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Feasibility of Near-Miscible Flooding By Production Gas Rejection with Varying CO_2 Content in Qinhuangdao Oilfield

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Abstract

A newly discovered offshore oilfield in QHD 29-2 block is facing the problem of selecting the appropriate developing method. It covers approximately 2300 km^2 and with an average water depth of 27.6m. The depth of the exploration well is over 3600 m with thick sand layer and oil zone. Conventional waterflood cannot be implemented due to the reservoir characteristics of small pores and throats, complex lithology, strong heterogeneity and low water injectivity. Near-miscible flooding is proposed considering the wide range of CO_2 content (24-90 mol%) in the production gas.

Slim tube test and slim tube simulation are conducted successively to determine the minimum miscible pressure (MMP) of the production gas and oil samples from the targeted reservoir. The relationship of displacement efficiency (DE), interfacial tension (IFT) and displacement pressure are provided and chosen as the basis for the division of the pressure interval of near-miscible flooding. The lower limit of the CO_2 content in the production gas to achieve near-miscible flooding are determined for the well 29-2E-5 with the well depth of 3308-3330 m. On this basis, an adjustment measures of adding intermediate components of (C_2-C_6) is proposed and assessed. The amount of the adding components is calculated and provided correspondingly.

Boundaries of the pressure region of near-miscible flooding are obtained for different CO_2 contents. Considering the reservoir conditions (112.1 ^oC, 31.96 MPa), the lower CO_2 content of 64% is estimated to be able to achieve near-miscible flooding for the targeted well. Accordingly, 2.3, 6.5, and 10.3 mol% of (C_2-C_6) are determined to be the lowest amounts for the adding components to achieve near-miscible injection for the CO_2 contents of 55%, 40%, and 24%, respectively.

Thus, the evaluation of the feasibility and optimization measures of near-miscible flooding by production gas re-injection with varying CO_2 content in a newly discovered offshore reservoir was conducted. Specific regions in the vicinity of MMP for impure CO_2 near-miscible flooding on the basis of comprehensive analysis of displacement efficiency and IFT from the views of both engineering and

physicochemical were determined. Also, an ideal adjustment measures of adding intermediate hydrocarbons (C_2-C_6) were proposed and assessed. Moreover, the tuned compositional model of the paper could be beneficial for providing a further pilot and field case study of production gas re-injection in this reservoir.

1. Introduction

Carbon dioxide miscible flooding is a proven oil recovery process, generally one of the most efficient and promising methods for enhancing oil recovery (EOR) methods (Farajzadeh et al., 2010). However, in view of the limitations of gas sources, sedimentary environments and oil characteristics, the application and promotion of miscible flooding is very difficult in China (Chen et al., 2013). Even though some reservoirs are experiencing miscible flooding, maintaining high pressures required for miscible injection is very difficult (Dong et al., 2001). However, laboratory tests and some field tests have fully verified that near-miscible flooding can also obtain very satisfactory recovery (Shyeh-Yung et al, 1991; Schechter et al., 1998; Crigg et al., 1997). Thomas et al. (1994) claims that many successfully miscible flooding would be better described as near-miscible, depending on the evaluation techniques. Theoretically, near-miscible flooding refers to the gas injection of close but not complete miscibility with the oil (Sohrabi et al., 2007). It sounds very attractive from both economic and operational standpoints. For one thing, lower pressure reduces the gas mobility, a certain degree of mobility control effect can be obtained. For another, injection gas volume and compression cost decrease with the pressure decrease (Shyeh-Yung and Stadler, 1995).

The first step in determining whether a field is a good CO_2 flooding candidate is to conduct a screening study to assess the injection performance. The minimum miscibility pressure (MMP) is a key parameter used to distinguish the flooding type, either immiscible or miscible. However, near miscible flooding is much more complicated. Both of the upper and lower boundaries of the near-miscible region in the vicinity of MMP has to be determined. There are several methods to determine MMP or miscibility degree for gas flooding, including both empirical, experimental and numerical simulation studies. Empirical correlations are easy to use and always serve as a tool for quick MMP prediction (Alomair and Iqbal, 2014). However, the accuracy is not very satisfactory because most of the formulas are established based on very limited data within certain reservoir conditions (Teklu et al, 2012). Comparatively, laboratory MMP measurements are more accurate, but time consuming and very expensive. The most widely used experimental method is slim tube test (Yellig and Metcalfe, 1980). Due to the drawbacks of the experimental methods and empirical formulas, computational methods for MMP determination are proposed over the years and are successfully applied to reproduce the MMP between the injected gas and crude oil using computational methods based on the principles of fluid flow and phase equilibrium, which is often modeled based on cubic equation of State (EOS) and flash calculations (Teklu et al, 2012).

It has been recognized that the CO_2 MMP for a reservoir oil depends on the reservoir temperature, oil composition, and the purity of injected CO_2. MMP increases with increasing reservoir temperature. The effect of oil composition has been observed by several researchers and reached consensus to substantially affect MMP. Pure CO_2 is not always available as an injection gas. Impure CO_2 streams, however, are available from a variety of sources, including natural reservoirs and process plant waste streams. Typically, the CO_2 -rich produced gas streams contain a wide variety of components from methane and nitrogen to intermediate hydrocarbons-such as ethane, propane, butane, and H_2S. Metcalfe (1982) has shown that the presence of impurities can affect the pressure required to achieve miscible displacement. In general, the presence of CH_4 or N_2 in CO_2 can substantially increase the CO_2 MMP, while the presence of H_2S, C_2H_6, or intermediate hydrocarbons (such as C_3, C_4) can reduce the CO_2 MMP.

Use of a CO_2 source diluted by impurities can substantially improve the economic prospects of an EOR project. Also, CO_2 flood candidates that cannot become miscible with pure CO_2 may be viable with enriched CO_2 streams. For gravity-stable CO_2 floods, density adjustment while maintaining miscibility can be achieved by diluting the CO_2 stream with selected components. Contamination of CO_2 by C_1 or N_2 has been shown to adversely affect the MMP. Conversely, the addition of C_2, C_3, C_4, or H_2S to CO_2 has been shown to have the effect of lowering the MMP. Rutherford (1962) empirically found pseudocritical temperature to show a correlation with the MMP required for hydrocarbon miscible floods. Jacobson (1972) applied the same concept with the acid gases of CO_2 and H_2S. Shang et al (2014) studied the effect of adding CH_4 and N_2 in the injection CO_2 on MMP. It was found that with the increase of the contaminants, MMP increases significantly. Comparatively, the impact of N_2 is more obvious. Hou et al (2013) summarized the main factors of MMP. It was concluded that for a certain gas composition and reservoir temperature, the more the intermediate components (C_2-C_6) in the oil and the smaller the relative molecular mass, the smaller the MMP is. On the contrary, the heavier the oil, the more difficult to achieve miscibility. For a certain reservoir, the reservoir temperature and oil composition are mostly stable, thus, the intermediate components (C_2-C_6) in the injection gas is one of the key factors influencing the miscibility of oil and gas system. Actually, the detrimental effect of nitrogen and methane can be offset by the beneficial effects of intermediate hydrocarbons. Thus, the produced gas from a CO_2 flood may be miscible with the oil at reservoir conditions even though it contains a high level of impurities.

QHD 29-2 block is an offshore oilfield of China with very thick oil zone, complex lithology, and strong heterogeneity. Conventional waterflood cannot be implemented due to the small pores and throats, and low water injectivity. The discovery of a big natural gas sources with varying CO_2 content just on top of the oil layer, provides big potential for the production gas re-injection to develop the oilfield effectively. Thus, in view of the wide range of CO_2 contents and huge costs of gas separation in an offshore oilfield, near-miscible flooding, is presented for the rational development of the reservoir.

So far, researches focusing on near miscible flooding is still very limited. Firstly, there is no reliable way to determine the pressure interval of near-miscible flooding, especially for impure CO_2 near-miscible flooding. In addition, the effect of contaminants in the injection gas on miscibility degree is still unclear. Thus, in this paper, the well 29-2E-5 with the well depth of 3308-3330 m in QHD offshore oilfield is taken as an example, pressure interval of near-miscible flooding under different CO_2 contents are determined. Also, the lower limit of the CO_2 content to implement near-miscible flooding under reservoir conditions is predicted. For the CO_2 content blow the lower limit, the effect and feasibility of adding intermediate components (C_2-C_6) in the injection gas are studied. On this basis, the amount of (C_2-C_6) needed for different CO_2 content are forecasted.

2. Methodology

Both experimental and simulation studies were conducted. The experimental part includes chromatographic analysis, PVT test, and slim tube test. The simulation part includes phase matching of reservoir fluids, compositional modeling and slim tube simulation.

2.1 Materials

Physical properties of the crude oil samples collected from the well 29-2E-5 with the depth of 3308-3330 m and 3475-3500 m, were shown in Table 1. Fig.1 showed the composition comparison of the oil-solvent system for these two layers. Obviously, for the upper layer, the content of light components (C_1+N_2) is higher while the content of intermediate components (C_2-C_6) is lower, which is more difficult to achieve miscibility with the injection gas. Table 2 is the compositions of the gas samples used in this paper, determined by gas chromatography (GC) analysis.

Table 1 Physical properties of crude oil in well 29-2E-5

	Parameters	well 29-2E-5		Units
		3308-3330	3475-3500	m
Reservoir condition (*)	Pressure	31.96	34.04	MPa
	Temperature	112.1	116.7	°C
Fluid properties	Saturation pressure	17.92	17.49	MPa
	Gas/oil ratio	107.50	84.30	m^3/m^3
	Volume coefficient of the oil	1.3360	1.2650	m^3/m^3
	Oil density*	0.6986	0.7354	g/cm^3
	Oil viscosity*	0.29	1.39	mPa.s
	Died oil density	0.8391	0.8502	g/cm^3
Composition of Well-flow content	C_1+N_2	42.92	38.40	%
	CO_2+C_2~C_{10}	27.33	29.11	%
	C_{11}^+	29.75	32.49	%

Table 2 compositions of the injection gases in the test

Component	CO_2	N_2	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	C_6
Fraction, %	100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	85	0.16	13.67	0.72	0.27	0.04	0.08	0.02	0.02	0.03
	70	0.33	27.35	1.44	0.53	0.08	0.15	0.04	0.04	0.05
	55	0.49	41.02	2.16	0.80	0.12	0.23	0.05	0.06	0.08
	40	0.65	54.69	2.87	1.07	0.16	0.31	0.07	0.08	0.11

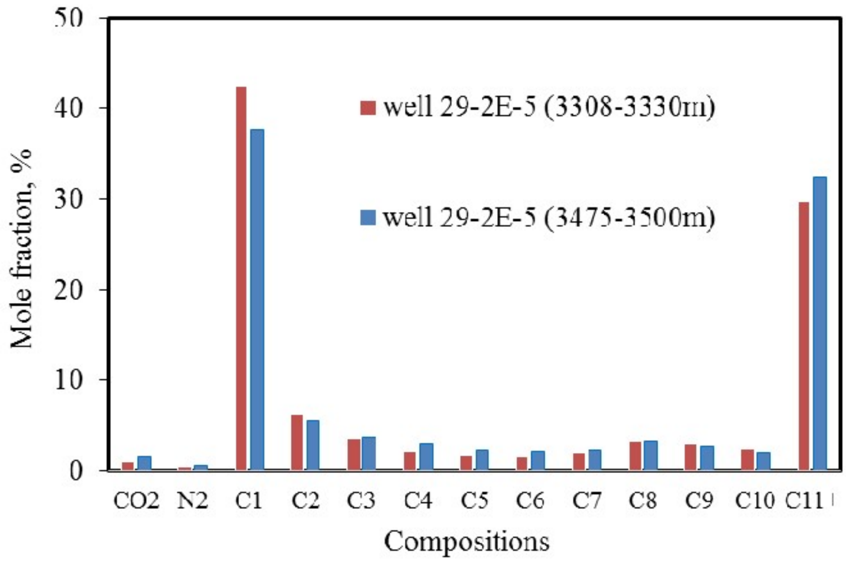

Fig.1 Composition of oil-solvent system (well 29-2E-5)

2.2 Slim tube test

RUSKA-2730 high pressure high temperature visual PVT apparatus produced by Ruska Company (Houston, Texas, USA) and CFS-200 CO_2 core flooding system produced by Corelab Company (Houston, Texas, USA) were used together to recombine the live oil and conduct the slim tube test, respectively. Experiments were conducted according to the measurement method for MMP by slim tube test (SY/T

6573-2016) of oil and gas industry standard of People's Republic of China. Physical parameters of the slim tube was shown in Table 3. More details of the experiments can be found in previous publications (Chen et al., 2017).

Table 3 Physical parameters of the slim tube

Parameter	Length, m	Diameter, mm	Porosity, %	Pore volume, cm^3	Gas permeability, $10^{-3}um^2$
Value	12.51	4.58	37.17	76.60	5275

2.3 slim tube simulation

PVTi of the Eclipse 300 was used to construct the compositional model by component lumping technique and tuning Peng-Robinson Equation of State (PREOS) based on the experimental data. More parameters such as displacement efficiency, IFT, GOR, viscosity and density of both liquid and gas phases, can be obtained.

3. Results and discussion

Based on the oil samples collected from the upper and lower depths of the well 29-2E-5, MMP and MNMP under different CO_2 contents were obtained from both slim tube test and slim tube simulation. On this basis, the effect of impurities of the injection gas on the miscibility was discussed. Moreover, the feasibility of adding intermediate components (C_2-C_6) to enhance the miscibility degree was studied.

3.1 Determination of pressure interval of near-miscible flooding

IFT and displacement efficiency are two parameters for the determination of MMP from physicalochemical and engineering point of views, respectively. Different from miscible flooding, a pressure interval with two endpoints, instead of a single point, is needed for determining near-miscible flooding. Fig.2 is the relationship of IFT, displacement efficiency and injection pressure for the oil sample from the well 29-2E-2 (3308-3330 m) with pure CO_2. Obviously, with the pressure increase, IFT of oil and gas system decrease sharply and then slows down. While the displacement efficiency increase linearly first then slows down and finally leveled off. Thus, it is not easy to distinguish a region from the smooth curves.

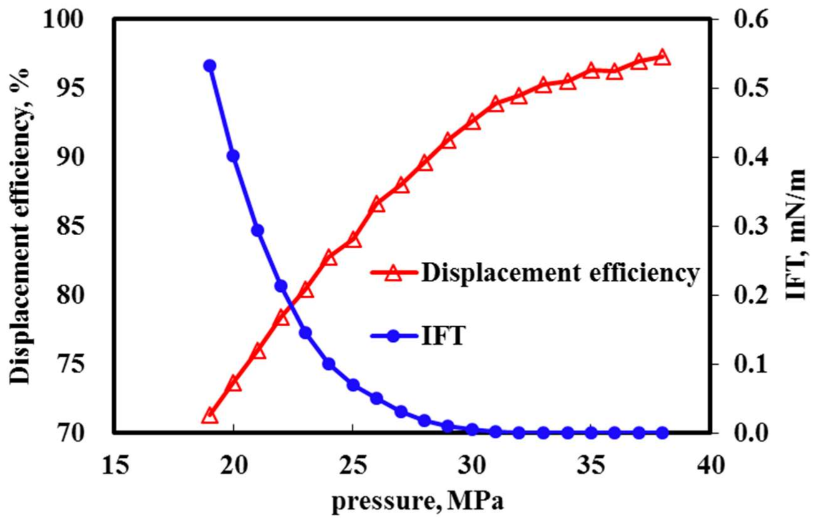

Fig.2 IFT, displacement efficiency and injection pressure (100% CO_2)

In this paper, the IFT data obtained from the slim tube simulation was transformed to semilog coordinate with the pressure. A much more obvious breakpoint can be identified, which is regarded as the lower boundary of the pressure region of near-miscible flooding. From the engineering point of view, 0.001 mN/m is generally chosen as the ultra-low IFT which can be used as the sign of complete miscibility. Thus, a pressure region of near-miscible flooding can be determined. Similarly, the upper and lower boundaries can also be obtained according to the relationship of displacement efficiency and pressure. More test points are needed to represent the trend of the curve clearly. As is shown in Fig.3, in the vicinity of MMP determined by conventional slim tube test, a new region can be distinguished which is significantly different from the immiscible region and miscible region. Thus, pressure interval of near-miscible flooding can be determined and compared by both IFT and displacement efficiency. And what we find is, statistically, the displacement efficiency and IFT of this transition interval are about 88%-96% and 0.001-0.05 mN/m, respectively.

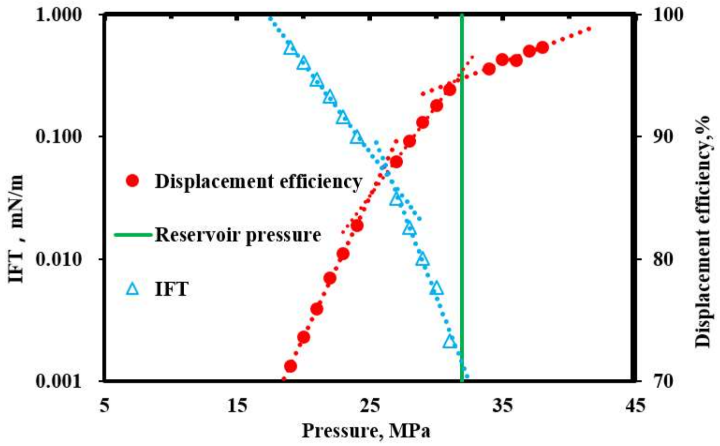

Fig.3 Displacement efficiency and IFT VS pressure (100% CO_2)

Slim tube tests with more test points under three different CO_2 contents (100%, 80%, and 55%) were conducted for oil samples from the well depth of 3308-3330 m of the well 29-2E-5. On this basis, slim tube simulation under 5 different CO_2 contents (100%, 85%, 70%, 55%, 40%) were conducted using the software Eclipse based on the compositional model matched with the data of PVT tests. Similarly, the upper and lower boundaries of the pressure region were calculated for different CO_2 contents. Three regions includes immiscible flooding, near-miscible flooding, and miscible flooding, were divided by these two boundaries. Table 4 is the summary of the MMP and MNMP determined by slim tube test and slim tube simulation. Obviously, the simulation results obtained by displacement efficiency and IFT are very close. Thus, the average values were taken as the MMP or MNMP. Compared with the slim tube results, the relative error is all less than 8%.

Table 4 Summary of the determined MMP and MNMP of the well 29-2E-5 (3308-3330 m)

CO_2 content, mol%	MNMP, MPa				MMP, MPa			
	simulation			test	simulation			test
	E_D	IFT	AVE.		E_D	IFT	AVE.	
100	26.85	26.18	26.52	27.26	33.21	32.53	32.90	30.49
85	28.47	29.46	28.97	---	35.43	35.22	35.19	---
70	31.80	30.79	31.30	---	36.87	37.10	37.09	---
55	33.38	33.68	33.53	34.14	41.08	39.09	40.11	38.56
40	34.95	35.01	34.98	---	42.72	41.51	42.52	---

Note: ED: Results obtained by displacement efficiency; IFT: Results obtained by IFT;

3.2 The effect of mixing gas on miscibility

Fig.4 is the relationship of the forecasted average upper and lower boundaries of near-miscible flooding and the CO_2 content for the well 29-2E-5. Considering the mixing gases of the injection gas, CH_4 is the main components. Thus, with the decrease of CO_2 content, the miscibility becomes more and more difficult. Both MMP and MNMP increase greatly. It is found that the trends basically obey liner relationship. Specifically, for the oil samples of the well 29-2E-5, for each 10% of impurities increase in the injection gas, MMP and MNMP increase 1.6 MPa and 1.4 MPa, respectively. It can also be concluded that with the decrease of CO_2 content, the potential scope, which belongs to near-miscible flooding, enlarges. In addition, compared with the reservoir pressure of 31.96 MPa, CO_2 content below 64% cannot achieve near-miscible flooding for the well depth of 3308-3330 m of the well 29-2E-5. Thus, for the production gases of the reservoir, the lower limit of the CO_2 content can be re-injected to implement near-miscible flooding is 64%.

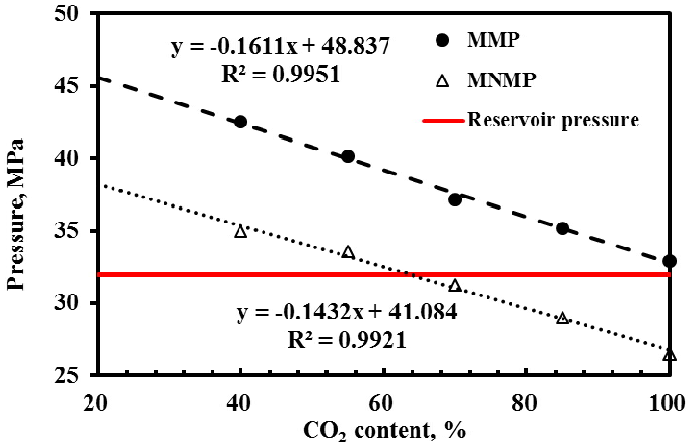

Fig.4 MNMP and MMP VS CO_2 content

3.3 Miscibility control by adding intermediate components

Generally, the mixing of N_2, O_2, and CH_4 can increase the difficulty of miscibility, while the mixing of H_2S, SO_2, and intermediate hydrocarbons (C_2-C_6) are beneficial for the miscibility. For near-miscible flooding, the whole process is the dual function of combined condensing/vaporizing mechanism. Taken the oil samples from the well depth of 3308-3330 m of the well 29-2E-5 as an example, the feasibility of adding a certain amount of intermediate components (C_2-C_6) in the injection gas to lower the pressure interval of near-miscibility was studied. This will definitely be helpful for implementing and enlarging the potential of near-miscible flooding in QHD offshore oilfield.

Firstly, for a certain CO_2 content, different contents of intermediate hydrocarbons (C_2-C_6) were added to three groups of gas samples (55%, 40%, and 24% CO_2) to test the effect on the lower and upper boundaries of pressure interval. Obviously, the adding of 5 mol% (C_2-C_6) greatly reduce the MMP and MNMP of the targeted oil samples, the reducing ranges are 8% and 11%, respectively. As is shown in Fig.5, the corresponding CO_2 content for the pressure range of near-miscible flooding expands to (34.5%-76.6%). The lower limit of CO_2 content decreased by nearly 30%, which effectively enlarge the CO_2 content limit for implementing near-miscible flooding. Two of the three gas samples can achieve near-miscible flooding due to the adding of 5 mol% intermediate hydrocarbons. It should also be noted that with the adding of light components, the appropriate range of CO_2 contents for implementing near-miscible flooding also expands, nearly 1/3 for the targeted well depth.

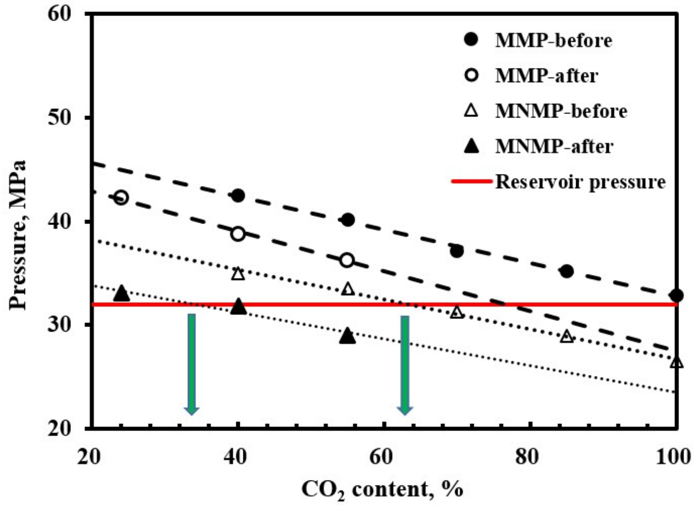

Fig.5 the effect of 5% (C_2-C_6) on MNMP

It is well known that the adding of intermediate components can effectively reduce the MNMP and MMP, and enlarge the range of near-miscible flooding. However, the amount of light components needed to add for achieving near-miscible flooding for different CO_2 contents was still unclear. Thus, different contents (1%, 3%, 5%, 8%, 10%, and 15%) of intermediate components were added to the injection gases with the CO_2 contents of 55%, 48%, 40%, 32% and 24%. The relationship of the amount of (C_2-C_6) needed for each CO_2 content are obtained, as is shown in Fig.6. It can be concluded that for each 10% contaminants content increase in the well depth of 3308-3330 m in well 29-2E-5, about 2.6% intermediate hydrocarbons (C_2-C_6) is needed to keep near-miscible flooding.

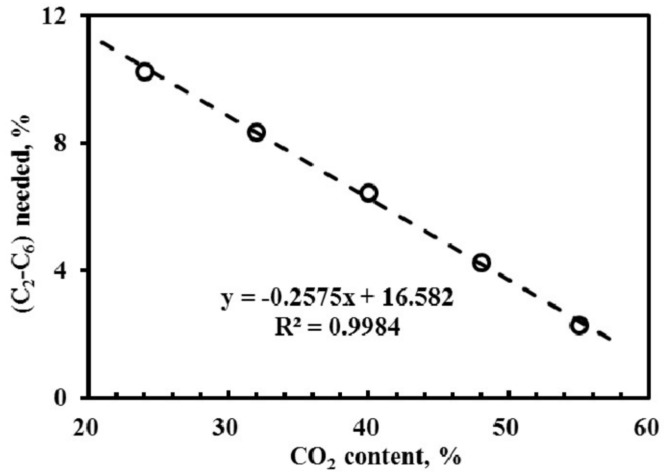

Fig.6 CO_2 content VS intermediate components (C_2-C_6) needed to achieve near-miscible flooding

From Fig.6, it can be concluded that for the CO_2 content of 55%, 40%, and 24%, about 2.29%, 6.46% and 10.28% of the intermediate components (C_2-C_6) are needed for achieving near-miscible flooding in the well QHD 29-2E-5 with the depth of 3308-3330 m, as is shown in Table 5.

Table 5 The amount of (C_2-C_6) needed for different CO_2 contents

CO_2, mol%	55	48	40	32	24
(C_2-C_6) needed, mol %	2.29	4.26	6.46	8.38	10.28

4. Conclusions

(1) Based on the data obtained from slim tube test and slim tube simulation with denser test points, pressure regions of near-miscible flooding with different CO_2 content were determined for the well depths of 3308-3330 m of the well 29-2E-5.

(2) For the reservoir conditions, the lower limit of CO_2 content for achieving near-miscible flooding in well depth of 3308-3330 m of the well 29-2E-5 is 64%.

(3) The mixing of the contaminants (mainly methane) can greatly enhance the difficulty to achieve miscibility. For the targeted layer of the well 29-2E-5, for each 10% increase of contaminant contents, MNMP and MMP increase 1.4 MPa and 1.6 MPa, respectively.

(4) By adding 5 mol% light components of (C_2-C_6), the lower limit of CO_2 content for achieving near-miscible flooding can be decreased effectively. The corresponding CO_2 content range for near-miscible flooding can be decreased to (34.5-76.6%) with 1/3 interval enlarge.

(5) The (C_2-C_6) contents needed for achieving near-miscible flooding in the upper layer of the well QHD 29-2E-5 under different CO_2 contents was obtained. For each 10% decrease of CO_2 content, 2.6% of the intermediate components is needed.

Acknowledgments

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