IPCC, 2011). These objects are so challenging that rapid implementation of CO_2

mitigation measures and technologies are required, such as improving energy efficiency, adoption of marine renewable energy sources and carbon capture and storage systems (CCS).

Geological storage of CO_2 is one of the effective CCS methodologies (Pires *et al.*, 2011) to partially decrease anthropogenic CO_2 emission (Holloway, 2005; IPCC, 2005, 2011; Holloway *et al.*, 2007). There are five major geologic systems for CO_2 storage: oil and gas reservoirs, saline formations, unmineable coal areas, shale and basalt formations (Shen and Jiang, 2009). In addition, development of tight oil reservoirs, whose permeability is less than $0.1 \times 10^{-3} \mu m^2$, faces a large challenge. Due to extremely low permeability, water can not be injected into reservoirs easily. Therefore, formation energy can not be replenished. However, CO_2 can solve the problem because its viscosity is far lower than water, and it has large solubility in oil. Therefore, the Chinese government emphasizes geological storage of CO_2, in order to reduce CO_2 emission and enhance oil productivity. Worldwide, many researchers are investing much energy to assess CO_2 geologic storage potential. Relatively speaking, estimation of CO_2 storage capacity in oil reservoirs is simpler and more straight forward than other media because characters of oil reservoirs are better known as a result of exploration and development. However, existing methods to evaluate CO_2 storage capacity is not adaptable to tight oil reservoirs due to neglecting characteristics of fractures. In the present study, a new method was presented to evaluate CO_2 storage capacity in tight oil reservoirs and CO_2 storage capacity of tight oil reservoirs in China was estimated.

Materials and Methods

Modified method to estimate effective CO_2 storage capacity in tight oil reservoirs : CO_2 storage capacity can be classified into 4 parts. The CO_2 storage capacity contains theoretical storage capacity, effective storage capacity, practical storage capacity and matched storage capacity (Fig. 1) (Bradshaw *et al.*, 2005; Bradshaw *et al.*, 2007). Theoretical storage capacity, which forms the base of whole resource pyramid, represents the physical limit which the geological system can accept. The effective storage capacity is obtained by applying some technical cutoff limits to a storage capacity assessment. Effective storage capacity is the CO_2 storage capacity considering reservoir properties, close reservoir, storage depth, pressure system of reservoir and pore volume. It is always smaller than the theoretical one. Practical storage capacity is determined by considering technical, legal, regulatory, infrastructure and general economic conditions of a certain country or area limited to CO_2 geological storage. Matched storage capacity is obtained by the detailed matching of large stationary CO_2 sources, which are adequate in terms of capacity, injectivity and supply rate.

The method to calculate CO_2 effective storage capacity was modified in the present study as theoretical capacity ignores so many important factors and is inaccurate. Practical capacity and matched capacity contain many anthropogenic factors, so the results are uncertain. Therefore, the results of effective storage capacity are objective and the method to calculate effective storage capacity is most significant.

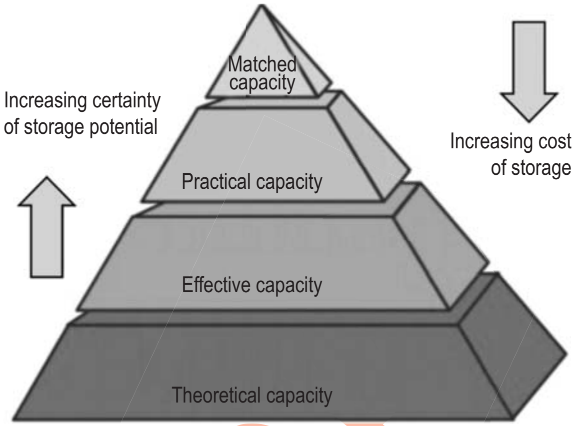


Fig. 1 : Techno-economic resource-reserve pyramid for CO_2 sequestration capacity

Reservoir characteristics, such as buoyancy, mobility ratio, nonhomogeneity, water saturation and aquifer can reduce the actual CO_2 storage capacity (Bradshaw *et al.*, 2005). So the effective storage capacity was lower than the theoretical storage capacity. Bradshaw (2005) proposed a methodology to calculate the effective storage capacity by the following formula :

$$M_{CO_2e} = C_e \times M_{CO_2t} = C_m \times C_b \times C_h \times C_w \times C_a \times M_{CO_2t} \quad (1)$$

where, M_{CO2e} is the effective reservoir capacity for CO_2 storage; m, b, h, w and a are mobility, buoyancy, heterogeneity, water saturation and aquifer strength respectively; C_e is the effective capacity coefficient that incorporates the effects of mobility, buoyancy, heterogeneity, water saturation and aquifer strength. Zhao *et al.* (2013) introduced an alternate equation for calculating effective storage capacity which is as follows:

$$M_{CO_2e} = \rho_{CO_2r} \times A \times h \times \phi \times S_{CO_2} \quad (2)$$

where, ρ_{CO2r} is CO_2 density in reservoirs; A is the area; h is the formation thickness and S_{CO2} is CO_2 storage coefficient.

The tight oil reservoir was not close. Sandstone and shale coexisted and were not separated. Therefore, material balance theory was not adaptable to tight oil reservoirs. In the present study, expression of S_{CO2} was modified. CO_2 storage capacity consisted of three parts: free CO_2, CO_2 dissolved in oil and CO_2 dissolved in water. Therefore, expression of S_{CO2} is as follows:

$$S_{CO_2} = Ce x \left[S_{CO_2} + \frac{E_f x S_{pw} x (1-R_w) x m_{CO_2 inwater}}{\rho_{CO_2 r}} + \frac{E_f x (1-S_{pw}) x (1-R_f) x m_{CO2inoil}}{\rho_{CO_2 r}} \right] \quad (3)$$

where, S_w : initial water saturation; R_f : oil recovery; R_w : water recovery; S_{pw} : present water saturation; $m_{CO2inwater}$: CO_2 solubility in water and $m_{CO2inoil}$: solubility in oil.

Geological properties of Ordos Basin: Ordos Basin is the second largest basin in China with 37×10^4 km^2 area. The dip angle is less than 1° and altitude becomes larger when moving toward east. Ordos Basin is a polycyclic cratonic basin. The tectonics of Ordos Basin is simple. The basin has experienced rise and fall entirely and movement of sunken. The bottom consists of metamorphic rocks, deposited during archaeozoic and Lower proterozoic era. Sedimentary cover contains Changcheng, Jixian, Sinian, Cambrian, Ordovician, carboniferous, Permian, Triassic, Jurassic, cretaceous and Tertiary quaternary system. Thickness ranges from 5000m to 10000m. Reservoirs are mainly Triassic, Jurassic and Ordovician system. Oil reservoirs are mainly located in the south of basin, while gas reservoirs are mainly located in the north. The reservoir area is large and widely distributed (Ordos Basin News Network, 2013).

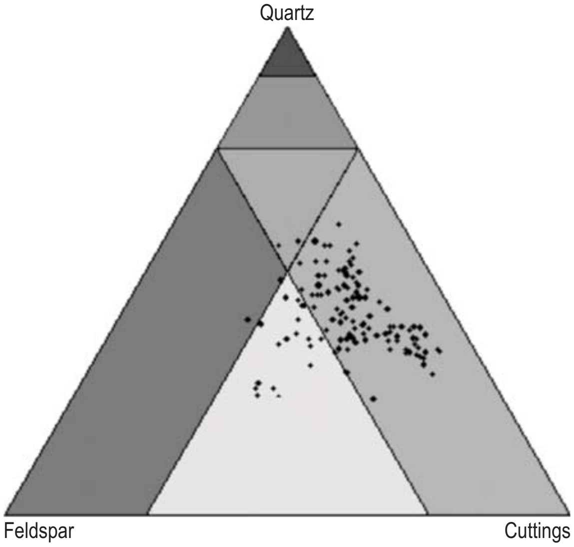
Geological characteristics of tight oil reservoir : Changqing oilfield is an old and big oilfield in the west of China (Fig. 2) (Jia *et al.*, 2012). The exploration and development of Changqing oilfield dates from 1970 and it has been breaking through the permeability limit. Currently, Changqing oilfield is tackling key problems in developing tight oil reservoirs, whose permeability is less than $0.1\times10^{-3}\mu m^2$. Meanwhile, Changqing oilfield becomes the largest oilfield in China. The production in 2013 is 50 million tons of oil and gas equivalent, while it was 1 million tons in 1992 (Baidu Encyclopedia, 2013).

Chang 7 reservoir of Changqing oilfield in Longdong area belongs to hemi-deep lake and deep lake subfacies, including Chang 7_1, Chang 7_2 and Chang 7_3 sections. The turbidite sandstone is the main reservoir and is located in Chang 7_1 and Chang 7_2 section. The sedimentary thickness of sand body is 20"50 m with an average of 30 m and lithology of reservoir is mainly fine lithic sandstone (Fig. 3) as a result of proximal and rapid deposition. The proportion of interstitial material in rock ranges from 5.5% to 39.6% and the average value is 16.9%. Among them, the proportion of hydromica (Fig. 4 (a)) is largest. Therefore, majority of pore type is micropore (Fig. 4 (b)). As a result, porosity of reservoir ranges from 3.2% to 13.2% and average value is 9.5%. Permeability ranges from 0.011 to $1.60\times10^{-3}\mu m^2$ and the average value is $0.15\times10^{-3}\mu m^2$.

Geological model of tight oil reservoir : To build the geological models of reservoir, using Petrel software from Schlumberger Company, different kinds of data were collected, including the coordinate data of production and injection wells, stratified data, logging data, deposition facies maps, flow unit maps, core analysis data, producing test and various kinds of well test data.

Fig. 2 : Location of Ordos Basin

Reservoir model controlled by flow unit were built based on the collected data. When the geological models were built, first of all, formation structure models were established, then interwell interpolations and stochastic simulations for formation properties, such as facies, flow units porosity, permeability, net gross and oil saturation, were accomplished based on the distribution law of formation parameters. Finally, reservoir volume was calculated.



I. Pure quartz sandstone; II. Quartz sandstone; III. Second cutting-feldspar sandstone; IV. Cuttings-feldspar sandstone; V. Feldspar sandstone; VI. Cuttings sandstone

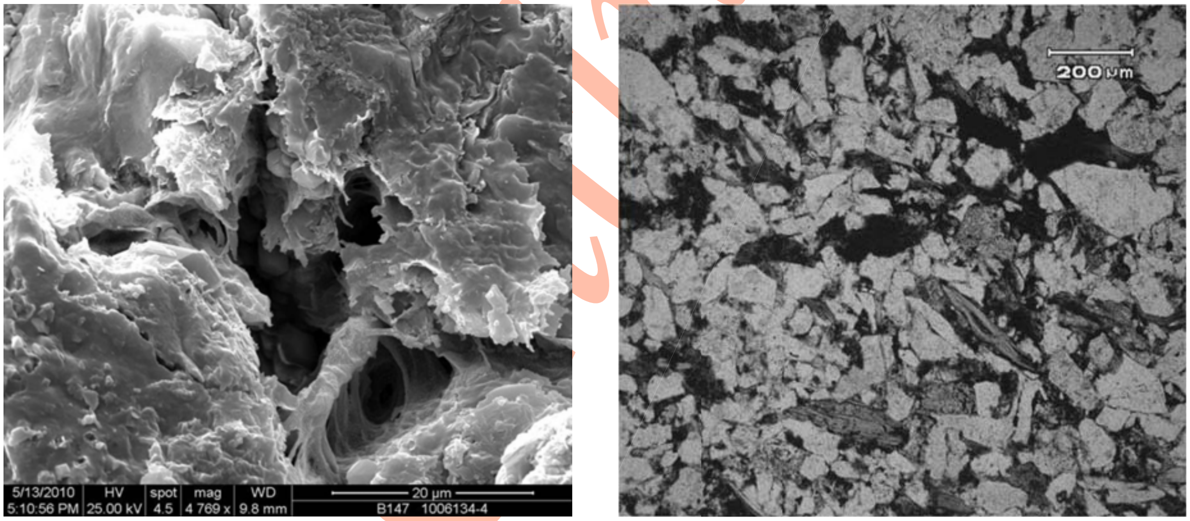
Fig. 3 : Composition of sandstone

Minimum miscible pressure : In the present study, a slim tube experiment was conducted to determine minimum miscible pressure (MMP), under the conditions of Chang 7 tight oil reservoir in Longdong area. The experimental process is shown in Fig. 5. The basic parameters of facilities used in the experiment is shown in Table 1. The temperature of reservoir was 27°C.

CO_2 enhanced oil recovery and storage capacity calculation of the tight oil reservoir : Based on geological model, the numerical model was established. The basic parameters are shown in Table 2. $m_{CO2inoil}$ was determined according to the equation developed by Xue (2005). $m_{CO2inwater}$ could be determined using the prediction model derived by Duan *et al.* (2003). ρ_{CO2r} could be obtained according to Wang *et al.* (2014) data. The development process injecting water and CO_2 were simulated respectively, using Eclipse software from Schlumberger Company. Gas wells injected CO_2 when the well bottom pressure was 35 MPa. Water wells injected water when the well bottom pressure was 35 MPa, too. Oil wells worked when the well bottom pressure was 5 MPa, respectively. Based on numerical results CO_2 storage capacity was calculated, using the modified method.

Results and Discussion

The geological model is shown in Fig. 6 and the model parameters are shown in Table 3. The permeability of Chang 7 tight oil reservoir in Longdong area was $0.26\times10^{-3}\mu m^2$, larger than $0.1\times10^{-3}\mu m^2$. This was because Chang 7 tight oil reservoir in Longdong area was "sweet pot". It is the best area of tight oil reservoir. Therefore, the properties of Chang 7 tight oil reservoir in Longdong area were better than average properties. Fig. 6 showed that shale had least porosity, permeability and net



(a) Incision of hydromica

(b) Micropore

Fig. 4 : Diagenesis in tight oil reservoir

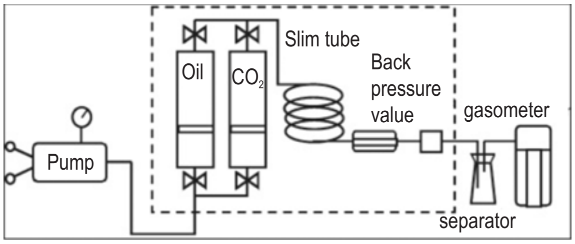


Fig. 5 : Process flow diagram for slim tube experiment

Table 1 : Basic parameters of slim tube facilities

Parameters	Value
Maximum temperature (°C)	150
Maximum pressure (MPa)	50
Length (m)	20
Inner diameter (mm)	3.86
Outside diameter (mm)	6.35
Filler (quartz sand) (mesh)	170-325
Porosity (%)	39
Air permeability (im^2)	5.43

Table 2 : PVT parameters of Chang 7 tight oil reservoir in Longdong area

Parameters	Value
M_{CO2e} (t)	1.88×10^7
Temperature (°C)	27
Pressure (MPa)	16.8
$ñ_{CO2r}$ (tm^{-3})	0.29
$m_{CO2inoil}$ (tm^{-3})	0.196
$m_{CO2inwater}$ (tm^{-3})	0.0627

sandstone thickness/gross sandstone thickness (NTG). Therefore, no fluid could flow through shale. Fig. 6 (a) shows that shale was not continuously distributed on the top and bottom of the reservoir. This was because tight oil reservoirs belonged to lithologic reservoirs, greatly differing from tectonic reservoirs. As a result, CO_2 could flow to adjacent reservoirs through sandstone with high permeability. The yellow part on top and bottom of the reservoir in Fig. 6 (c) is sandstone with high permeability. Therefore, the tight oil reservoir was not close and material balance theory was not adaptable.

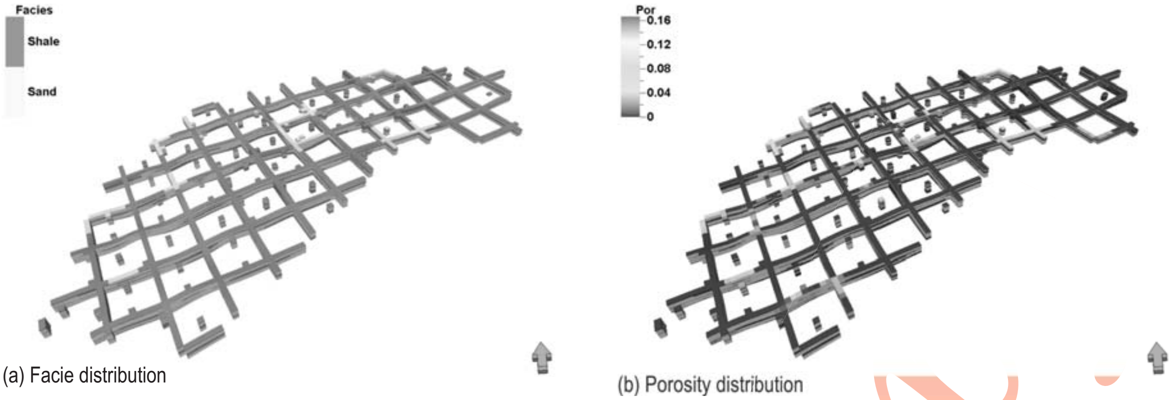
Minimum miscible pressure : Fig. 7 reveals that MMP of Chang 7 tight oil reservoir in Longdong area was 20 MPa. The flow of gas flooding in reservoirs can be divided into miscible flooding and immiscible flooding. When the flow is miscible displacement, oil and gas can be mixed without the presence of interfacial tension due to diffusion and mass transfer between two fluids (Yang *et al.*, 2005). As a result, oil recovery could greatly be improved and the residual oil saturation decreases. Therefore, the miscible flooding efficiency was much higher than that of immiscible flooding proved by theory and practice (Gao *et al.*, 2009; Koottungal, 2012; Wang *et al.*, 2013). The oil displacement efficiency of CO_2 injection largely depends on displacement pressure. It can achieve miscible flooding when the displacement pressure is higher than MMP. On the contrary, it cannot achieve miscible flooding and high oil recovery when displacement pressure was less than MMP. MMP is a key parameter to identify if tight oil reservoirs can achieve miscible flooding. The formation pressure was 16.8 MPa and far less than MMP. Therefore, the flow was immiscible flooding in Chang 7 tight reservoir.

If oil is produced form reservoirs or gas and water is injected into reservoirs, the oil saturation decreases. When the oil saturation decreases, the reservoir is regarded to be drained. 1 represents that reservoir is undrained and 0 represents that reservoir is drained. From the simulation result (Fig. 8), it was found that the drainage range of injecting CO_2 (54.5%) was far larger than that of injecting water. The sweep efficiency of injecting CO_2 was 54.5%, while that of injecting water was only 30%. This was due to CO_2 viscosity. The viscosity of CO_2 was 0.03-0.1mPa·s in tight oil reservoirs (Hao *et al.*, 2010) and was far less than that of water, so CO_2 could easily flow in tight oil reservoirs. As a result, injecting CO_2 enhanced the sweep efficiency (Cheng *et al.*, 2008). Fig. 8 shows the section which was drained by CO_2 was connected while the section which was drained by water was not. This indicated that injecting CO_2 contributed a lot to oil production while injecting water had no contribution. The oil around production wells was majority of the production of injecting water. Therefore, oil production of injecting CO_2 was higher than that of injecting water. If tight oil reservoir developed for 16 years, the recovery efficient of injecting CO_2 would be 11.5%, while that of injecting water would be 4% (Fig. 9).

Meanwhile, injecting CO_2 could reduce anthropogenic CO_2 emission. If tight oil reservoir developed for 16 years, injection volume of CO_2 would be 7.5×10^8 m^3, while the production volume of CO_2 would only be 11.5×10^7 m^3 (Fig. 10). However, the value of injection volume of CO_2 minus the production volume of CO_2 was not exactly the CO_2 storage capacity because tight oil reservoirs contain large amount of vertical natural fractures (Zeng *et al.*, 2008). CO_2 injected into tight oil reservoir partially flowed into other layers and reservoirs through fractures. Therefore, this part of CO_2 was not effective storage capacity of this reservoir. According to modified method, CO_2 effective storage capacity was 1.88×10^7 t. From the CO_2 effective storage capacity map (Fig. 11), it was found that the area where gas injection wells were

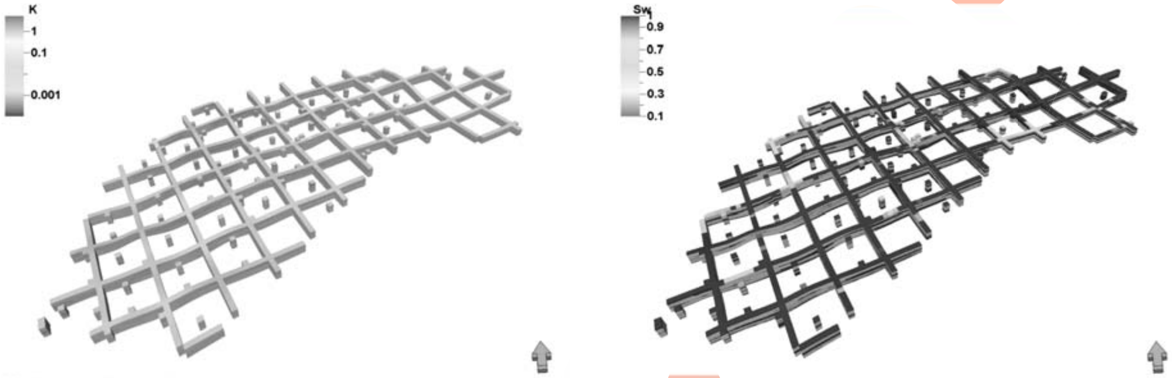
Table 3 : Basic parameters of Chang 7 tight oil reservoir in Longdong area

Parameters	Value
Area (km^2)	10.9
Porosity (%)	11.6
Permeability ($\times10^{-3}\mu m^2$)	0.26
Oil saturation (%)	53.9
Reservoir volume ($\times10^4$t)	851.6



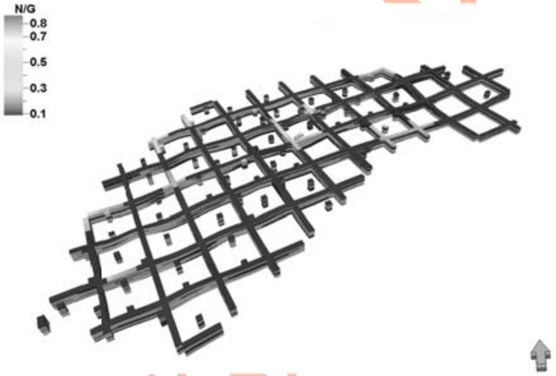
(a) Facie distribution

(b) Porosity distribution



(c) Permeability distribution

(d) Water saturation distribution



(e) NTG distribution

Fig. 6 : Properties of the Chang 7 tight oil reservoir in Longdong area

located and where the effective formation thickness was large (Fig. 12), CO_2 effective storage capacity was large. The reservoir oil, where gas injection wells were located, was displaced to production wells and the reservoir where gas injection wells were located had the most CO_2, so the residual oil of reservoir was least and the reservoir was filled with CO_2. Moreover, the pressure around gas wells was highest and the compressibility of CO_2 was high (Xiang *et al*., 2011), so the volume of CO_2 around gas wells was large. In addition, area where effective formation thickness was large had large volume pore and oil. If oil was displaced, larger volume pore could contain larger volume CO_2. If oil was not displaced, larger volume oil could dissolve larger volume CO_2. Therefore, larger effective formation thickness had larger CO_2 effective storage capacity.

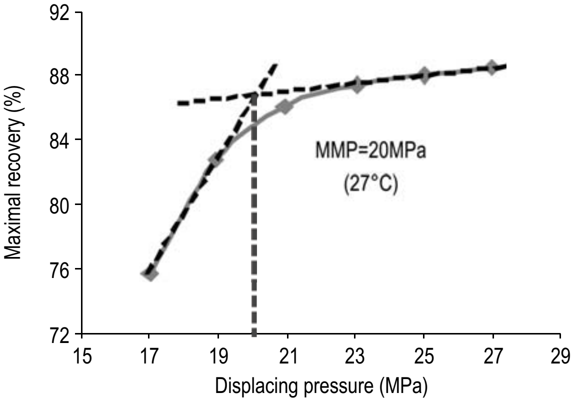
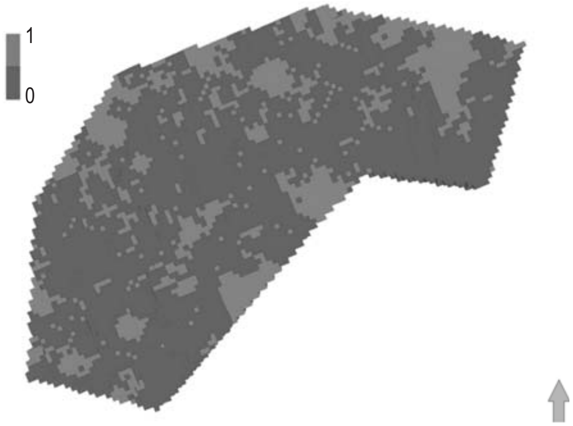
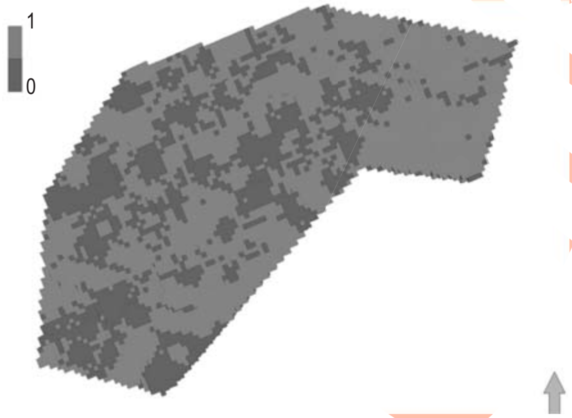


Fig. 7 : MMP of CO_2 and oil of tight oil reservoir in Longdong area



(a) Distribution of drained area of CO_2



(b) Distribution of drained area of water

Fig. 8 : Distribution of drained area

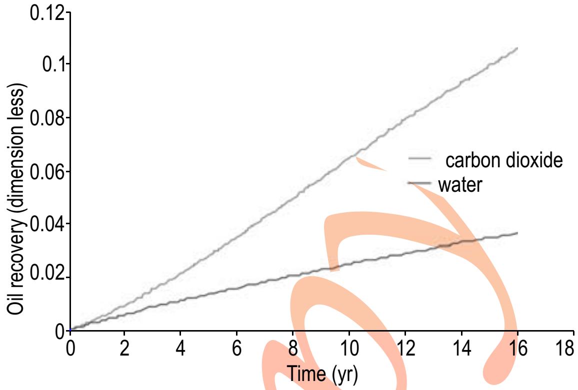


Fig. 9 : Comparison of recovery between CO_2 and water

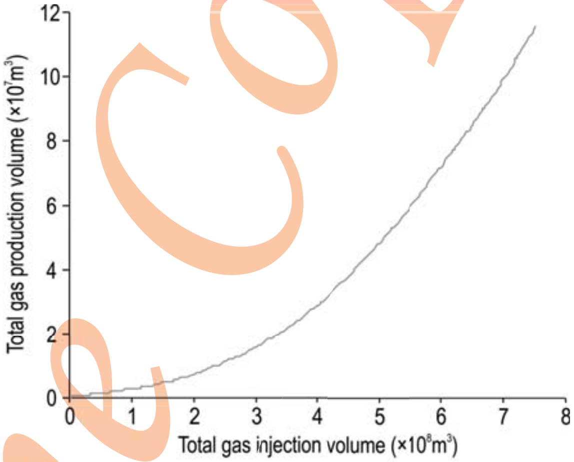


Fig. 10 : Volume of CO_2 injection and production

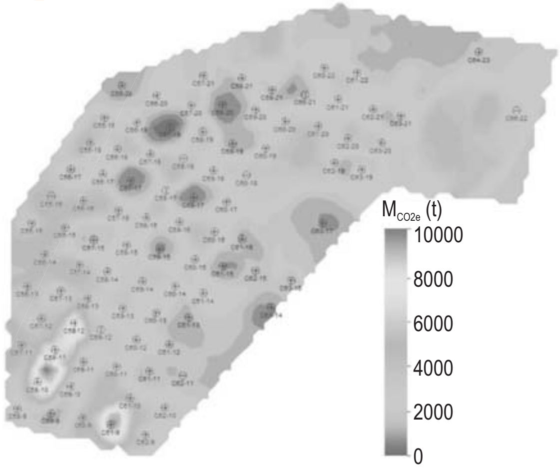


Fig. 11 : Distribution of CO_2 storage capacity

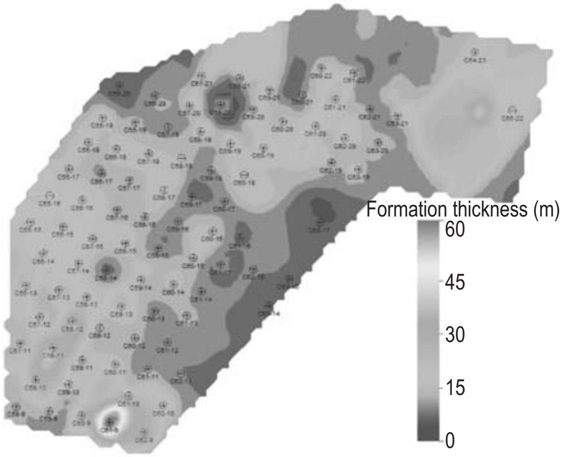


Fig. 12 : Distribution of formation thickness

The model area was 10.9 km^2 and the effective formation thickness was 15.6 m. The effective formation thickness of same member was similar and the Ordos Basin area was 37×10^4 km^2, so it was estimated that CO_2 effective storage capacity in Chang 7 tight oil reservoir was 6.38×10^{11} t. In addition, tight oil reservoirs were widely distributed in Songliao Basin, Sichuan Basin and so on. Therefore, geological storage capacity of CO_2 in China was theoretically potential.

Acknowledgments

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