Research on CO_2 EOR Technology and Application in China

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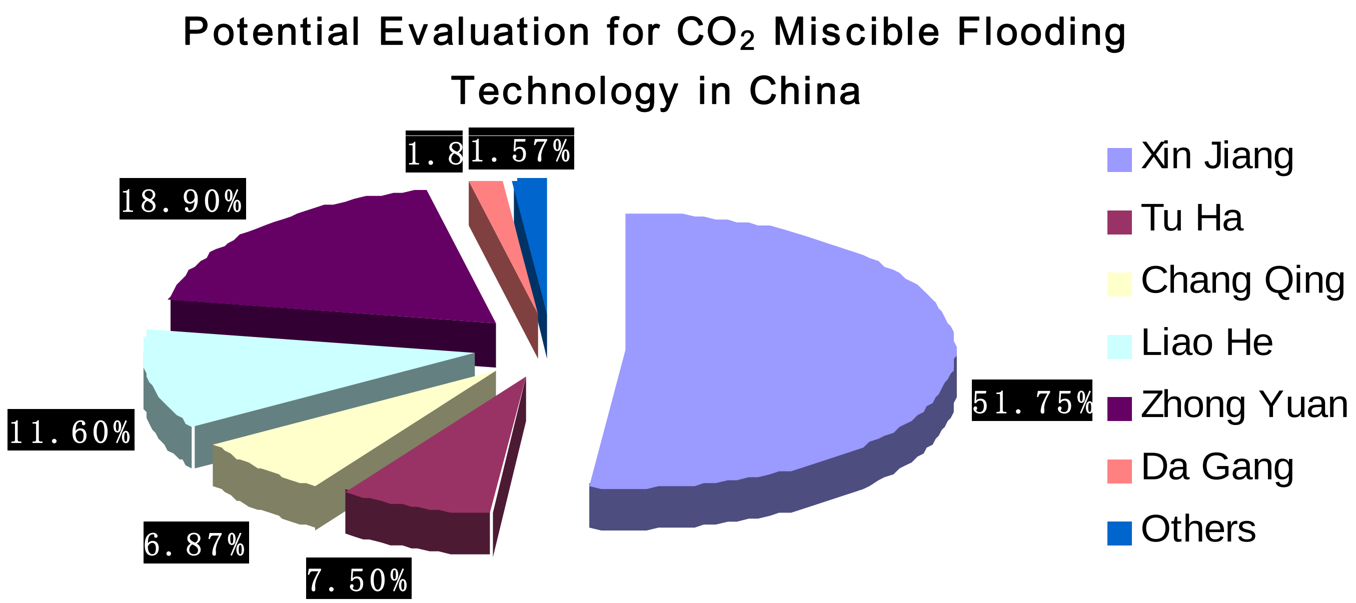
OUTLINE

- General Introduction of Domestic CO_2 EOR Practice

- Issues in Laboratory Research and Solutions

- Issues in Field Implementation and Solutions

Domestic Technical Potential Distribution For CO_2 Miscible Flooding （2000）



General Introduction of Domestic CO_2 EOR Practice

In 1963, firstly as main EOR technique, research on CO_2 EOR has been taken in DaQing oilfield. Then pilot projects have been put forward since 1966, 1969, 1985, 1991 and 1994.

In Jilin oilfield, with liquid CO_2 in Wanjinta CO_2 gas field , CO_2 huff & puff and foam fracturing have been operated in more than 100 wells.

In 1996, CO_2 huff & puff pilot projects in 48 wells were carried out in Fumin oilfield in Jiangsu Province.

General Introduction of Domestic CO_2 EOR Practice

In 2000, CO_2 huff & puff pilot projects in 16 wells were successfully fulfilled in Dongxin area of Shengli oilfield.

In 2002, CO_2 huff & puff were fulfilled after steam stimulation cycle in lots of blocks of Liaohe oilfield.

In 2007, CO_2 huff & puff were carried out in Deep heavy oil reservoir of Tuha oilfield and shallow heavy oil reservoir of Santanghu Basin.

General Introduction of Domestic CO_2 EOR Practice

Case I

Maintaining minimum miscibility pressure, in Fu 14 blocks of Jiangsu Province, CO_2-water alternating (WAG) injection project began in late 1998. After 6-cycle, water and gas ratio rise from 0.86:1 up to 2:1 and oil production were increased significantly. After water flooding, new oil-rich zone came into being.

Effect of increasing oil production in main producing wells of pilot area

井 号	试验前		见效初期			峰 值		累积增产油量 (t)
	产油量 (m^3/d)	含水率 (%)	见效时间 (年.月.日)	产油量 (m^3/d)	含水率 (%)	产油量 (m^3/d)	含水率 (%)	
富 61	0.1	99.6	1999.2.28	1.7	91.7	13	52	2169.9
富 111	0.7	95	1999.7.27	2.8	82.4	11.4	60	1036.4
富 66A	1.1	90	2000.6.22	6.8	89.8	8.3	87	892.2
富 29	0	100	2000.6.10	2.9	87.2	6.4	75.7	288.4
富 70	0	100	2000.9.09	1.0	97.8	4.4	89.7	334.3

General Introduction of Domestic CO_2 EOR Practice

Case II

Since March 2000, CO_2 huff & puff pilot projects have been carried out in selected 16 wells of different blocks and strata of Dongxin area with 70％ successful operating rate and 1.6755×10^4t of cumulative increasing oil production.

东辛采油厂 CO_2 吞吐工艺效果统计表(2001.11)

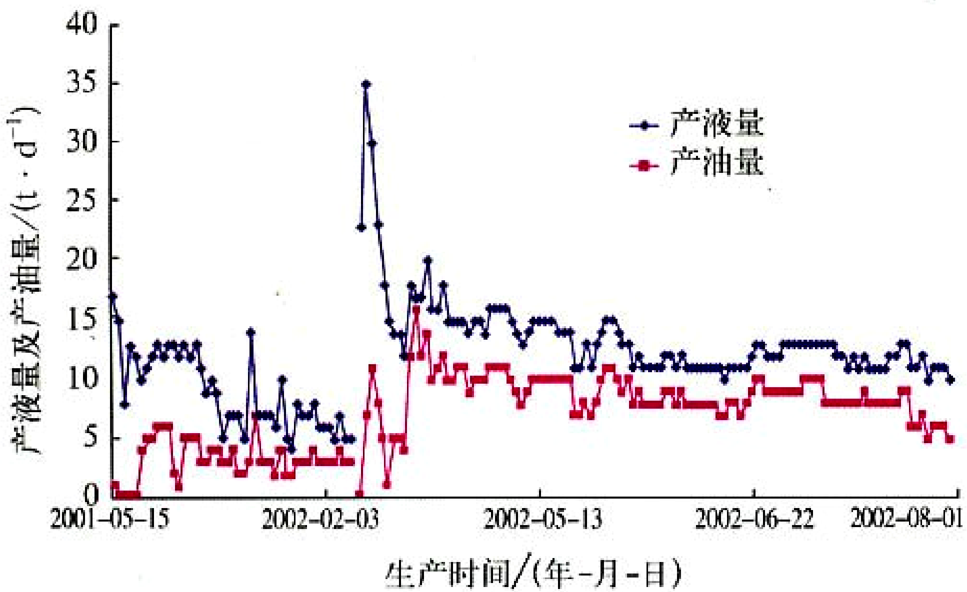
序号	井号	生产层位	注入 CO_2 总量 /t	累计增油 /t	增加采出程度 / %	换油率 t/ tco_2	分类
1	辛 50 - 斜 59	S_2^6	200	4762	40.79	23.81	I
2	辛 139 - 1	S_3 中^1	50	3504.4	8.66	70.09	I
3	辛 17 - 22	S_2^4	150	2835.7	3.66	18.9	I
4	营 13 - 斜 113	S_2^4	50	1597.4	1.03	31.95	I
5	辛 48 - 斜 25	$S_2 2^{4-5}$	60	906.4	1.21	15.11	II
6	辛 37 - 斜 40	S_2 稳	35	876.5	1.77	25.04	II
7	辛 34 - 45	S_2^9	80	445.1	1.23	5.56	II
8	辛 47 - 斜 54	S_2^{2-4}	80	429.7		5.37	II
9	辛 25 - 斜 14	S_2^{2-4}	50	368.3		7.34	III
10	辛 50 - 斜 43	S_2^6	50	213.1		4.26	III
11	辛 6 - 斜 30	S_2^{8-9}	80	173.8		2.17	III
12	辛 69 - 斜 7	S_2^1	70	148		2.11	III
13	辛 6 - 斜 47	S_1^4	15	115.5		7.7	III
14	营斜 591	S_2 稳 - S_3	60	22.2		0.37	III
15	营 87 - 50	S_2^4	50	12		0.24	III
16	营 2 - 斜 25	S_3	100	3.6		0.036	III
合计			1180	16375.9		13.88	

General Introduction of Domestic CO_2 EOR Practice

Case III

Jin 45-25-193 Well was put into operation in March 1998 and in 2002 six cycles were finished. Before CO_2 huff & puff, daily oil production was 2t/d and steam stimulation has attained to the economic limit.

In April 2002, after six cycles of steam stimulation, **CO_2 huff & puff was carried out with 16t/d of initial daily oil production**.



OUTLINE

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In China, most of oil reservoir is of continental deposit and non-marine origin of hydrocarbon. Domestic crude oil is of high viscosity, high content of wax and resin, high freezing point, the high minimum miscibility pressure (MMP) of CO_2-crude oil.

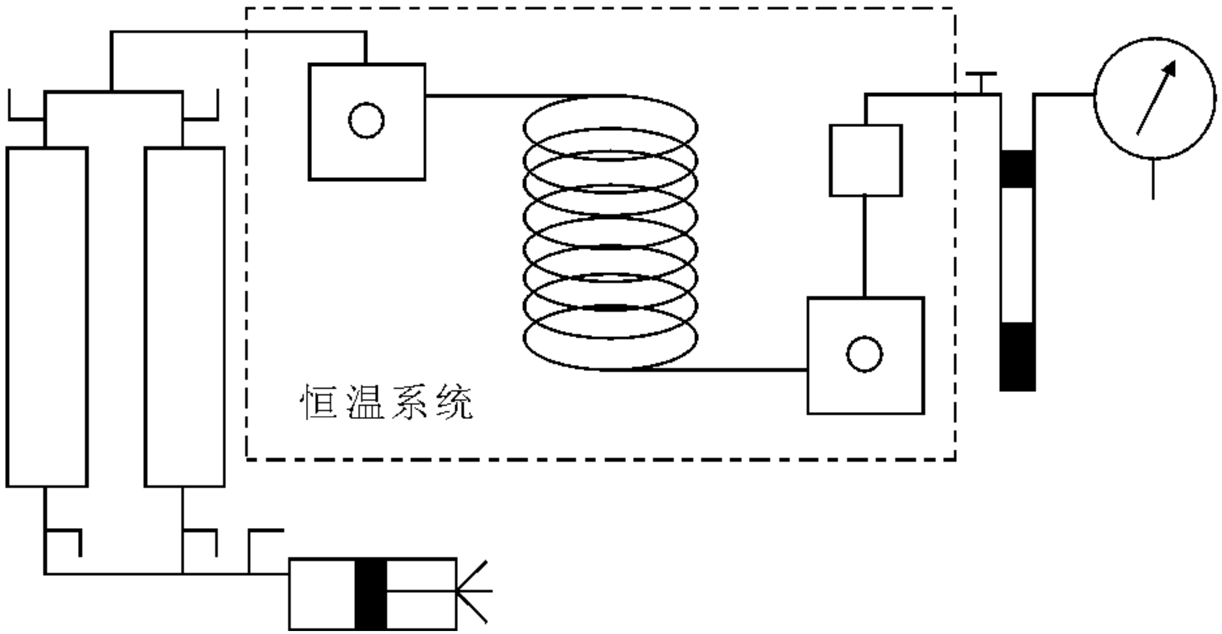
Solution I

Research on physical chemistry theory in CO_2 miscible recovery process：

- **Research on phase characteristics and influencing factors of CO_2-crude oil in CO_2 miscible recovery process.**
- **Searching for multi-component phase state characterization of CO_2 and complex hydrocarbons.**
- **Study on oil physical and chemical properties, pressure/temperature sensitivity, light component extraction and heavy components deposition in CO_2 miscible recovery process.**
- **Developing and establishing phase-state theory in equilibrium state process, in dynamic process and in porous media (micro scale) for improvement of CO_2 state equation suited to domestic crude oil.**

Slim Tube Experiment for CO_2-Crude oil

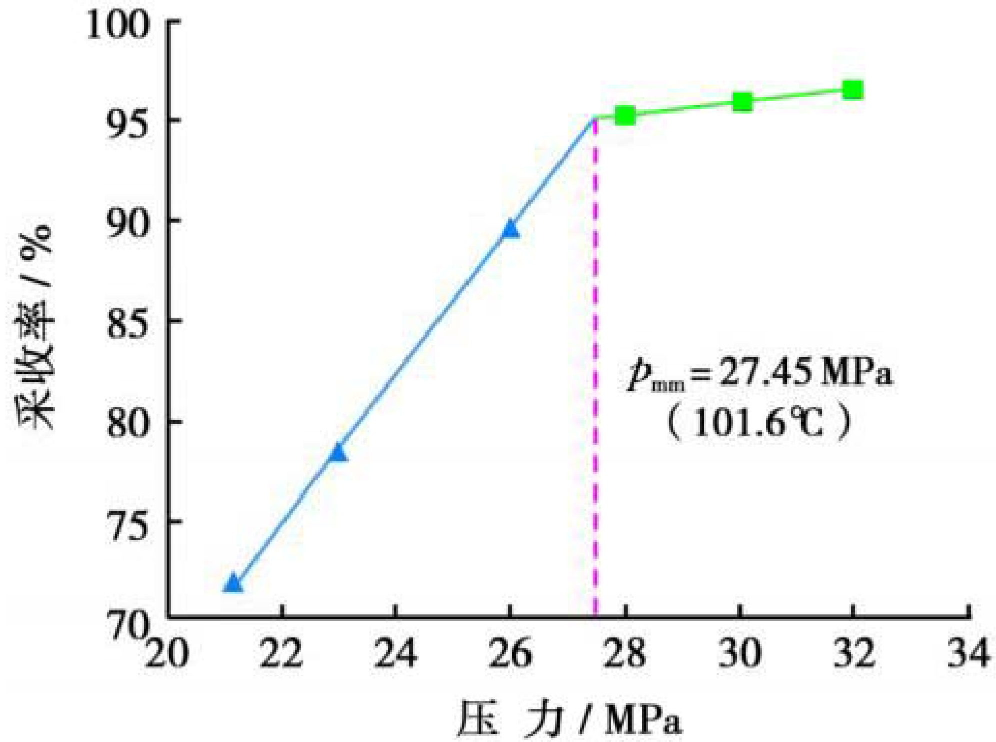
Slim tube device is an effective one-dimensional flowing experiment model simulating dynamic miscibility process of multi-contacts in CO_2 injection process and determining minimum miscibility pressure (MMP).



Slim Tube Experiment for CO_2-Crude oil

MMP acquired from slim tube experiment

Criteria for miscible flooding is 80% of oil recovery as gas breaks through or 90%~95% of ultimate recovery.



Ultimate oil recovery with different pressure

PVT Multi-Contact Tests for CO_2-Crude oil

Multi-contact tests could be divided into contacts as move forward and backward, respectively modeling crude oil phase state and composition of front and back edge in contact with CO_2.

Case：

T=101.6℃

P=21.2MPa(Reservoir pressure) , 30MPa(>MMP 27.45MPa)

Contacts forward: 4 times

Contacts backward: 6 times

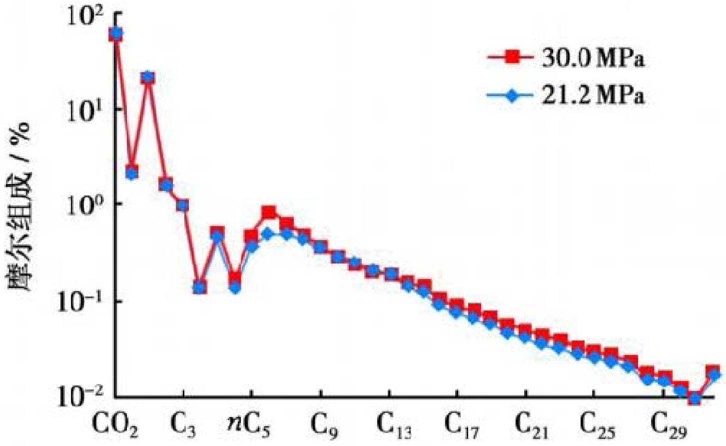
All in non-miscible and miscible process

Dynamic change of gas and liquid composition in multi-contact tests

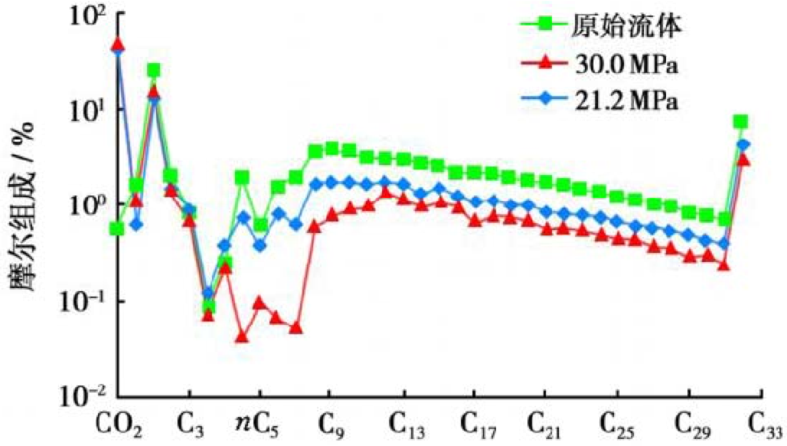
High extraction potent of CO_2-crude oil

CO_2 flooding can vaporize not only the light hydrocarbon less than C_{11}, but even the heavy hydrocarbon components such as C_{32}.

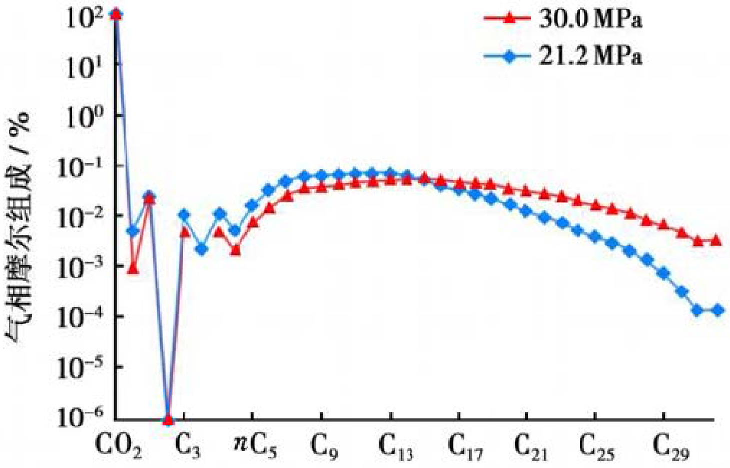
Pressure Effect on Phase Components of Multi-Contact tests



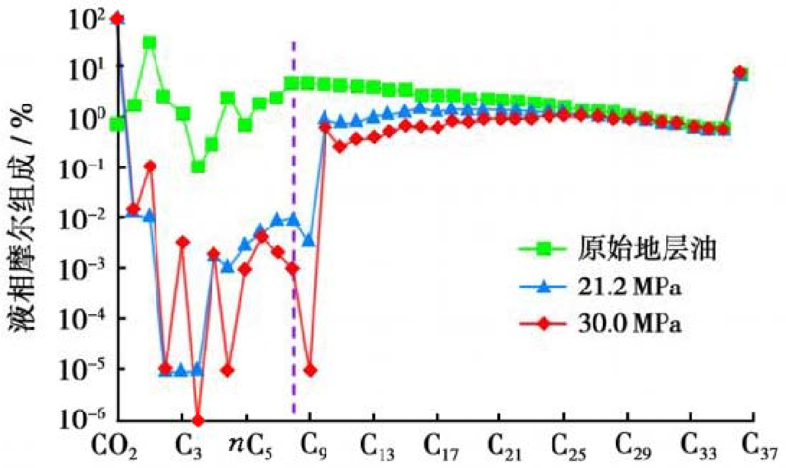
（a）压力对向前接触过程中气相组分的影响



（b）压力对向前接触过程中液相组分的影响



（c）压力对向后接触过程中气相组分的影响



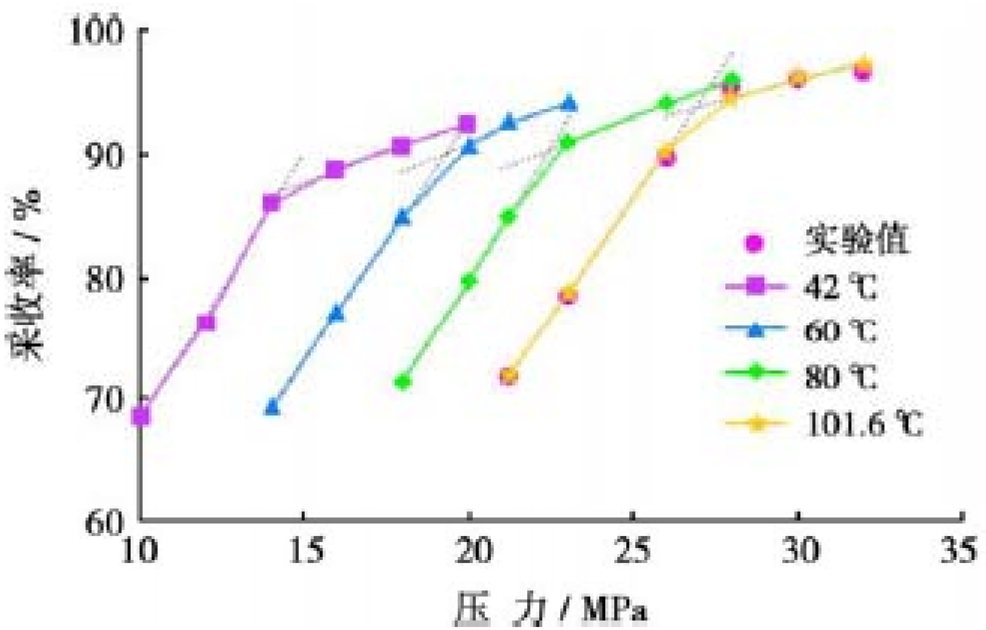
（d）压力对向后接触过程中液相组分的影响

Pressure Effect on Phase Components of Multi-Contact tests

Higher pressure is growing, greater CO_2 vaporization is, higher content of middle components is in gas phase and lower content of middle components is in liquid phase。

Temperature Effect on MMP

Temperature impacts on MMP greatly. Lower temperature is, lower MMP is.



Effect of contents of N_2 and CH_4 in CO_2 on MMP

With contents of CH_4 and N_2 increasing, MMP of CO_2-crude oil increases. On the same content of N_2 and CH_4, N_2 impacts on MMP more greatly than CH_4 does.

	MMP /MPa		
Content /%	10	20	30
N_2	35.8	41.2	46.3
CH_4	29.45	32.3	35.48

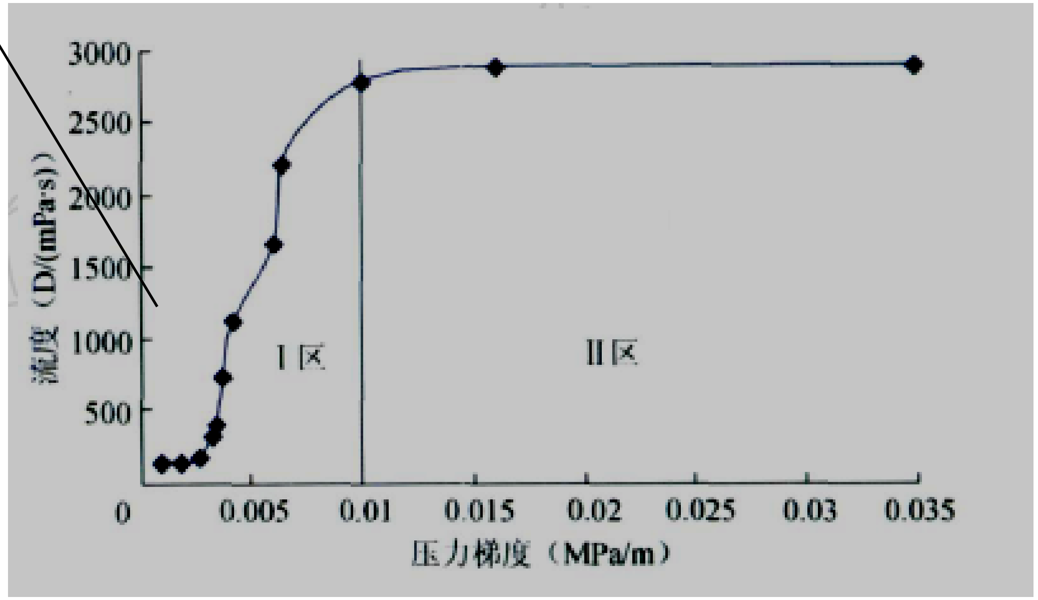
Heavy Hydrocarbon Components Deposition in CO_2 Miscible Flooding Process

For high content of wax and asphaltene in heavy oil reservoir, CO_2 stimulation process makes solid of wax and asphaltene deposite and formation damaged again. So it is necessary to study mechanism of solid phase precipitation to enhance oil recovery for CO_2 stimulation technique.

Setting Up Crude Oil Component Model Containing Asphaltenes in CO_2 Injection Process

In computation of the model, solution for non-newtonian fluid as following chart:

Asphaltene flocculates to be network structure, making crude oil flow slowly. With the pressure gradient increasing, network structure collapse, the other components of crude oil could be released gradually, flowing of crude oil shifts from non-Newtonian pattern to Newtonian pattern.



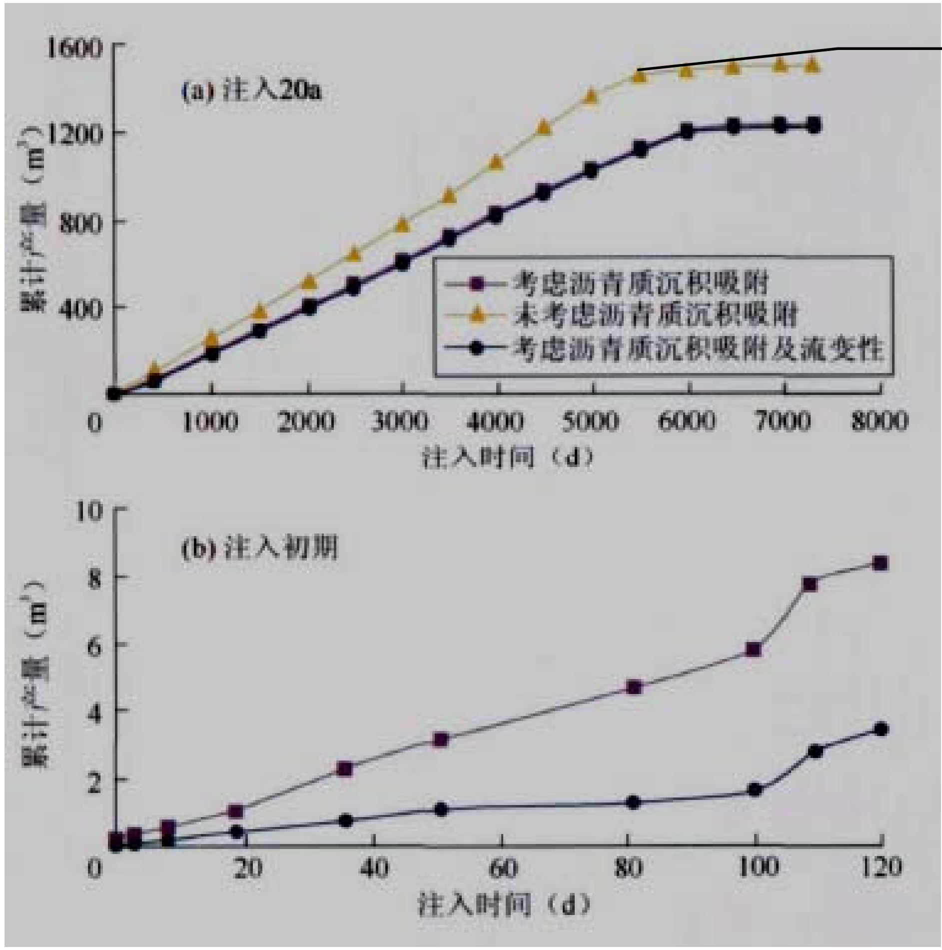
Relationship between pressure gradient and mobility as bituminous oil flowing in porous media.

Effect of Asphaltene Deposition on Oil Recovery in CO_2 Injection Process

Experiment results from CO_2 long model displacement test are compared with numerical model results.

Core No.	Core Length /cm	Differential Pressure /MPa	Recovery from Experiment /%	Recovery from New Numerical Model /%	Recovery from Classic Component Model /%
1	43.16	5	59.76	58.47	63.28
2	42.85	5	64.38	64.12	67.85
3	45.82	5	78.07	80.33	82.77
4	43.16	10	79.24	82.04	84.32

Effect of Asphaltene Deposition on Cumulative Production in CO_2 Injection Process



Not considering adsorption of asphaltene deposition, CO_2 breaks through in production wells much earlier than real case considering asphaltene deposition and cumulative oil production is more than the one considering asphaltene deposition .

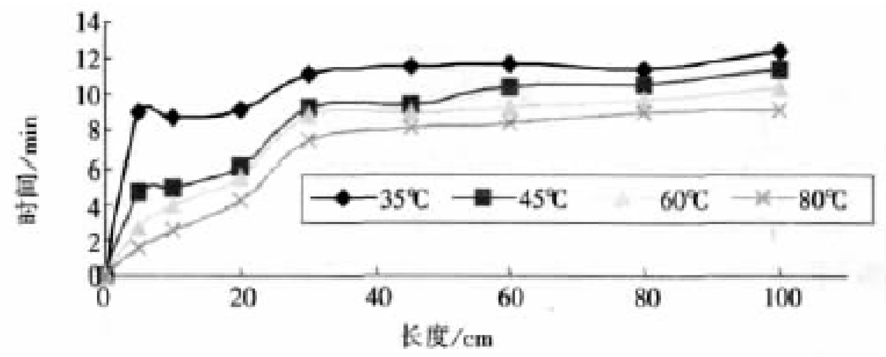
Solution II

Research on flowing mechanics in CO_2 flooding process:

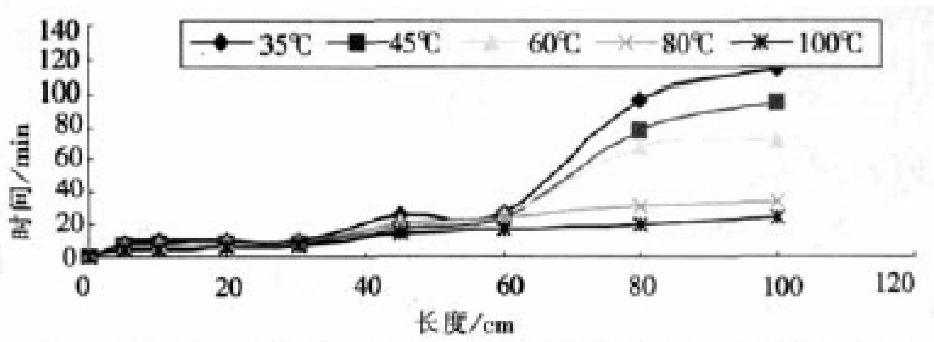
- Study on dispersion and diffusion theory in CO_2 Injection process
- Rheology of formation fluid in CO_2 injection process
- Research on complex flowing mechanism of CO_2, oil, brine and multi-phase mixture in heterogeneous reservoir with macro- and microscopic simulating experiment under HPHT
- Integrated phase-state experiments with physical simulating experiments, multi-phase multi-component non-linear numerical simulation theory and method should be developed

CO_2 Diffusion in Porous Media

CO_2 diffuse faster in porous media filled with brine under high-temperature than the one unfilled with brine. At 60cm ~ 80cm near the outlet, due to CO_2 breakthrough, pressure on outlet fluctuates, equilibrium time extends correspondingly.

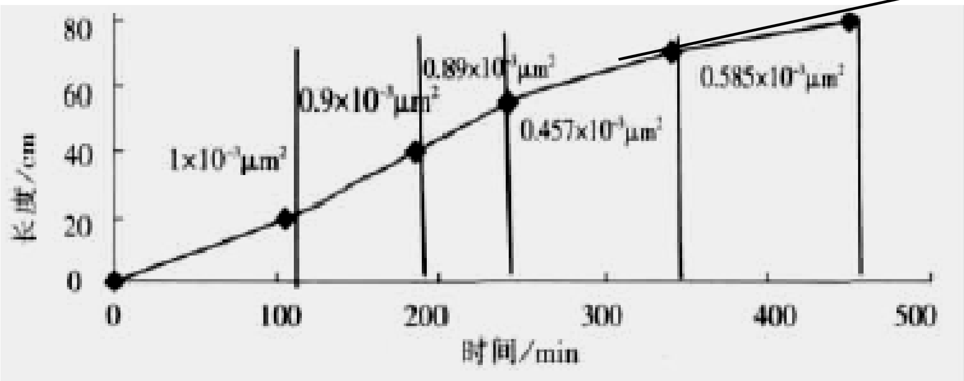


Relation between CO_2 diffusion equilibrium time and distance of core unfilled with brine



Relation between CO_2 diffusion equilibrium time and distance of core filled with brine

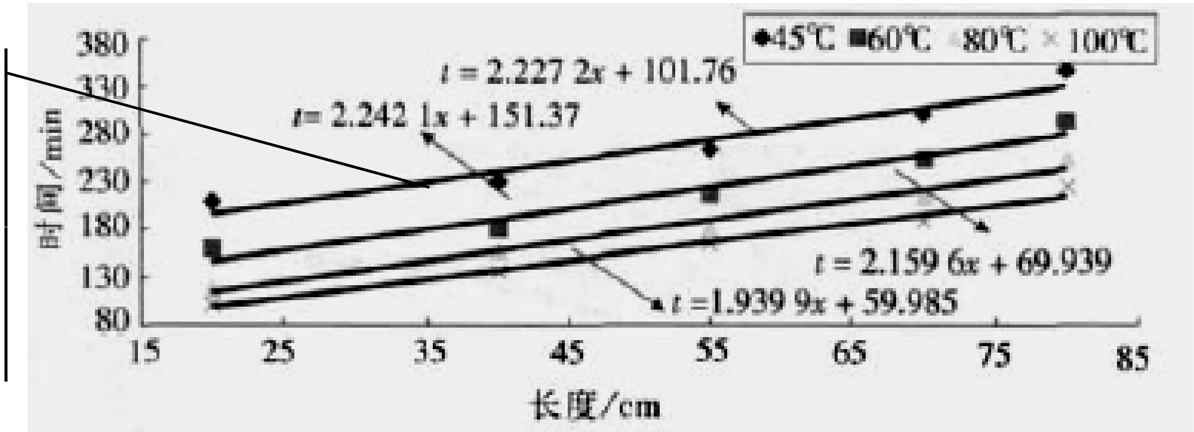
Effect of Permeability and Temperature on CO_2 Diffusion



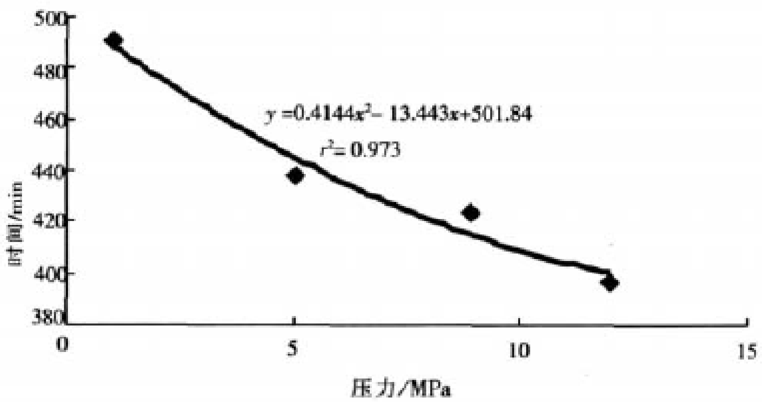
Effect of permeability on equilibrium time is greater than temperature does.

Capillary pressure increases as permeability is decreasing. The impact of much flowing resistance of CO_2 on equilibrium time is greater than temperature does.

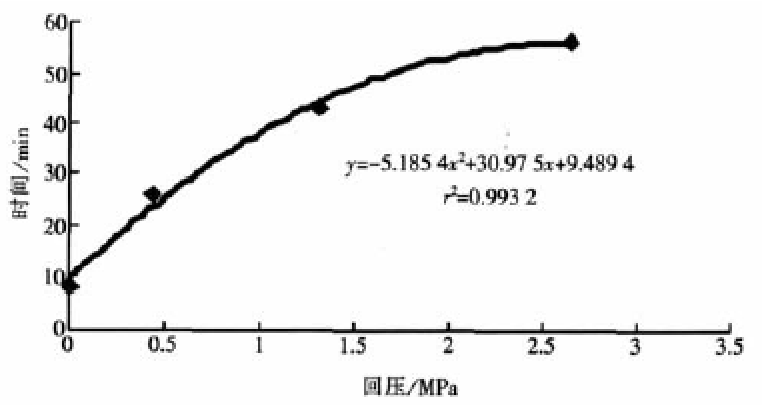
As temperature is increasing from 45℃ to 100℃, viscosity of brine decreases to 1/3 of original viscosity.



Effect of Inlet Pressure and Back Pressure on CO_2 Diffusion

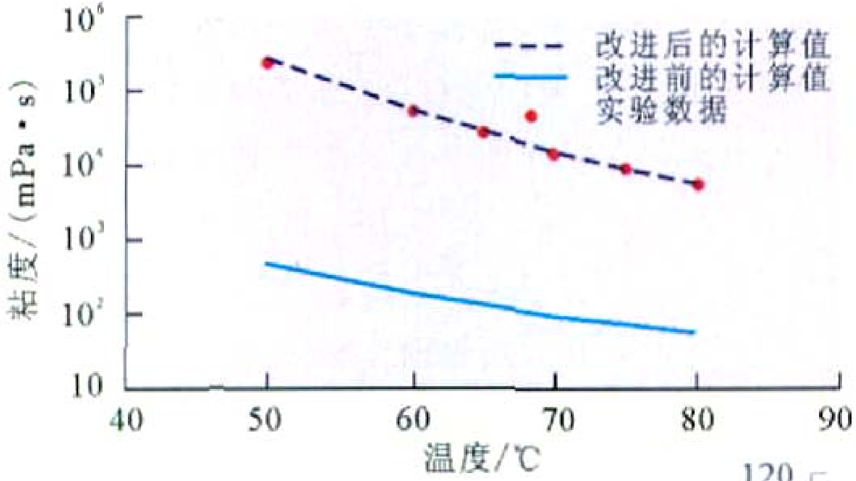


With **inlet pressure** increasing, diffusion equilibrium time starts to reduces rapidly, then reduces slowly by slowly.



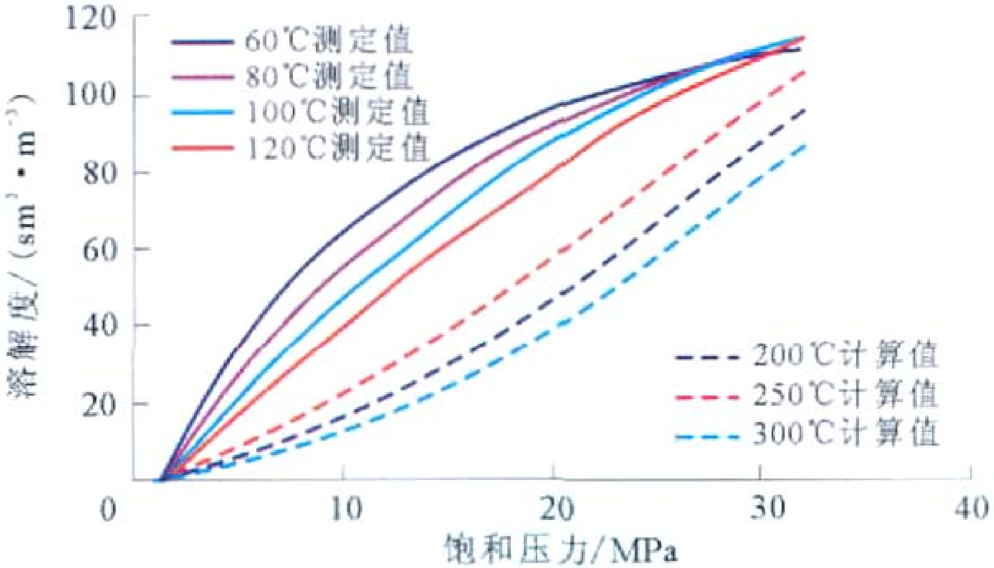
With **back pressure** increasing, CO_2 moving resistance increases correspondingly.

Effect of CO_2 on Reducing Viscosity of Extra-Heavy Oil



Viscosity-temperature curve of Zheng 411 extra-heavy oil

CO_2 solubility_ saturation pressure on different temperature



Effect of CO_2 on Reducing Viscosity of Extra-Heavy Oil

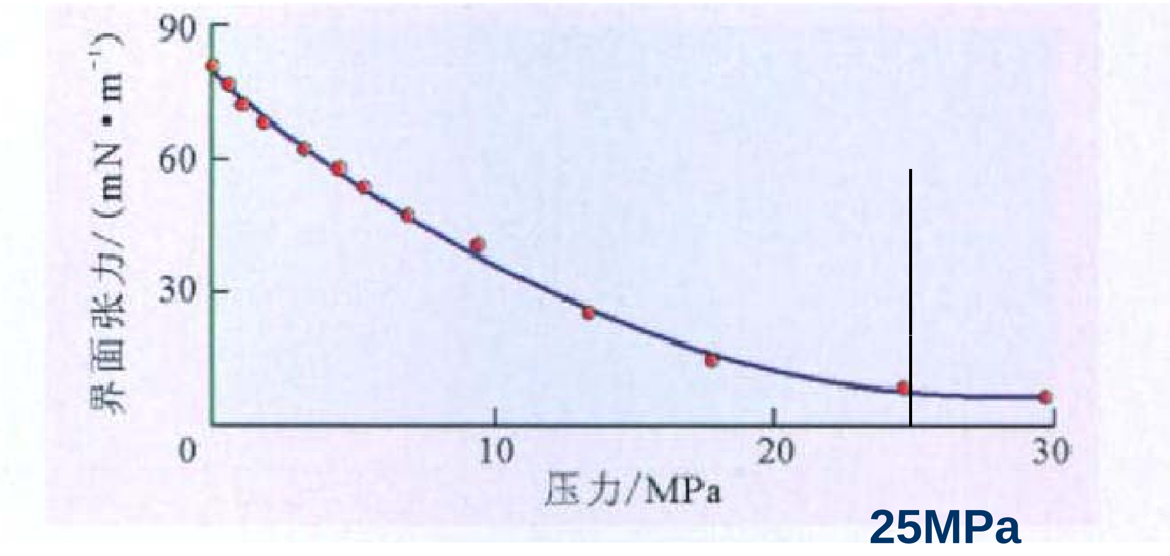
Volume factors of extra-heavy oil dissolved CO_2 on different solubility of CO_2 and temperature

CO_2的溶解度 /	体积系数 / ($m^3 \cdot m^{-3}$)			
($sm^3 \cdot m^{-3}$)	60 ℃	80 ℃	100 ℃	120 ℃
1	1.011	1.014	1.020	1.022
5	1.022	1.026	1.029	1.034
10	1.033	1.036	1.041	1.044
20	1.061	1.066	1.071	1.075
30	1.091	1.097	1.099	1.107
40	1.121	1.125	1.131	1.139
50	1.142	1.145	1.149	1.155
60	1.161	1.167	1.171	1.175
70	1.185	1.191	1.198	1.201
80	1.221	1.225	1.228	1.231
90	1.248	1.255	1.261	1.265
100	1.281	1.285	1.288	1.295
110	1.288	1.295	1.302	1.311

Viscosity of extra-heavy oil dissolved CO_2 on different solubility of CO_2 and temperature

CO_2的溶解度 /	粘度 / (mPa · s)			
($sm^3 \cdot m^{-3}$)	60 ℃	80 ℃	100 ℃	120 ℃
1	55 279	6 167	1 382	467
5	25 481	3 524	887	311
10	13 658	2 146	574	207
20	5 789	861	285	113
30	3 005	516	175	75
40	1 554	356	105	47
50	1 015	238	75	37
60	760	175	63	29
70	480	120	46	25
80	413	95	38	19
90	312	80	29	16
100	231	62	27	13
110	198	53	21	10

Effect of CO_2 on Reducing Viscosity of Extra-Heavy Oil



Interfacial tension of extra-heavy oil dissolved CO_2

Research on Complex Flowing Mechanism of CO_2, Oil, Brine and Multi-phase Mixture through Macroscopic Simulating Experiment

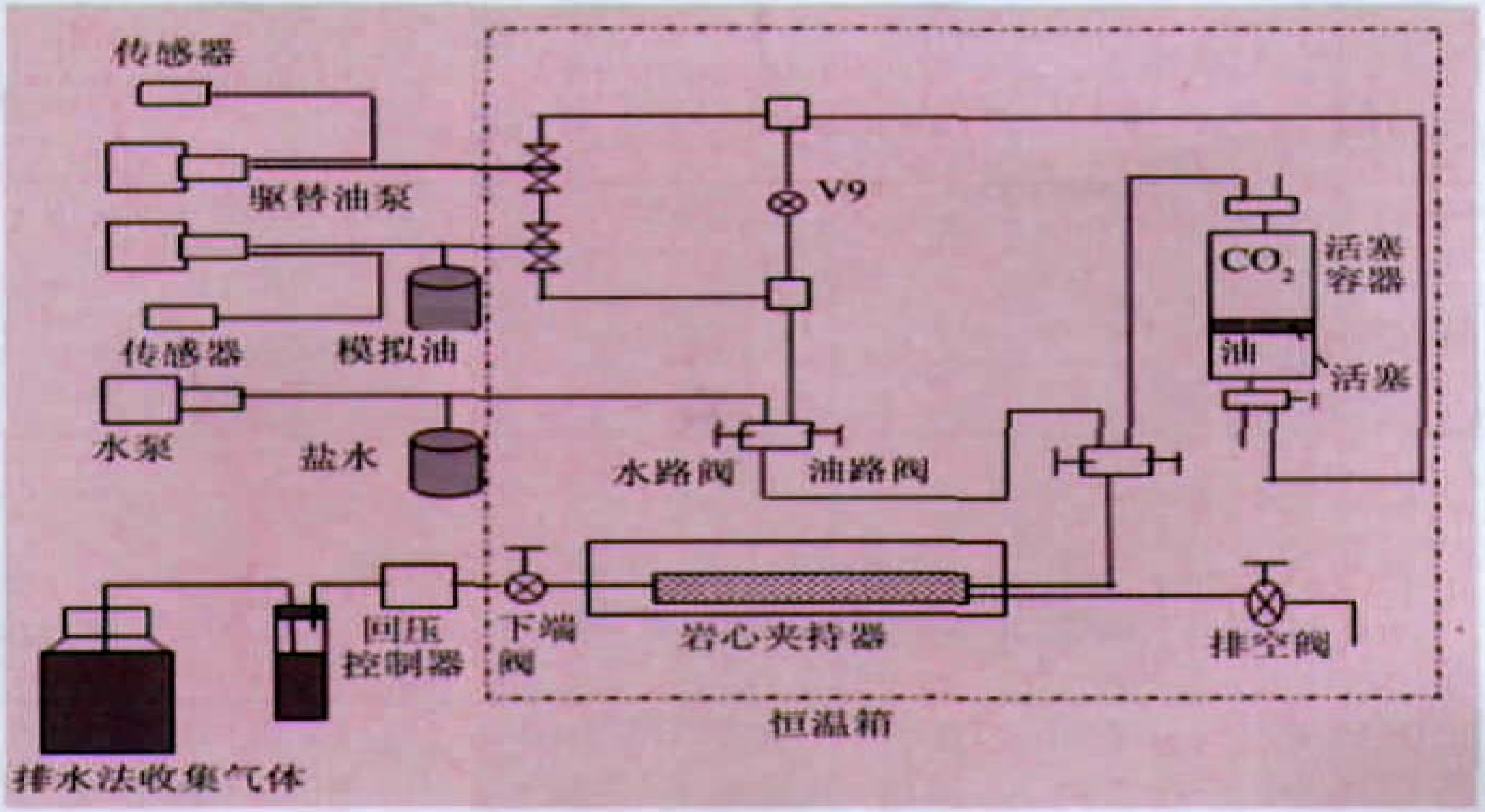
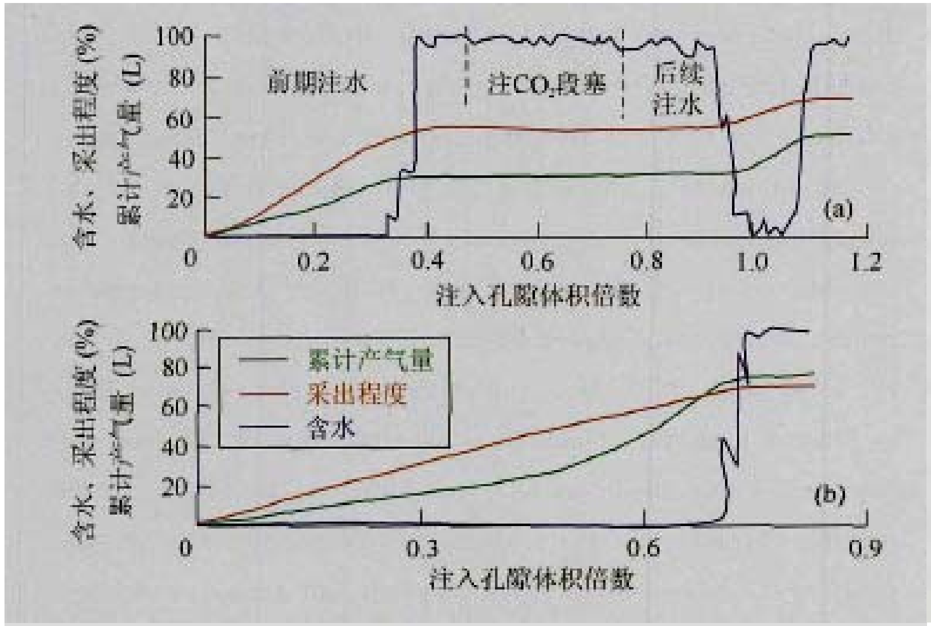
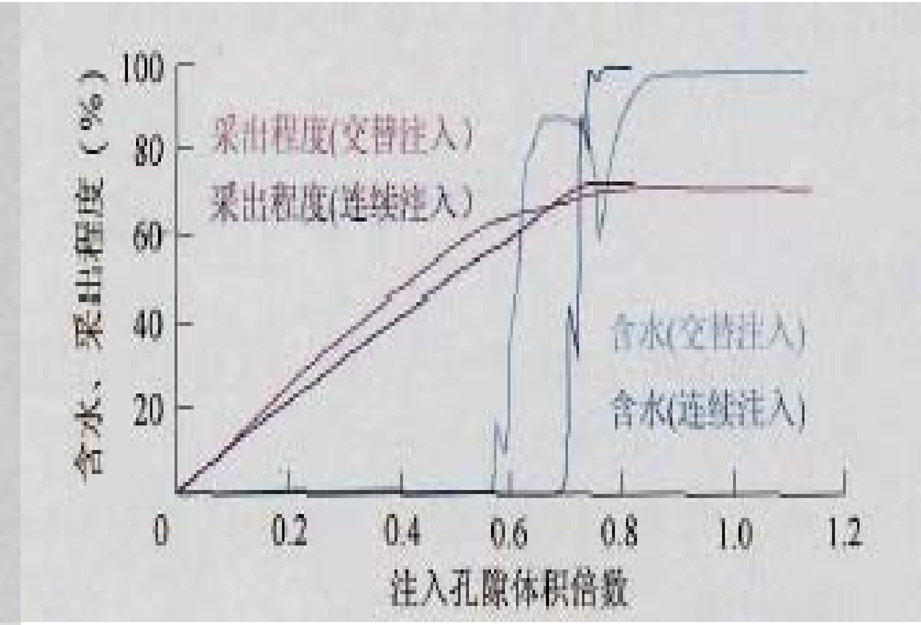


图 1 CO_2 驱替实验流程图

Fig. 1 Flowchart of CO_2 flooding test

Long-Core Physical Simulating Experiment Results



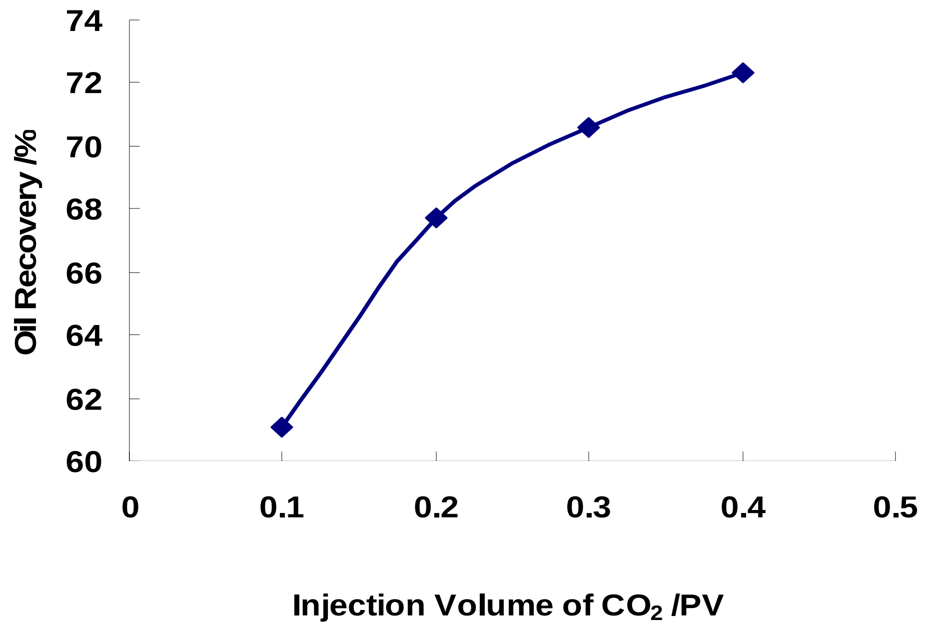


Enhanced oil recovery of CO_2 injection in water-free period is greater than the one in 99% of water cut.

Enhanced oil recovery of 0.3 PV CO_2 of WAG is greater than continuous injection (gas-water ratio is 1:1)

Long-Core Physical Simulating Experiment Results

Considering CO_2 channeling and leaking from injection equipment, CO_2 optimal injection volume is 0.25PV.



Long-Core Physical Simulating Experiment Results

Suggestion：

On CO_2 miscible flooding conditions, in the heterogeneous strata, water alternating CO_2 injection control gas channeling effectively. Optimization of the amount of CO_2 should be 0.25PV.

On CO_2 non-miscible flooding conditions, slug size of CO_2 and reservoir pressure are most key factors to impact on CO_2 flooding. Furthermore afflux of CO_2 is also important to the effect of CO_2 flooding. The Effect of alternating injection and gas-water ratio is minor than above factors.

CO_2 Flooding Experiment on Microscopic Model

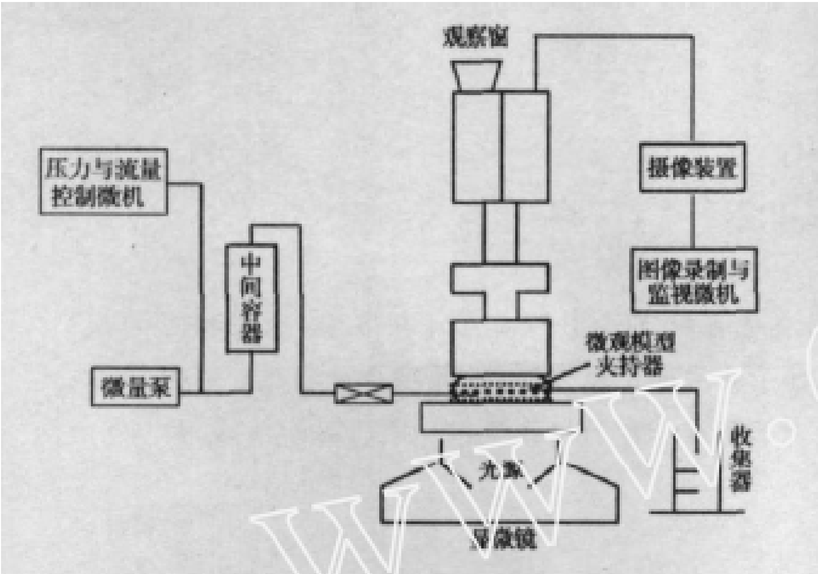


图 2　水驱

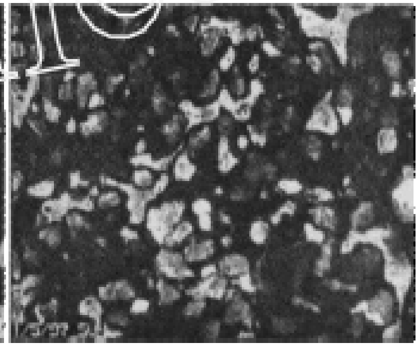


图 3　注入就地 CO_2 体系

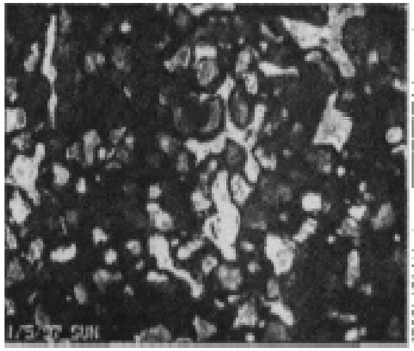
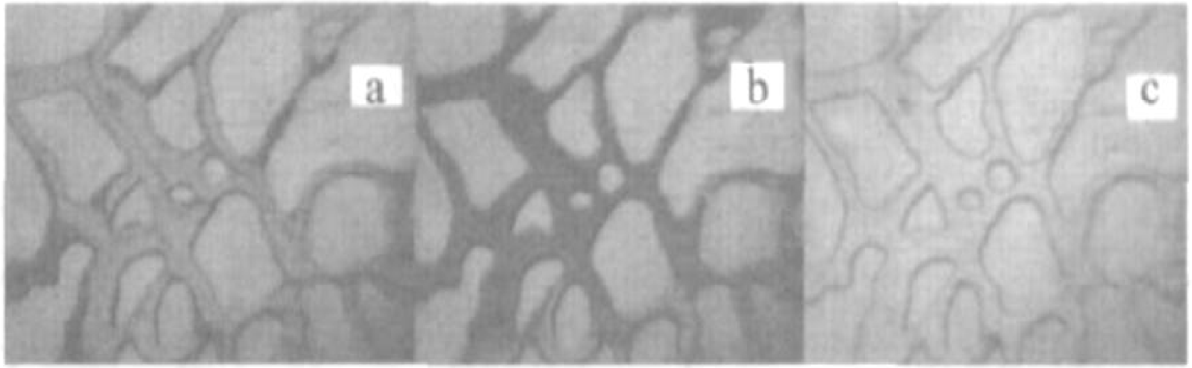


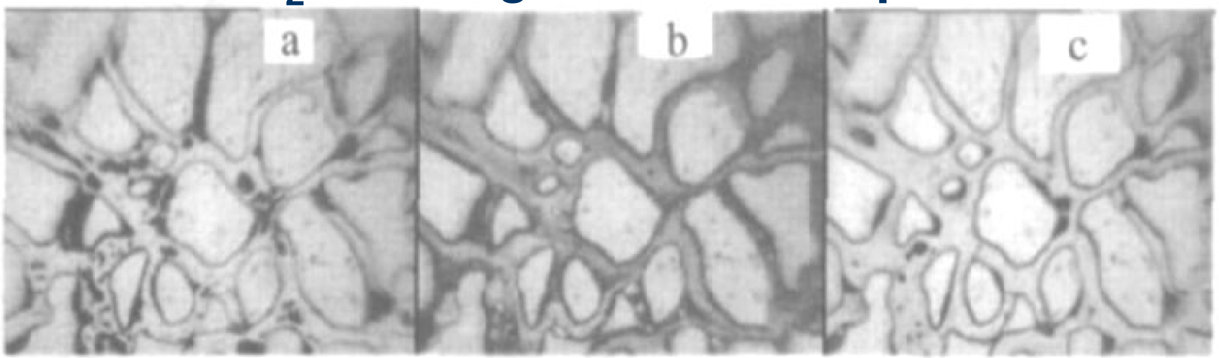
图 4　注入体系后 30 min

图 5　注入体系后 2 h

CO_2 Flooding Experiment on Microscopic Model



Microgram of enhanced oil recovery of CO_2 flooding in water-free period



Microgram of enhanced oil recovery of water-CO_2 alternating flooding

In heterogeneous strata, WAG increases sweep efficiency, postponing CO_2 breakthrough from outlet. But water could shelter oil flowing in pore-throat structure making displacement efficiency deteriorate.

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Issues of Field Implementation

- Applicability of Reservoir and Injection Pattern
- Premature Gas Channeling and Low Sweep Efficiency
- Corrosion
- CO_2 Source

Solution I

Set up CO_2 injection screening criteria suitable to characterization of domestic oil reservoir:

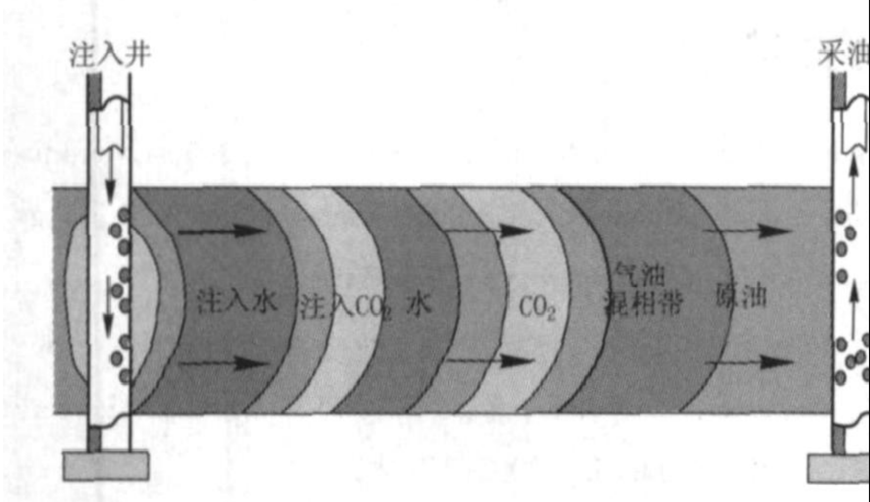
Displacement Type	Relative Density of Crude oil	Reservoir Depth /m	Oil Viscosity /mPa.s
CO_2 Miscible Flooding	<0.825	>762	<10
	0.825-0.865	>853	<10
	0.865-0.887	>1006	<10
	0.887-0.922	>1219	<10
CO_2 Non-Miscible Flooding	0.92-0.98	549	<600

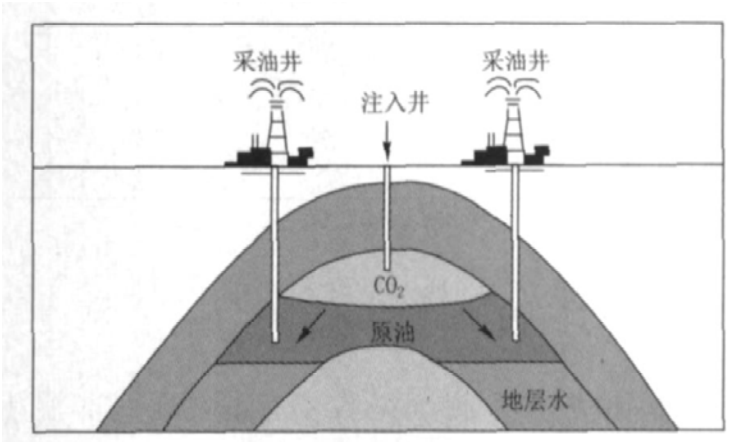
Solution I

Domestic oil reservoir suitable to miscible flooding:

- Low permeability reservoir with poor water flooding
- Completely depleted sandstone reservoir after water flooding
- Light hydrocarbon deep reservoir approaching production economic limits
- Exploitation of salt dome reservoir by CO_2 gravity miscible flooding

Solution I





Displacement Type	Miscible flooding	Non-miscible flooding
Duration /a	<20	10
Project commencement	Before water flooding or after water flooding	After water flooding
Flooding mechanism	complex	easy
CO_2 circulation	unusable	usable
Potential for EOR	low	high
Potential for geological storage	low	high
Worldwide application	Commercial scale	Limited scale

Solution I

WAG is still the most important on-site development means.

Comparative analysis on different CO_2 injection process

Injection Process	Advantage	Disadvantage	Impacting factors
Continuous injection	High displacement efficiency, low MMP	Large quantity of CO_2, earlier breakthrough, small sweep area	Injection rate, quantity of CO2, permeability and saturation of formation
WAG	High sweep efficiency, low CO_2 recovery	Water sheltering oil, oil bypassed and corrosion	Heterogeneous formation, wettability, relative parameter in WAG, permeability and fluid property etc.
CO_2 Huff and Puff	Low cost, high CO_2 utilization	Low oil recovery	Injection rate, cycle injection rate, shut-in time etc.
Drive by gravity	High oil recovery	Large quantity of CO_2, reservoir with large dip	Injection rate, formation dip
SSWG	Large sweep area	Gravity overriding and corrosion	Non-homogeneity, wettability

Solution II

Combined with other EOR methods, mobility ratio could be improved:

- ✓ Thickening agent
- ✓ Foam alternating CO_2 injection
- ✓ Surfactant alternating CO_2 injection

Intelligent completion technology:

With bottom-hole flowing control valve, recovery of CO_2 from production wells and afflux of CO_2 into injection wells could be controlled. Sweep efficiency is improved by reducing unnecessary circulation of CO_2 between pairs of wells.

Solution III

Corrosion theory

$$CO_2 + H_2O \rightarrow H_2CO_3$$

$$H_2CO_3 + OH^- \rightarrow HCO_3^- + H_2O$$

$$HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O$$

Anti-corrosion measure

- ✓ corrosion resisting metal material
- ✓ corrosion resisting coat
- ✓ corrosion resisting nonmetal material
- ✓ corrosion inhibitor treatment

Solution IV

Searching for CO_2 source and utilize industry exhaust gas:

Foreign Countries：CO_2 gas source and industry exhaust gas

China：CO_2 gas source is limited

Solution IV

CO_2 reservoir were discovered on east of China:

- CO_2 reservoir in Wanjinta of Songliao Basin
- Huanghua Depression Basin
- Jiyang Depression Basin
- Huangqiao CO_2 reservoir on the north of Jiangsu Province
- Sanshui Basin in Guangdong Province

Solution IV

Utilization of CO_2 venting in petrochemical industry:

Hydrogen technique：quantity of CO_2 venting is about 6.65×10^5t/a

Urea processing: quantity of CO_2 venting is about 10^5t/a

Concluding Remarks

CO_2 EOR technology has been paid more attention to in the world than before. Although there are some issues encountered on techniques, solutions have been put forward developing to CO_2 capture, storage and circulation for oil & gas development. Creating harmony of energy development and environment is inevitable trend for CO_2 EOR development.

Research on CO_2 EOR Technology and Application in China