Energy Proceedings
Vol 28, 2022
ISSN 2004-2965

Study on the Influence of Different Ratios of CO_2 and N_2 on Extra-Heavy Oil Reservoirs Developed by Multi-Thermal-Fluid Huff-Puff#

Zhihao Jia[1], Linsong Cheng[1], Baobiao Pu[1], Yongchao Xue[1]

1 China University of Petroleum (Beijing)

ABSTRACT

Flue gas assisted cyclic steam stimulation (CSS) has gradually gained prominence in the development of extra-heavy oil reservoirs. The flue gas produced by fuel combustion is primarily composed of CO_2, N_2, and steam, and it is injected directly into extra-heavy oil reservoirs to enhance oil recovery. This method is also known as multi-thermal-fluid (MTF) huff-puff technology, which is an important CCUS technology. In this paper, the effects of different CO_2 and N_2 ratios on the development of extra-heavy oil reservoirs are analyzed and discussed. To begin, the viscosity and components of crude oil are obtained through physical experiment. Second, the effects of different CO_2 and N_2 ratios on crude oil viscosity and phase state are analyzed using the phase equilibrium model and viscosity model. Finally, numerical simulation is used to optimize the CO_2 and N_2 ratios. The results show that the higher the CO_2 ratio, the lower the viscosity of the crude oil after MTF huff-puff. The phase diagram gradually narrows as CO_2 ratios rise while N_2 ratios fall. Because the primary function of CO_2 is to reduce viscosity and the primary function of N_2 is to improve formation energy, the optimal ratio of CO_2 and N_2 is 7:3.

Keywords: Extra-heavy oil reservoir, Multi-thermal-fluid huff-puff, Optimal ratios of CO_2 and N_2, PVT simulation, Numerical simulation.

NONMENCLATURE

Abbreviations	
MTF	Multi-thermal-fluid
CSS	Cyclic steam stimulation
SF	Steam flooding
SAGD	Steam assisted gravity drainage
ISC	In-situ combustion
Symbols	
a_m	Empirical coefficient
b_m	Empirical coefficient
K_i	Phase equilibrium constant
k_{ij}	Binary interaction coefficient
p	Pressure
T	Temperature
p_c	Critical pressure
T_c	Critical temperature
x_i	Liquid phase fraction
y_i	Gas phase fraction
Z	Deviation coefficient
ω_i	Acentric factor
μ	Viscosity

1. INTRODUCTION

Heavy oil represents approximately half of the world's oil and gas reserves. The development of heavy oil has piqued the interest of many people due to rising global oil consumption. Extra-heavy oil, in particular, has become the focus of attention in the world's oil fields, and its viscosity in formation is typically 10000mPa·s and 50000mPa·s. Cold production technology and hot production technology are the two primary types of heavy oil development technology. Because of the extra-heavy oil's high viscosity, only the thermal production method can effectively be used to develop extra-heavy oil reservoirs [1], [2], [3]. At present, thermal production methods mainly include cyclic steam stimulation (CSS), steam flooding (SF), steam assisted gravity drainage (SAGD), and in-situ combustion (ISC). CCS is the most important approach for developing extra-heavy oil reservoirs among them. The main principle of CCS is to exploit heavy oil by using the characteristics of the viscosity of heavy oil falling rapidly with temperature. In the manufacturing process, it has the advantages of being quick and flexible. However, the production of heavy oil will gradually decrease after numerous stimulation cycles due to the increased water cut and limited sweep area. The oil recovery rate of CCS technology is predicted to be between 10% and 20% [4], [5], [6].

Global climate change is intensifying as CO_2 levels rise, and the natural environment is deteriorating. CO_2 emissions were quite low from the Industrial Revolution

through the middle of the twentieth century. In 1950, the globe emitted 6 billion tons of carbon dioxide, which nearly doubled by 1990 to over 22 billion tons. CO_2 emissions are steadily increasing, with more than 34 billion tons of CO_2 emitted each year. To deal with the crisis and challenges of climate change, CO_2 emissions must be reduced and carbon utilization and storage must be realized [7], [8], [9]. A substantial volume of flue gas is created by steam generators in the process of heavy oil thermal production, which is inconsistent with the concept of sustainable development. Many researchers have discovered that the major components of flue gas produced by fuel burning are CO_2 and N_2, and that injecting these into the formation with steam can considerably improve oil recovery while also lowering carbon emissions, which is an essential CCUS technology. For the first time, flue gas assisted CSS technology was used on a wide scale in China's Bohai Bay Basin, and it was also dubbed multi-thermal-fluid (MTF) huff-puff technology [10], [11].

MTF technology can also improve the efficiency of CSS, allowing extra-heavy oil reservoirs to produce more oil. Solvents, CO_2, N_2, or flue gas co-injection as a thermal supplement are now used to improve the performance of CSS [12], [13], [14]. Flue gas-assisted-CSS is an effective approach to reduce heavy oil viscosity and swelling. Laboratory tests have shown that CO_2-assisted-CSS may reduce heavy oil viscosity by up to 80% compared to CSS [15], [16], [17]. Field applications and laboratory experiments have demonstrated that CO_2-assisted-CSS will increase more oil production than CSS [18], [19], [20], [21].

However, the comprehensive impacts of varied gas mixture ratios on the development of extra-heavy oil reservoirs are not evident due to the multiple components and complex mechanisms of MTF. As a result, it is crucial to investigate the impact of varying CO_2 and N_2 ratios in MTF on extra-heavy oil reserves. In this paper, we firstly used physical experiments to get the components and viscosity of extra-heavy oil sample, and then used the phase equilibrium model and viscosity model to analyze the impact of varying CO_2 and N_2 ratios on the viscosity and phase state of extra-heavy oil. Finally, numerical simulation is used to performed to investigate the impacts of CO_2 and N_2 in MTF, and the ratio of CO_2 and N_2 is optimized to 7:3.

2. EXTRA-HEAVY OIL SAMPLE VISCOSTY TEST

Crude oil data are obtained from the super heavy oil reservoir of M oilfield in Kazakhstan. The reservoir's initial depth, pressure, bubble point pressure, and temperature are 220m, 2.3MPa, 0.38MPa, and 287.4K(14.4°C), respectively. At reservoir conditions, crude oil density, viscosity, volume factor, and compressibility factor are 0.953g/cm3, 19500mPas, 1.0009, and $1.892\times10^{-5}MPa^{-1}$, respectively. The detailed composition of crude oil is analyzed by gas chromatograph, which is shown in **Table 1.**

Table 1 Composition of formation crude oil

Components	Molar volume content of surface degassed oil/ mol %	Molar volume content of formation oil/ mol %
CO_2	0.000	0.013
N_2	0.000	0.106
C_1	0.000	2.549
C_2	0.000	0.003
C_3	0.000	0.004
iC_4	0.000	0.002
nC_4	0.000	0.006
iC_5	0.000	0.003
nC_5	0.000	0.005
C_6	0.000	0.004
C_7	0.000	0.003
C_8	0.501	0.489
C_9	0.182	0.177
C_{10}	0.288	0.280
C_{11}	0.986	0.960
C_{12}	2.150	2.092
C_{13}	4.064	3.954
C_{14}	5.276	5.133
C_{15}	6.800	6.616
C_{16}	5.845	5.687
C_{17}	7.147	6.954
C_{18}	5.536	5.387
C_{19+}	61.224	59.571

The viscosity-temperature curve of crude oil samples is obtained by laboratory experiments, which is shown in Fig.1.

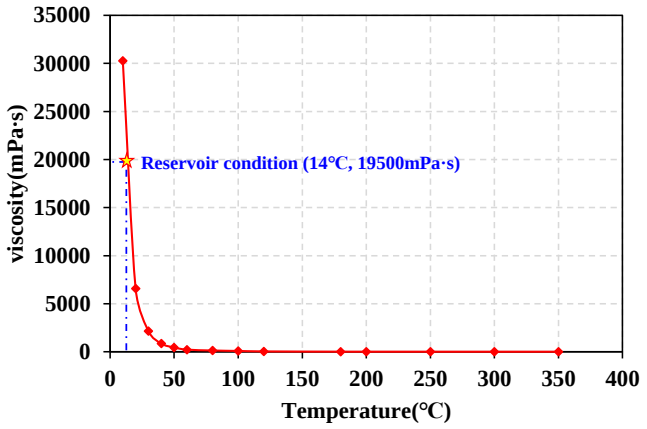

Fig.1 Viscosity-temperature curve of crude oil by physical experiment

3. PHYSICAL PROPERTIES CALCULATION OF EXTRA-HEAVY OIL BEFORE AND AFTER MTF HUFF AND PUFF USING PVT SIMULATION

3.1 Phase equilibrium calculation

Phase equilibrium calculation mainly includes dew-point phase, bubble point phase and isothermal flash phase equilibrium calculation [22]. It is usually calculated by numerical iteration. Because the influence of molecular density on molecular gravity is further considered in gravitational term, the PR(Peng-Robinson) equation is more reasonable in structure, and is also most commonly used in the phase state calculation of hydrocarbon systems in petroleum engineering.

Phase equilibrium calculation should first calculate the initial phase equilibrium constant K_i, Whitson's formula is as follows:

$$K_i = \frac{e^{\left[5.37(1+\omega_i)\left(1-\frac{1}{T_{ri}}\right)\right]}}{p_{ri}} \tag{1}$$

Where, T_{ri} is reduced temperature; P_{ri} is reduced pressure; ω_i is acentric factor.

The PR state equation for multi-component mixed system:

$$p = \frac{RT}{V-b_m} - \frac{a_m(T)}{V(V+b_m)+b_m(V-b_m)} \tag{2}$$

The coefficients a_m and b_m in the formula need to be calculated by van der Waals' mixed rule:

$$a_m(T) = \sum_{i=1}^{n}\sum_{j=1}^{n} X_i X_j \left(a_i a_j \alpha_i \alpha_j\right)^{0.5}\left(1-k_{ij}\right) \tag{3}$$

$$b_m = \sum_{i=1}^{n} x_i b_i \tag{4}$$

The deviation coefficient Z cubic equation corresponding to PR equation is as follows:

$$Z_m^3 - (1-B_m)Z_m^2 + \left(A_m - 2B_m - 3B_m^2\right)Z_m - \left(A_m B_m - B_m^2 - B_m^3\right) = 0 \tag{5}$$

$$A_m = \frac{a_m(T)\,p}{(RT)^2} \tag{6}$$

$$B_m = \frac{b_m p}{RT} \tag{7}$$

By substituting the PR equation (2) into the basic thermodynamic equation, the fugacity calculation formula of multi-component mixed system corresponding to the PR equation can be obtained as follows:

$$\ln\left(\frac{f_i}{x_i p}\right) = \frac{b_i}{b_m}(Z_m - 1) - \ln(Z_m - B_m) - \frac{A_m}{2\sqrt{2}B_m}\left(\frac{2\psi_j}{a_m} - \frac{b_i}{b_m}\right)\ln\left(\frac{Z_m + 2.414B_m}{Z_m - 2.414B_m}\right) \tag{8}$$

$$\psi_j = \sum_{j}^{n} x_j \left(a_i a_j \alpha_i \alpha_j\right)^{0.5}\left(1-k_{ij}\right) \tag{9}$$

According to the theory of fluid thermodynamic equilibrium equation, when the hydrocarbon-hydrocarbon system reaches gas-liquid equilibrium, the fugacity of each component in the gas and liquid phases are equal, so a new phase equilibrium constant can be calculated:

$$K_i = \frac{y_i}{x_i} = \frac{\frac{f_{il}}{x_i}}{\frac{f_{ig}}{y_i}} \tag{10}$$

Table 2 Thermodynamic properties of each component

Components	Molecular Weight, kg/kg·m	Specific Gravity	Critical temperature T_{ci}, K	Critical pressure P_{ci}, MPa	Acentric factor ω_i
CO_2	44.010	0.818	304.190	7.382	0.228
N_2	28.013	0.809	126.200	3.460	0.038
C_1	16.043	0.300	190.560	4.599	0.012
C_2	30.070	0.356	305.320	4.872	0.100
C_3	44.097	0.507	369.830	4.248	0.152
iC_4	58.123	0.563	407.800	3.640	0.184
nC_4	58.123	0.584	425.120	3.796	0.200
iC_5	72.150	0.625	460.400	3.380	0.228
nC_5	72.150	0.631	469.700	3.370	0.252
C_6	84.000	0.690	512.800	3.330	0.250
C_7	96.000	0.727	547.200	3.120	0.280
C_8	107.000	0.749	575.600	2.890	0.312
C_9	121.000	0.768	602.800	2.640	0.348
C_{10}	134.000	0.782	626.700	2.420	0.385
C_{11}	147.000	0.793	647.800	2.240	0.419
C_{12}	161.000	0.804	668.300	2.080	0.454
C_{13}	175.000	0.815	686.700	1.970	0.484
C_{14}	190.000	0.826	705.600	1.860	0.516
C_{15}	206.000	0.836	724.400	1.830	0.550
C_{16}	222.000	0.843	740.000	1.660	0.582
C_{17}	237.000	0.851	755.600	1.590	0.613
C_{18}	251.000	0.856	766.700	1.530	0.638
C_{19+}	475.000	1.100	1060.694	1.550	0.741

3.2 *Viscosity calculation*

At present, the LBC model and Pedersen model are the most widely used viscosity models in petroleum engineering. the LBC model relates the viscosity at high density with the viscosity at low density and the relative density of the system, and the equation is as follows [23], [24]:

$$\left[\left(\mu-\mu^{*}\right)\cdot\zeta+10^{-4}\right]^{\frac{1}{4}}=\sum_{i=1}^{5}a_i\cdot b_r^{i-1} \tag{11}$$

According to Pedersen's model, the viscosity ratio of two fluids with similar properties has a certain functional relationship with their critical temperature ratio, critical pressure ratio, molar mass ratio and coupling coefficient ratio, and the equation is as follows [23], [25]:

$$\mu(p,T)=\left(\frac{T_c}{T_{c0}}\right)^{-\frac{1}{6}}\left(\frac{p_c}{p_{c0}}\right)^{\frac{2}{3}}\left(\frac{M_w}{M_{wc0}}\right)^{\frac{1}{2}}\frac{\alpha_c}{\alpha_{c0}}\mu_0(p_0,T_0) \tag{12}$$

3.3 *Result and discussion*

1. Effects of different CO_2 and N_2 ratios on viscosity

As shown in **Fig.2**, comparing the crude oil viscosity test results with the viscosity calculated by LBC and the viscosity calculated by Pedersen, it can be found that for the viscosity calculation of extra-heavy oil, the LBC method has a large error in calculating the viscosity, and the Pedersen method is more reliable for the viscosity calculation of extra-heavy oil.

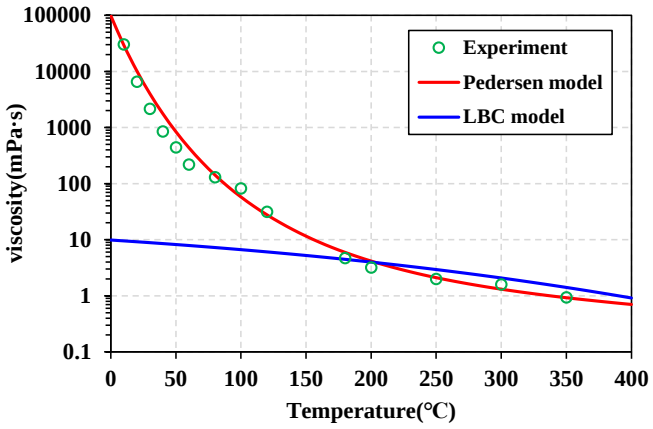

Fig.2 Comparison of the viscosity-temperature curves calculated by the Pedersen and LBC models with those from experimental tests

The ratios of CO_2 and N_2 1:9, 3:7, 5:5, 7:3 and 9:1 were designed respectively, and the viscosity-temperature curves of different gas mixture ratios were calculated by the Pedersen model, and the fitted gas mixture ratio-viscosity-temperature surfaces are shown in **Fig.3.** CO_2 is the main contributor to gas dissolution viscosity reduction, and the higher the content of CO_2, the lower the viscosity of the crude oil after injection. Once the CO_2 ratio exceeds 70%, continued increase of CO_2 has little effect on viscosity reduction of extra-heavy oil.

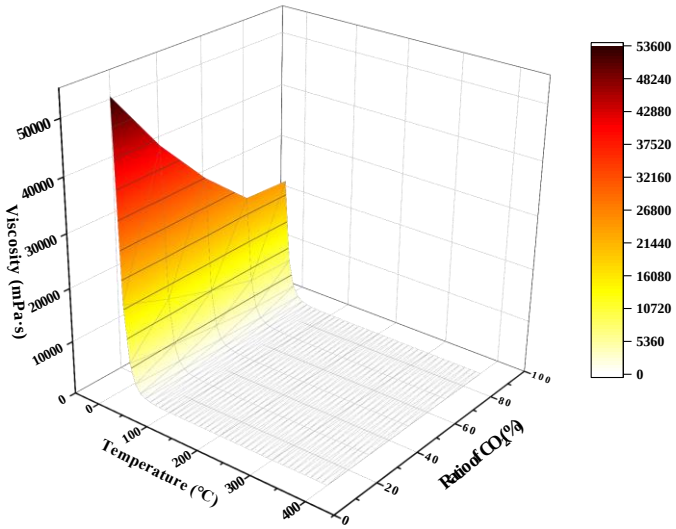

Fig.3 Viscosity-temperature surfaces at different CO_2 ratios

2. Effect of different CO_2 and N_2 ratios on the phase diagram

With the increase of CO_2 ratio and the decrease of N_2 ratio, the phase diagram becomes narrower gradually, and there are obvious changes for the crude oil components and properties after the multi-thermal-fluid throughput.

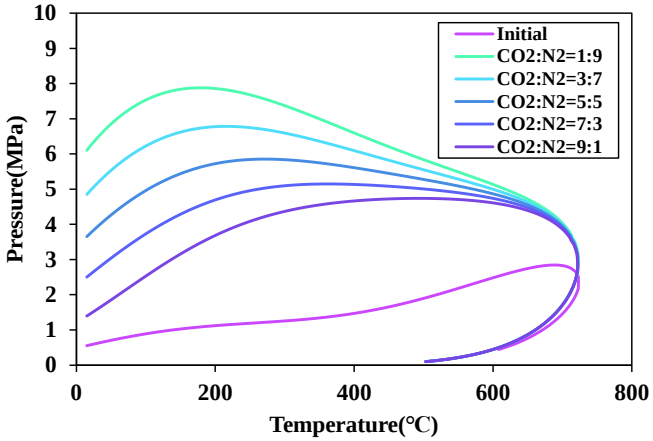

Fig.4 Comparison of the viscosity-temperature curves calculated by the Pedersen and LBC models with those from experimental tests

4. OPTIMIZATION OF RATIO OF CO_2 AND N_2 USING NUMERICAL SIMULATION

Since CO_2 and N_2 in the multi-thermal-fluid(MTF) not only have the effect of viscosity reduction, but also the effect of increasing the formation pressure, where the viscosity reduction is mainly contributed by CO_2, while the effect of replenishing the formation energy is mainly contributed by N_2. Therefore, in order to study the optimal ratio of CO_2 and N_2, a numerical simulation mechanism model was first established using the CMG-STARS module, as shown in **Fig. 5**. The grid system of the established base model is 50×50×15, with a grid step of 10m×10m×2m; the rock fluid and thermal physical parameters used in the base model are shown in **Table 3.**

Table 3 Geological and fluid parameters of reservoir

Parameter	Unit	Value
Temperature	℃	16.6
Pressure	MPa	2.6
Rock heat capacity	J/(m³·℃)	2.575×10^{6}
Rock thermal conductivity	J/(m·d·℃)	1.634×10^{5}
Water thermal conductivity	J/(m·d·℃)	5.35×10^{4}
Oil thermal conductivity	J/(m·d·℃)	9.62×10^{3}
Rock compressibility	MPa^{-1}	3.00×10^{-7}
Oil compressibility	MPa^{-1}	8.28×10^{-7}
Water compressibility	MPa^{-1}	5.25×10^{-7}
CO_2 phase equilibrium constant	/	479.17

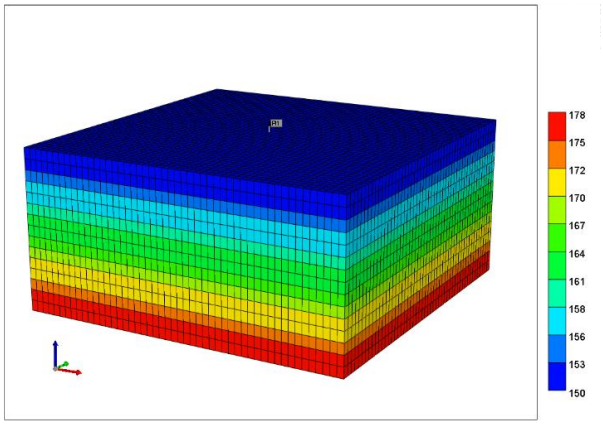

Fig. 5 3D diagram of numerical simulation model

The predicted results from the numerical simulation show that the maximum cumulative oil production is achieved when CO_2 and N_2 are 7:3 (i.e., when the CO_2 ratio is 70%). It indicates that the contribution of viscosity reduction and energy increase is the largest synergistically.

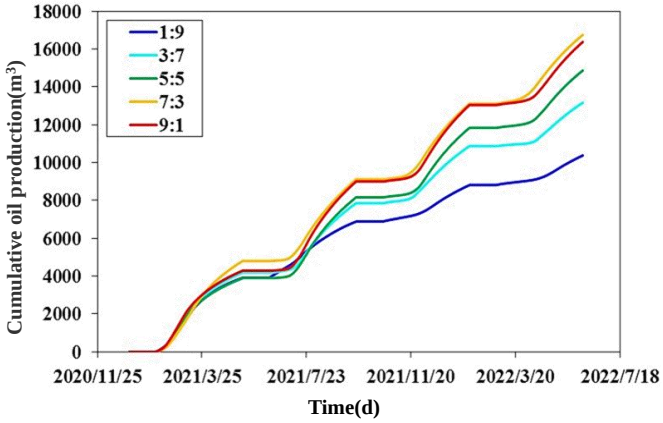

Fig. 6 Cumulative oil production curves under different CO_2 and N_2 ratios

5. CONCLUSION

In order to improve CCUS technology, the use of MTF huff-puff to develop heavy oil is gaining more and more attention. In this paper, the effects of different ratios of CO_2 and N_2 in MTF on extra-heavy oil are researched by PVT simulation and numerical simulation, and the conclusions are as follows:

(1) The Pedersen model is more accurate than the LBC model for calculating heavy oil viscosity, and the viscosity computed by the Pedersen model matches experimental data well.

(2) The higher the ratio of CO_2, the lower the viscosity of the crude oil after MTF huff-puff. With the increase of CO_2 and the decrease of N_2, the phase diagram becomes narrower gradually.

(3) The primary function of CO_2 is to reduce viscosity while the primary function of N_2 is to improve formation energy. The optimal ratio of CO_2 and N_2 is 7:3.

ACKNOWLEDGEMENT

The authors acknowledge that this study was partially funded by the National Natural Science Foundation of China (52174038) for financial support.

Zhihao Jia: Writing manuscript- original draft; Conceptualization. Methodology;

Linsong Cheng: Project administration; Supervision;

Baobiao Pu: Translation; Formal analysis;

Yongchao Xue: Validation;

REFERENCE

[1] Wang Z, Li S, Li Z. A novel strategy to reduce carbon emissions of heavy oil thermal recovery: condensation

heat transfer performance of flue gas-assisted steam flooding[J]. Applied Thermal Engineering, 2022: 118076.
DOI: 10.1016/j.applthermaleng.2022.118076
[2] Frauenfeld T, Lillico D, Jossy C, et al. Evaluation of partially miscible processes for Alberta heavy oil reservoirs. Journal of Canadian Petroleum Technology, 1998,37:17-25.
DOI: 10.2118/98-04-01
[3] Das, S. K . Vapex: An Efficient Process for the Recovery of Heavy Oil and Bitumen. SPE journal 1998;3:232-237.
DOI: 10.2118/50941-pa
[4] Wu X , Xu A , Fan H . An integrated evaluation on factors affecting the performance of superheated steam huff and puff in heavy oil reservoirs. Petroleum Exploration and Development 2010;37:608-613.
DOI: 10.1016/S1876-3804(10)60059-6
[5] Xu J N , Feng G Q , Ren X , et al. TECHNICAL COUNTERMEASURES FOR STABLE PRODUCTION BY STEAM HUFF AND PUFF IN SUPER-HEAVY CRUDE RESERVOIR. Journal of Southwest Petroleum University, 2007, 29(5):90-93.
DOI: 10.1016/S1872-5813(07)60034-6
[6] Murtaza M , He Z , Dehghanpour H . An approach to model three‐phase flow coupling during steam chamber rise. The Canadian Journal of Chemical Engineering 2014;92(6):1100-1112.
DOI: 10.1002/cjce.21944
[7] Li S , Wang Y , Zhang K , et al. Diffusion Behavior of Supercritical CO2 in Mirco- to Nanoconfined Pores. Industrial & Engineering Chemistry Research 2019.
DOI: 10.1021/acs.iecr.9b04750
[8] Li S , Wang Q , Li Z . Stability and Flow Properties of Oil-Based Foam Generated by CO2. SPE Journal 2019;25(1).
DOI: 10.2118/199339-PA
[9] Li S , Wang Q , Zhang K , et al. Monitoring of CO2 and CO2 oil-based foam flooding processes in fractured low-permeability cores using nuclear magnetic resonance (NMR). Fuel 2020;263:116648.1-116648.11.
DOI: 10.1016/j.fuel.2019.116648
[10] Dong X , Liu H , Zhang Z , et al. The flow and heat transfer characteristics of multi-thermal fluid in horizontal wellbore coupled with flow in heavy oil reservoirs[J]. Journal of Petroleum Science & Engineering, 2014, 122:56-68.
DOI: 10.1016/j.petrol.2014.05.015

[11] Huang S , Meng C , Cheng L . Experimental study on the mechanism of enhanced oil recovery by multi-thermal fluid in offshore heavy oil[J]. International Journal of Heat and Mass Transfer, 2018, 122(JUL.):1074-1084.
DOI: 10.1016/j.ijheatmasstransfer.2018.02.049
[12] Li J D , Saraireh M , Thorpe G . Condensation of vapor in the presence of non-condensable gas in condensers. International Journal of Heat & Mass Transfer 2011;54:4078-4089.
DOI: 10.1016/j.ijheatmasstransfer.2011.04.003
[13] Akhlaghinia M , Torabi F , Chan C W . Effect of Temperature on Two-Phase Relative Permeabilities of Heavy Oil, Water, Carbon Dioxide, and Methane Determined by Displacement Technique. Energy & Fuels 2013;27:1185-1193.
DOI: 10.1021/ef301248y
[14] Erpeng G , Yongrong G , Youwei J , et al. Super Critical CO2 and Steam Co-Injection Process for Deep Extra-Heavy Oil Reservoir[C]// Spe Eor Conference at Oil & Gas West Asia.
[15] Hornbrook M W , Dehghani K , Qadeer S , et al. Effects of CO2 Addition to Steam on Recovery of West Sak Crude Oil. SPE Reservoir Engineering 1991;6(3):278-286.
DOI: 10.2118/18753-PA
[16] Huang S , Xiao C , Hao L , et al. Experimental and numerical study of steam-chamber evolution during solvent-enhanced steam flooding in thin heavy-oil reservoirs - ScienceDirect. Journal of Petroleum Science and Engineering 2019;172:776-786.
DOI: 10.1016/j.petrol.2018.08.071
[17] Lawal, Akintayo K . Alternating Injection of Steam and CO2 For Thermal Recovery of Heavy Oil. Imperial College London, 2011.
[18] Leung, Louis C . Numerical Evaluation of the Effect of Simultaneous Steam and Carbon Dioxide Injection on the Recovery of Heavy Oil[J]. J. Pet. Technol.; (United States), 1983;35:10(09):1591-1599.
DOI: 10.2118/10776-PA
[19] Li B , Zhang Q , Li S , et al. Enhanced heavy oil recovery via surfactant-assisted CO2 huff-n-puff processes. Journal of Petroleum Science and Engineering, 2017:S0920410517307301.
DOI: 10.1016/j.petrol.2017.09.029
[20] Li S , Li Z , Sun X . Effect of flue gas and n-hexane on heavy oil properties in steam flooding process[J]. Fuel, 2017, 187:84-93.
DOI: 10.1016/j.fuel.2016.09.050
[21] Wan T , Wang X J , Jing Z , et al. Gas injection assisted steam huff-n-puff process for oil recovery from deep heavy oil reservoirs with low-permeability[J]. Journal of Petroleum Science and Engineering, 2019, 185:106613.
DOI: 10.1016/j.petrol.2019.106613
[22] Bharath R , Inomata H , Adschiri T , et al. Phase-Equilibrium Study for the Separation and Fractionation of Fatty Oil Components Using Supercritical Carbon-Dioxide[J]. science of the total environment, 1992, 408(23):5667-87.

DOI: 10.1016/j.scitotenv.2009.05.002
[23]Wu H . Adaptability of Equation of State and Viscosity Model to Bohai Crude Oil. 2021.
[24] Yang T , Fevang O , Christoffersen K R , et al. LBC Viscosity Modeling of Gas Condensate to Heavy Oil[C]// Spe Technical Conference & Exhibition.
[25] Adejuwon, Adeyemi. An extension of Pedersen's viscosity model for saturated black oil systems[J]. texas a & m university, 2000.