Open Access Library Journal
2023, Volume 10, e10665
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Research Status and Development Trend of Air-Foam EOR Technology

Hongmin Yu[1,2]

[1]SINOPEC Petroleum Exploration and Development Research Institute, Beijing, China
[2]Research and Development Center for The Sustainable Development of Continental Sandstone Mature Oilfield by National Energy Administration, Beijing, China
Email: yuhm.syky@sinopec.com

How to cite this paper: Yu, H.M. (2023) Research Status and Development Trend of Air-Foam EOR Technology. *Open Access Library Journal*, **10**: e10665.
https://doi.org/10.4236/oalib.1110665

Received: August 30, 2023
Accepted: December 26, 2023
Published: December 29, 2023

Abstract

In order to improve the development efficiency of low permeability and medium-high permeability medium-light reservoir, the research status, existing problems and development trends of air-foam enhanced recovery technology are summarized. The low temperature oxidation kinetics of air injection and the mechanism of foam micro flooding have been studied, but there are few studies of air-foam injection technology to improve oil recovery. Based on the previous studies, this paper systematically analyzes and evaluates the air-foam enhanced oil recovery (EOR) technology from the aspects of oil displacement mechanism, laboratory experiment, numerical simulation and field application. The studies show that there are two reactions between injected air and crude oil: low temperature oxidation (LTO) and high temperature oxidation (HTO) with two reaction pathways of oxidation reaction and decarbonization reaction. Many lab studies need to be conducted such as low temperature oxidation and composition analysis, dynamic displacement experiment, air foam injection and safety control experiment. The numerical simulation is mainly used to study the enhanced recovery mechanism of air-foam injection, determine the necessary oxidation kinetic parameters, fit the indoor experiment of air displacement, predict the dynamic and design of field test and improve the reliability of air injection reservoir simulation and the feasibility of field implementation. And it is proved from lab studies, numerical simulation and field application that air-foam EOR technology is suitable for low permeability reservoir, high permeability heterogeneity and high temperature and high salt reservoir.

Subject Areas

Petroleum Geology

Keywords

Air Injection, Foam, Oil Recovery, Flooding Mechanism, Laboratory Experiment, Numerical Simulation, Field Application

1. Introduction

Conventional gas injection technology (such as nitrogen, carbon dioxide or natural gas) is an efficient oil recovery technology for the oil field after water injection development, but the problems are insufficient gas sources and high cost. Air injection EOR technology has been paid more and more attention by oil companies both in China and abroad because of its low cost and abundant gas sources [1]. At present, air injection becomes a potential technology which is more economical and feasible to excavate the residual oil in low permeability and medium potential reservoirs. Air-foam injection combines the advantages of air flooding and foam flooding.

For air foam injeciton, the theory of low temperature oxidation kinetics, seepage characteristics, large channel plugging and oil displacement are still not clear, and the reservoir screening criteria need further analysis and verification.

A lot of research for air injection have been carried out such as universities and companies in the United States, Britain, Canada and other countries, China Petroleum University, PetroChina Exploration Institute, Southwest Petroleum University, China University of Geosciences, Tuha Oilfield, Shengli Oilfield and others.

At present, there is no complete mathematical model and simulation method for air injection low temperature oxidation simulation in China and abroad, which can be indirectly used in numerical simulation of air injection foam reservoir.

Since the 1960s, a great deal of work has been done abroad, mainly in the United States, to improve the recovery of light oil reservoirs by air injection. The technology and theory are well studied. Air injection has been applied in many field and the supporting technology of air injection is gradually improved, but there is less study on air foam flooding. So we need to systematically summary the air-foam enhanced oil recovery (EOR) technology from the aspects of oil displacement mechanism, laboratory experiment, numerical simulation and field application.

2. Mechanism of Enhanced Oil Recovery Flooding with Air Foam

Based on lab experiments and mathematical expressions, the mechanisms of enhanced oil recovery flooding with air foam are summarized such as low temperature oxidation, high pressure air injection, air-assisted steam puff heavy oil extraction and so on.

2.1. Air Injection Low Temperature Oxidation to Enhance Oil Recovery Technology

1) Principle of low temperature oxidation

After the air is injected into the reservoir, the oxygen and crude oil react exothermicly, the degree of reaction is related to the characteristics of crude oil, rock and fluid, temperature and pressure, but not to the partial pressure of oxygen; according to the Moore, the reaction degree is related to the characteristics of crude oil, rock and fluid, temperature and pressure [2] [3] [4]. The point view of Moore *et al.*, under the condition of oil layer, the oxidation processes of light oil and heavy oil are different. There are two reactions between injected air and crude oil: low temperature oxidation (LTO) and high temperature oxidation (HTO). The reaction pathway is also divided into two reactions: oxidation reaction and decarbonization reaction. The reaction mechanism of the LTO is certain (especially saturated) hydrocarbons, oxides that consume oxygen to form carbon and oxygen-containing hydrocarbons (such as acids, aldehydes, ketones, alcohols, etc.), while the radical R·, RO· and HO· in crude oil can continue to react with oxygen or other hydrocarbons; the oxidation reaction will continue and the oxygen concentration will gradually decrease in a continuous manner; the heat generated increases the oil layer temperature and causes the evaporation of oil light components. So the gas which drive oil finally are the CO, CO_2, N_2 generated in the reservoir and evaporated light hydrocarbon components and other components of the flue gas.

2) High pressure air injection (HPAI)

The compressed air is injected into the high pressure light oil reservoir, and the oxygen in the air at high temperature (generally higher than 60˚C) reacts with a small part of the crude oil in the reservoir to form CO_2. The main flue gas flooding process, including high temperature oxidation mixture air drive (HTO-MAF) and low temperature oxidation mixture air drive (LTO-MAF), does not need to ignite, and the oxidation reaction is maintained in the range of 150˚C - 300˚C.

3) Air-assisted steam puff heavy oil extraction

Ren [5] proposed the process of steam huff and puff and steam drive, air injection is proposed to improve recovery and engineering benefit of heavy oil reservoir. After drilling, the heavy oil layer is completed with casing sand control, artificial bottom hole is built during completion, hot steam is injected into completion (more than 200˚C) section, air can be injected into the same reservoir after the reservoir temperature rises, and then the well is shut down. Oxidation of crude oil and oxygen occurs. A low-temperature oxidation reaction between oxygen and crude oil releases heat and produces CO_2 and N_2. The oxidation reaction can crack heavy oil to change crude oil composition, improve crude oil fluidity and oil quality, and most of the oxygen in the air can be consumed by oxidation reaction. Rich air resources can reduce economic costs.

2.2. Air Foam Injection Technology for Enhanced Recovery

Air foam flooding technology combines the advantages of air flooding and foam flooding, which can not only improve the sweep coefficient, but also improve the efficiency of oil flooding. Considering the actual situation of heterogeneous reservoir, it is necessary to apply this technology in two stages: air foam profile control and air foam flooding. The former is mainly characterized by regulating gas drive or water drive by air foam plug, selectively plugging hypertonic layer (or large pore) or high water-bearing formation, controlling gas injection/water profile and reducing gas production/water quantity. The latter is mainly to improve oil recovery by using air foam to produce water drive or other displacement methods.

2.3. Reservoir Adaptability and Screening Criteria

According to field test and reservoir screening criteria for low temperature oxidation of air drive [6] [7], reservoir screening criteria for air foam flooding are recommended combined with the characteristics of foam flooding technology (see Table 1).

3. Indoor Study on Enhanced Oil Recovery with Air Foam Injection

Previous techniques of air-foam injection for oil recovery in light reservoirs have carried out a lot of indoor oil recovery [8]-[18] and security control [19] [20] [21] [22] [23]. However, the research system for air-foam enhanced oil recovery was not formed. The research aims are as follows: 1) selecting suitable reservoirs

Table 1. Reservoir adaptability and screening criteria.

Reservoir parameters	Scope	Remarks
Reservoir temperature/˚C	>60 - 80	Bottom limit of low viscosity and low permeability reservoir can be 60˚C
Crude oil viscosity/mPa·s in reservoir	<50	Determination of foam system performance
Oil specific gravity	0.83 - 0.88	Crude oil has good oxidation kinetic activity
Reservoir permeability/10^{-3} μm^2	>5	Air foam flooding permeability is not too low
Reservoir pressure/MPa	20 - 30 MPa	Considering air compressor injection capacity, reservoir depth 900 - 4000 m
Reservoir thickness/m	3 - 25 m	After flooding, it is better to have a large dip angle for gravity-stabilized flooding
Applicable reservoir type	Low permeability light weight reservoir	Medium and high permeability heterogeneity is serious and high temperature and high salt reservoir and heavy oil reservoir
Suitable reservoir rock type	Sandstone	Dolomite or limestone
Other	Good reservoir performance	EOR is about 8 - 15 percent

for air/air foam injection, defining its low temperature oxidation and oil displacement mechanism, studying the oxidation performance and technical feasibility of crude oil in target reservoir; 2) studying oxygen consumption, oxidation reaction rate and its influencing factors during air/air foam injection and its influence on safety control; establishing oxidation kinetics model to evaluate the oxidation activity and property change of crude oil in reservoirs; 3) studying the sealing ability of air foam injection, the influence law of oil displacement efficiency and improving recovery mechanism; the main engineering and production parameters are determined, the reference range of the explosion limit and critical oxygen content of combustible gas are given, and the corresponding field monitoring scheme and safety control measures are formulated.

3.1. Indoor Air Injection Experiment in Light Oil Reservoirs

3.1.1. Low Temperature Oxidation and Composition Analysis

This part mainly includes static oxidation experiment, dynamic oxidation experiment and crude oil composition analysis experiment. In the 1980's to1990's, Low temperature oxidation experiments were successfully carried out in West Hackberry, MPHU, Buffalo, Horse Creek oil fields in the United States and Maureen and North Sea oil fields in the United Kingdom (static ARC oxidation and dynamic combustion tube oxidation experiments). In the'90s, at the University of Bath in the United Kingdom, researchers first proposed the concept of low-temperature oxidation oxygen consumption rate. The temperature increment of the sand filling model with the adiabatic reaction was not detected. Calgary University of Canada has carried out 3000 - 4000 air injection experiments, and water-driven crushing core combustion tube experiment. Air injection oil recovery in high water-cut light oil reservoir is feasible, and the residual oil displaced by combustion front is enough to supply the consumption of fuel crude oil.

In recent years, The static constant temperature cycle experiment of air injection for crude oil from Tuha Shanshan oilfield, the thermal analysis experiments of high pressure injection air acceleration, pressure differential thermal analysis (PDSC) and thermogravimetric and differential thermal analysis (TG/DSC) were carried out by Southwest Petroleum University in China; Ren Shaoran *et al.* in China University of Petroleum did the static oxidation, dynamic oxidation and dynamic displacement experiments of air and air foam with different oil samples such as crude oil in Hu12 block of Zhongyuan oilfield, in Bin 425 block of Shengli oilfield and in Xinjiang oilfield. The indoor evaluation technique of air injection and air foam injection is studied systematically and comprehensively. Study on low temperature oxidation model of Cao Tai high condensate oil and block leng-1 heavy oil was proposed in the Changjiang University. If the temperature is higher than 120˚C, 6.86% - 10.24% crude oil can be produced by air injection with Cao Tai high condensate oil. Experiment on static low temperature oxidation of light crude oil in Liaohe Oilfield was conducted. The content of aromatic hydrocarbons decreased obviously and colloid content increased significantly. The physical properties of crude oil become worse. Experiment on low temperature oxidation and displacement of air injection with crude oil in Xindu 1 block in Liaohe Oilfield was reported. It is proved that aie injection technique is an effective method to replenish formation energy. The simulation experiment of low temperature oxidation process under reservoir conditions (90˚C, 13 MPa) shows that the content of carbon, hydrogen and nitrogen in crude oil has not changed and the oxygen content has increased. The simulation study of low temperature oxidation process of air injection was carried out by China University of Geosciences according to the actual reservoir conditions of Daqing, which proved that the change of crude oil composition in the oxidation process did not adversely affect the flow performance of crude oil.

3.1.2. Dynamic Displacement Experiment

The results show that the oxygen content in the air and reservoir temperature have few effects on the oxygen consumption. The effect of yield air drive is higher than that of nitrogen drive. A number of displacement experiments of air and air foam have been carried out at the University of Bath and the University of Petroleum of China, which prove the feasibility of air injection in different reservoirs.

3.2. Air Foam Injection for Oil Recovery

The micro and macro oil displacement mechanisms of foam have been studied detailly in China, but there is few study of air foam enhanced oil recovery. Some studies were reported by China University of Petroleum, Xi'an University of Petroleum, Zhongyuan Oilfield, Changqing Oilfield and other units. The results show that Hu12 block has good oxidation activity. The oxidation rate is related with the temperature, pressure, water saturation and clay content. Air foam has influence on static oxidation of crude oil, but not on dynamic oxidation under reservoir conditions. From air foam displacement experiments we find that when the gas-liquid ratio is between 1:1 to 2:1, the foam stability and plugging ability are improved with low temperature, high pressure and permeability. The air foam flooding can improve the oil displacement efficiency by 13% - 24%, which is suitable for improving the oil recovery in heterogeneous severe strata. Through laboratory experiments, Xi'an University of Petroleum evaluated the feasibility of air foam composite flooding in low permeability reservoirs to improve oil recovery, and expanded the application of air foam injection. The foaming property, foam stability and salt resistance of the foam agent are evaluated by the compound air foam flooding test of Chang-6 reservoir in Wuliwan Changqing Oilfield.

3.3. Air Foam Safety Control Experiments

The characteristics of gas corrosion and explosion were also studied in China

Petroleum University, Daqing Oilfield and Zhongyuan Oilfield. The results show that the explosion range increases with the increment of temperature, pressure and oxygen content and the critical oxygen content decreases with the increment of temperature and pressure. Lu Xin *et al.* estimated the explosion limit of natural gas, which proved that the air foam flooding technology was safe and reliable. Daqing Oilfield Exploration Institute designed an explosion limit measuring device for combustible gas and studied the explosion limit of output gas after low temperature oxidation. The results show that the mixed gas prepared according to the proportion of output gas components did not explode under reservoir conditions. Aiming at the corrosion problem in the process of air foam flooding, Zhongyuan Oilfield Oil production Institute simulated the field test conditions, studied the effects of gas-liquid alternate injection frequency, air injection parameters (temperature, pressure, humidity, flow rate) and different foam dispensing systems on corrosion rate and also investigated the corrosion inhibition effect of corrosion inhibitor and sacrificial anode. The relevant corrosion rules and anticorrosion technology of air foam injection is reported. From the lab corrosion experiment we can conclude that the corrosion inhibition rate of the synergistic corrosion inhibition process between the inhibitor and the sacrificial anode is 92.4%.

4. Numerical Simulation of Enhanced Oil Recovery with Air Foam Injection

There is no complete mathematical model and simulation method indirectly used in numerical simulation of air injection foam reservoir [24]-[34].

The softwares used most often are Canadian CMG thermal production module STARS and American SSI company thermal production reservoir simulator THERM. The numerical simulation is mainly used to study the enhanced recovery mechanism of air-foam injection, determine the necessary oxidation kinetic parameters, fit the indoor experiment of air displacement (oxidation kinetics experiment, core displacement experiment), predict the dynamic and design of field test and improve the reliability of air injection reservoir simulation and the feasibility of field implementation. At abroad, some researches about the over-injection air by using the black oil mixed-phase displacement simulator were proposed by S. Sakthikumar, BATH University of England, Horse Creek and West Hackberry oil fields in the United States and Maureen oil reservoirs in the United Kingdom. In China, the numerical simulation of air-foam injection was carried out by China Petroleum University, PetroChina Exploration Institute and Tuha Oilfield Exploration Institute.

The simulation process contains 1-D lab oil displacement experiment simulation, low temperature oxidation reaction simulation, air foam injection simulation *et al.*

4.1. LTO Kinetic Parameters with Matching Experimental Results

S. Sakthikumar and other researchers establish a one-dimensional model for indoor LTO experiment. According to the Arrhenius equation, the kinetic parameters of low temperature oxidation were determined by fitting the experimental results. In University of BATH, software CMG-STARS is used to establish 1D experimental model, 2D plane model and 3D reservoir model based on SBR test and oxidation tube test. It proves that the model has a good match with the experimental results and the sensitivity of the influence factors is analyzed. In Horse Creek oilfield, many works were done to determine the relevant process parameters, such as fitting of experimental results of combustion tube, simulation of radial displacement of air injection single well and simulation of whole oil field using numerical simulator of thermal production. SSI company's THERM simulator was used to simulate the air injection gravity flooding process in the U.S. West Hackberry oil field. British Maureen reservoir simulated air injection using black oil mixed drive simulator, and two types of gas injection after water flooding were carried out in oil field for dynamic prediction of oil recovery.

On the basis of crude oil oxidation experiment, a low temperature oxidation kinetic model is established and the main influence factors are analyzed by the researchers in China University of Petroleum. At the same time, the improved low temperature oxidation reaction model is proposed. The low temperature oxidation kinetic parameters of the improved model are obtained by ARC experiment and the oxidation tube (OT) experiment results are fitted and verified by thermal mining numerical simulation method. CNPC applied numerical simulation method to fit the process of low permeability reservoir model experiments (core flooding, low temperature oxidation of slender tube and combustion tube experiment), and the model which has a good match with the experimental results is used to study the sensitivity of oxidation reaction parameters and the mechanism of air flooding. Air injection can build the reservoir pressure more efficiently than water injection. The contribution of nitrogen flooding to the total oil recovery of air flooding is 69% and the contributions of temperature rise and carbon dioxide to oil recovery are 26.7% and 4.3% respectively. The oil recovery of air flooding is 21.5% for 30 years. The development mechanism of air injection in light oil reservoirs, represented by Tuha Shanshan oilfield, was studied and elucidated by using the numerical simulation method of thermal production (low temperature oxidation reaction process, phase state change and distribution characteristics, reservoir energy change law).

4.2. Air Foam Simulation

The characteristics of air and foam are combined to achieve foam plugging and oil displacement. At present, the common numerical simulation methods of foam displacement are: semi-empirical relation model, total foam balance model, critical capillary force model, resistance coefficient model, component method, seepage and network model, semi-total balance model and so on. This paper focuses on the application of foam empirical models. In the foam empirical models, the foam mobility is characterized as a function of surfactant concentration, gas flow rate (or capillary number) and oil saturation, etc., and the principle of which is mainly by reducing the gas relative permeability, that is, gas phase permeability multiplied by the factor of interpolation dimensionless F_M. In order to reduce the flow rate and adjust the displacement, three regions with different surfactant concentration are considered: no foam, weak foam and strong foam, which characterize the decrease of gas flow rate. The characteristics of foam plugging hypertonic layer in the model can be investigated by the change of gas mobility, pressure field and foam flow rate in the foam region.

5. Field Application of Air Foam Injection EOR Technology

In China, field tests and field applications of air foam flooding have been applied in Guangxi Baise, Zhongyuan, Shengli, Daqing, Qisheng, Yanchang and Changqing oil fields [35]-[40]. The oil reservoir parameters and oil displacement effect of air and air foam flooding are shown in **Table 2**. The test applications contain many types, such as air flooding, flue gas test, nitrogen foams, air foam injection. The injection pressure is 4.3 - 32.4 MPa and oil viscosity is 0.5 - 9 mPa·s.

The air flooding and air foam flooding technology in sandstone, limestone and carbonate reservoirs are applied successfully. It is suitable for low permeability reservoirs, high permeability heterogeneity and high temperature reservoirs and high salt reservoirs (such as Hu 12 block in Zhongyuan Oilfield).

The injectors with formation dip angle can improve the vertical sweep efficiency; there is good Foaming effect when the gas-liquid ratio of foam flooding is determined to be 1:1 to 1:2, and the foaming method is mainly foaming in the ground; and injection mode is the mixed air foam-air-water; the injection slugs are mainly multi round small slugs, and no safety accident occurred in the test.

6. Problems and Trends

6.1. Problems

1) There are potential safety problems, such as oxygen corrosion in injection wells, CO_2 corrosion in production wells; and the, well explosion. It is necessary to pay more attention to the field safety monitoring, even no such safety accidents have been reported;

2) The mechanism of air-foam enhanced oil recovery is not well studied;

3) The foam injection system for the target reservoir is unstable and it is difficult to form a reliable system;

4) The influence of low temperature oxidation on reservoir crude oil is not clear;

5) The field size scale test is few and it is difficult to popularize air foam injection.

6.2. Trends and Directions

1) Air foam profile control or flooding in ultra-low permeability, low permeability and low temperature reservoirs;

Table 2. Oil reservoir parameters and oil displacement effect of air-foam flooding field test.

Country/company	Oil field	Time/year	Rock	Layer thickness /m	Pressure /MPa	Temperature /°C	Well depth /m	Permeability /mD	Oil density / g/cm^3	Oil viscosity /mPa·s	porosity / %	Injection pressure /MPa	Type of test
Amoco of the United States	Nebraska Sloss	1963-1966	Sandstone	6	22.8	93	1890	190	0.8299	0.8	11	25	Air flooding
	West Hackberry High pressure zone after water flooding	1994	Sandstone	10	—	94	3658	300	—	0.9	27	20	Field test
	West Hackberry Low pressure zone	1996	Sandstone	21	—	94	2438	1000	0.860	0.9	26	4.3	Field test
Chevron Gulf of the United States	W.Heidelberg Mississippi/Mei Valley	1971-1982	Sandstone	18.9	35.2	105	3444	85	0.8927	6	14	26	Air injection/ Flue gas test
S.Dakota of the United States	BRRU	1977	Dolomites	3	24.8	102	2590	10	0.8735	0.5	19	30.3	Field test
S.Dakota of the United States	Buffalo	1978	Carbonate	4	24.8	101.6	2602	10	0.87	2.4	18	—	Field test
Koch of the United States	Madison CAPA	—	Limestone	—	—	99	2621	10	—	0.5	11	30	Field test
Continental of the United States	MPHU	1987-1994	Dolomites	5.5	28	104	2896	5	0.8291	0.5	17	30	Field test
N.Dakota of the United States Montana, Shell	Coral Creek	—	Dolomites	6-24	—	97	1706	10	0.852	1	15-20	—	Experimental simulation
Total Indonesia	Handil	1995	Sandstone	—	—	92	1500 - 2200	10 - 500	—	0.8	23	17	Field test
N.Dakota Total of the United States	Horse Creek	1996	Limestone	6	27.6	104	2781	1 - 20	0.8654	1.4	16	32.4	Field test
Domestic oil fields	Daqing Oilfield	1982	Sandstone	5.6	—	45	910	630	—	—	28.7	—	Air flooding
	Bose son Yin Lun 16	1996	Sandstone	9.3	10	49.5	870 - 900	72	0.8405	5.9	19	—	Nitrogen foams
	Baise Upper France 1004	1996	Limestone	26.8	2	78	1260 - 1354	13.4 - 450	0.8327	9	4	—	Air foam
	Qisheng Oilfield, Northern Shaanxi	2005	Sandstone	20	7.15	72	1920 - 2250	0.5 - 3.5	0.779	2.13	7-11	15-20	Air foam
	Changqing Maling Oilfield	2006	Sandstone	4.6	—	70	1560	—	—	—	14.6	—	Air foam
	Zhongyuan Oilfield	2007	Sandstone	11.9	22.3	87	2205	235.5	0.886	3.96	21	30	Air foam
	Yanchang Ganguyi Oilfield	2007	Sandstone	14.3	5.19	27.25	570	0.87	0.824	—	9.2	—	Air foam
	Shengli Oilfield	2009	Limestone	10-30	—	100	3000 - 3300	19.8	—	—	18.9	—	Air trial
	Changqing Wuliwan Oilfield	2009	Sandstone	15.7	12.26	54.4	—	3.67	—	4.97	11.6	10-18	Air foam

2) Low-temperature oxidation technology for heavy oil reservoirs;

3) Air injection assisted steam huff and puff heavy oil recovery;

4) Mathematical model and numerical simulation of air foam injection for oil recovery;

5) Study on enhanced oil recovery seepage characteristics of air foam;

6) Study on the kinetic characteristics of low temperature oxidation of air;

7) Effect and influence of steam on oxidation kinetics at relatively low temperature in high pressure air injection (HPAI);

8) Assessment of reservoir potential of air foam flooding technology;

9) Air foam injection EOR technology system;

10) Oil recovery mechanism and reservoir adaptability evaluation of air foam;

11) Field practice and experience in air foam injection for oil recovery.

7. Conclusions

1) Air foam flooding technology combines the advantages of air flooding and foam flooding, which can not only improve the sweep coefficient, but also im-

prove the displacement efficiency.

2) The explosion range increases with the increment of temperature, pressure and oxygen content and the critical oxygen content decreases with the increment of temperature and pressure, and air foam injection with oxygen reducing is safe to be conducted for a field pilot.

3) The air flooding and air foam flooding technology in sandstone, limestone and carbonate reservoirs are applied successfully. It is suitable for low permeability reservoirs, high permeability heterogeneity and high temperature reservoirs and high salt reservoirs.

Acknowledgements

This work is funded by SINOPEC Science and Technology Project P18080, the project funded by China Postdoctoral Science Foundation (2022M723499), and by a National Energy Administration Research and Development Center project for the "Sustainable Development of Mature Continental Sandstone Oilfields". We thank the technology and translation supports from Dr. Yao Zhang, Dr. Quanqi Dai, Dr. Peng Wang, and Dr. Chuanjie Cheng.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] Ren, S.R., Greaves, M. and Rathbone, R.R. (2002) Air Injection LTO Process: An IOR Technique for Light-Oil Reservoirs. *Society of Petroleum Engineers Journal*, **7**, 90-99. https://doi.org/10.2118/57005-PA

[2] Teramoto, T., Uematsu, H., Takabayashi, K., *et al.* (2006) Air-Injection EOR in Highly Water-Saturated Light-Oil Reservoir. *SPE Europec/EAGE Annual Conference and Exhibition*, Vienna, 12-15 June 2006, 1-10. https://doi.org/10.2118/100215-MS

[3] Moore, R.G., Mehta, S.A. and Ursenbach, M.G. (2002) A Guide to High Pressure Air Injection (HPAI) Based Oil Recovery. *SPE/DOE Improved Oil Recovery Symposium*, Tulsa, 13-17 April 2002, 1-7. https://doi.org/10.2118/75207-MS

[4] Ren, S.R., Greaves, M. and Rathbone, R.R. (1999) Oxidation Kinetics of North Sea Light Crude Oils at Reservoir Temperature. *Chemical Engineering Research and Design*, **77**, 385-394. https://doi.org/10.1205/026387699526368

[5] Ren, S.R., Liu, Y.J., Wang, J.X., *et al.* (2007) Air Assisted Steam Puff Heavy Oil Extraction Technology.
https://pss-system.cponline.cnipa.gov.cn/documents/detail?prevPageTit=changgui

[6] Zhang, X.L., Zhang, Y.T., Wu, Y.B., *et al.* (2007) EOR by Air Injection. *Journal of Southwest Petroleum University*, **29**, 80-84.

[7] Wang, M.K. and Zhang, Y. (1999) Technical Screening Guides and Economic Index for the *in situ* Combustion. *Oil and Gas Recovery Technology*, **6**, 7-11.

[8] Clara, C., Durandeau, M., Quenault, G. and Nguyen, T.H. (1999) Laboratory Studies for Light Oil Air Injection Projects: Potential Application in Handil Field. *SPE Asia Pacific Oil and GasConference and Exhibition*, Jakarta, 20-22 April 1999, 1-16. https://doi.org/10.2118/54377-MS

[9] Cao, W.Z., Luo, L., Zhang, L.P., *et al.* (2008) Laboratory Experiment on Air Injection and N2 Injection in Extra-Low Permeability Reservoir. *Petroleum Geology & Oilfield Development in Daqing*, **27**, 113-117.

[10] Guo, P., Wang, Y., *et al.* (2008) Combustion-Tube Test of Air Injection for Light-Oil Reservoir. *Journal of China University of Petroleum*, **32**, 60-63, 71.

[11] Niz-Velasquez, E. (2006) Numerical and Laboratory Assessment of the Oil Recovery Mechanisms in High-Pressure Air Injection (HPAI) Process. *SPE Annual Technical Conference and Exhibition*, San Antonio, 24-27 September 2006, 1-9. https://doi.org/10.2118/106526-STU

[12] Yu, H.M., Ren, S.R., Zuo, J.L., *et al.* (2009) Experiment of Improved Oil Recovery by Air Foam Injection Low Temperature Oxidation Process. *Journal of China University of Petroleum*, **33**, 94-98.

[13] Du, J.F., Guo, P., Wang, Z.L., *et al.* (2007) Laboratory Research of Accelerating Rate Calorimeter Test of High-Pressure Air Injection at Light Oil Reservoirs. *Journal of Southwest Petroleum University*, **29**, 17-21, 179-180.

[14] Du, J.F., Guo, P., Wang, Z.L., *et al.* (2008) Research on Reactivity of Oil with Air in High-Pressure Air Injection at Light Oil Reservoirs. *Journal of Southwest Petroleum University*, **30**, 92-96, 210-211.

[15] Liu, Y., Liu, Y.F., Chen, Y., *et al.* (2010) Experimental Study on Static Low Temperature Oxidation of Light Oil with Injected Air. *Special Oil and Gas Reservoirs*, **17**, 96-98, 125.

[16] Cheng, Y. (2007) Study on the Variation of Composition and Gas Composition of Crude Oil Oxidized at Low Temperature in Air. Ph.D. Thesis, Harbin Engineering University, Harbin.

[17] Yu, H.M., Ren, S.R., Niu, B.L., *et al.* (2010) Experimental Study on Oxidation Reaction Rate Byair Injection in Light-Oil Reservoirs. *Journal of Petrochemical Universities*, **23**, 55-57.

[18] Song, Y.J., Xu, Y.B., Cao, J., *et al.* (2009) Experimental Study on Air-Foamflooding for Low-Permeability Reservoirs. *Special Oil and Gas Reservoirs*, **16**, 79-81, 109.

[19] Yu, H.M., Zuo, J.L., Ren, S.R., *et al.* (2010) Explosion Characteristics of Oil Well Produced Gas by Air Injection for Improved Oil Recovery. *Journal of China University of Petroleum*, **34**, 99-103.

[20] Ji, Y.J., Zhou, L.P., Zhao, Z.Z., *et al.* (2007) Risk Analysis and Safety Control Technology of Air Injection Oil Production Process. *Petrochemical Safety and Environmental Protection Technology*, **23**, 19-22, 68.

[21] Lu, X., Yue, X.A., Wu, Y.C., *et al.* (2005) Analysis on the Safety of Air-foam Driven Oil Recovery Technology. *Oil and Gas Geology and Recovery*, **12**, 44-46, 85.

[22] Cao, W.F., Cao, W.Z., Zhang, J.L., *et al.* (2009) Explosion Limit Study on Air Low Temperature Oxidation of Crude Oil Producing Gas. *Journal of Southwest Petroleum University*, **31**, 99-103, 166-171, 220-221.

[23] Lin, W.M., Li, X.F., Chen, X.L., *et al.* (2010) A Study on Corrosion and Protection during Oil Repelling by Air Foam Injection. *Oil Field Chemistry*, **27**, 342-345.

[24] Yang, Z.H., Xu, B.T., Liu, B., *et al.* (2005) Mechanism Research of Air Injection Development in Light Oil Reservoirs in Tu-Ha Basin. *Oil and Gas Geology and Recovery*, **12**, 68-70, 87.

[25] Sakthikumar, S., Madaoui, K. and Chastang, J. (1995) An Investigation of the Feasibility of Air Injection into a Waterflooded Light Oil Reservoir. *Middle East Oil Show*, Bahrain, 11-14 March 1995, 343-356. https://doi.org/10.2118/29806-MS

[26] Clara, C., Zelenko, V., Schirmer, P., *et al*. (1998) Appraisal of the Horse Creek Air Injetion Project Performance. *Abu Dhabi International Petroleum Exhibition and Conference*, *Abu Dhabi International Petroleum Exhibition and Conference*, Abu Dhabi, 11 November 1998, 573-583.

[27] Germain, P. and Geyelin, J.L. (1997) Air Injection into a Light Oil Reservoir: The Horse Creek Project. *Middle East Oil Show and Conference*, Bahrain, 15-18 March 1997, 233-242. https://doi.org/10.2118/37782-MS

[28] Gillham, T.H., Cerveny, B.W. and Fomea, M.A. (1998) Low Cost IOR: An Update on the W. Hackberry Air Injection Project. *SPE/DOE Improved Oil Recovery Symposium*, Tulsa, 19-22 April 1998, 401-406. https://doi.org/10.2118/39642-MS

[29] Hou, S.M., Liu, Y.H., Yu, H.M., *et al*. (2011) Kinetics of Low Temperature Oxidation of Light Oil in Air Injection Process. *Journal of China University of Petroleum*, **35**, 169-173.

[30] Yang, B.Q., Ren, S.R., Yu, H.M., *et al*. (2009) Numerical Simulation of Low Temperature Oxidation Mechanism of Air Injection in Light Oil Reservoirs. *Xinjiang Petroleum Geology*, **30**, 358-361.

[31] Yu, H.M., Yang, B.Q., Ren, S.R., *et al*. (2008) Numerical Simulation of Air Injection Low Temperature Oxidation in Low Permeability Reservoirs. *Journal of Southwest Petroleum University*, **30**, 117-120, 213.

[32] Jiang, Y.W., Zhang, Y.T., Liu, S.Q., *et al*. (2010) Displacement Mechanisms of Air Injection in Low Permeability Reservoirs. *Petroleum Exploration and Development*, **37**, 471-476. https://doi.org/10.1016/S1876-3804(10)60048-1

[33] Zhang, L.H., Hu, Y. and Tu, Z. (2000) A New Empirical Model and ItsApplications for Foam Flooding. *Journal of Southwest Petroleum University*, **22**, 50-52.

[34] Ren, S.R., Yu, H.M., Zuo, J.L., *et al*. (2009) EOR Technology of Profile Control and Displacement Process by Air Foam Injection in Zhongyuan Oil Field. *Acta Petrolei Sinica*, **30**, 413-416.

[35] Zhang, X.G. (2006) Air Injection Technology. *Chinese and Foreign Science and Technology Intelligence*, **3**, 3-31.

[36] Yan, F.P., Yang, X.L. and Zhang, J.C. (2008) Effect Analysis of Enhancing Ultra-Low Permeability Oilfield Recovery by Air-Foam Flooding. *Journal of Yan'an University*, **27**, 58-60.

[37] Shen, H.W., Liu, Y.S., Zhao, H., *et al*. (2011) The Experimental Effect Appraisal of Compound Air-Foam Drives in Wuliwan Chang 6 Oil Deposit. *Petrochemical Applications*, **30**, 63-66, 99.

[38] Zhang, L., Dong, L.Q., Zhang, K., *et al*. (2009) Research of the Air-Foam Flooding Technique Test in the Maling Oil-Field. *Xinjiang Geology*, **27**, 85-88.

[39] Kumar, V.K., Gutierrez, D., Thies, B.P. and Cantrell, C. (2010) 30 Years of Successful High-Pressure Air Injection: Performance Evaluation of Buffalo Field, South Dakota. *SPE Annual Technical Conference and Exhibition*, Florence, 19-22 September 2010, 1-12. https://doi.org/10.2118/133494-MS

[40] Pang, Y.M., Guo, H.Y., Yang, Z.S., *et al*. (2001) Example of Gas Injection Development in Foreign Oilfields. Petroleum Industry Press, Beijing.