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CO_2 mobility control and sweep efficiency improvement using starch gel or ethylenediamine in ultra-low permeability oil layers with different types of heterogeneity

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ABSTRACT

Reservoir heterogeneity and natural fractures greatly affect CO_2 flooding efficiency in ultra-low permeability oil reservoirs. CO_2 water alternating gas (WAG) flooding and the combinations of continuous CO_2 flooding and gas channeling treatments are recognized as effective approaches to improve CO_2 sweep efficiency. It is of major interest to propose the novel gas channeling treatments and conduct a feasibility study of different CO_2-EOR technologies. Heterogeneous cores with different permeability ratios and fracture model were utilized in the laboratory experiments to simulate different types of heterogeneity in the oil reservoirs. Continuous CO_2 flooding, CO_2 WAG flooding, continuous CO_2 flooding + one-stage gas channeling control, and continuous CO_2 flooding + two-stage gas channeling control were conducted after water flooding in homogeneous and heterogeneous cores and fracture model. Ethylenediamine and modified starch gel were proposed as blocking agents to mitigate gas channeling. During the experiments, the CO_2 flooding efficiency was evaluated through the oil recovery increment, fluid mobility control and the changes of producing pressure drop. Experimental results show that producing pressure drop during continuous CO_2 flooding decreases rapidly with an increase in permeability ratio. Continuous CO_2 flooding cannot displace much of remaining oil in low permeability layers due to high mobility of CO_2 and serious heterogeneity. WAG flooding can effectively control the fluid mobility and improve CO_2 flooding efficiency when the permeability ratio is less or equal to 30. Plenty of remaining oil can be displaced by combining continuous CO_2 flooding and gas channeling treatments. When the permeability ratio is less or equal to 100, ammonium carbamate, the reaction product of injected ethylenediamine and CO_2 can block off high permeability layer and impel the injecting gas into low permeability layer. The two-stage injection of modified starch gel and etheylenediamine can significantly mitigate the gas channeling within high-capacity gas channel model and fracture model during continuous CO_2 flooding, and the incremental oil recovery could be more than 20%. Pilot test of CO_2 flooding was operated in Northwest China and concentrations of CO_2 are monitored in six production wells. Two kinds of construction plans for gas channeling treatments have been preliminary designed to control the gas channeling in the pilot.

1. Introduction

Since the demand for oil is increasing and the exploitation of conventional hydrocarbon reserves becomes more difficult, EOR projects have been widely implemented across the world. Among those projects, gas EOR projects account for a large proportion. According to the analysis for EOR projects conducted by Adasani and Bai (2011), the percentage of gas EOR technology making up the world EOR projects has increased to 41% due to the adoption of miscible flooding methods.

CO_2 flooding cannot only enhance oil recovery, but also sequestrate CO_2 and effectively reduce gas emission, which has a great potential and application prospect in China. Evaluation of CO_2-EOR and sequestration potential in low permeability layers, Yanchang Oilfield, China shows that CO_2 flooding performed after water flooding can produce 180.21×10^6 t or even more crude oil

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Nomenclature

V_k	permeability ratio;
$\bar{M}_{w\text{-}o}$	average water/oil mobility ratio;
$\bar{M}_{g\text{-}o}$	average gas/oil mobility ratio;
K_e	absolute permeability of linear dimensional model, mD;
K_{wi}	the effective permeability of water phase, mD;
K_{oi}	the effective permeability of oil phase, mD;
K_{gi}	the effective permeability of gas phase, mD;
$\bar{S}_w$	average water saturation after displacement front;
$\bar{S}_o$	average oil saturation before displacement front;
λ_w	water mobility;
λ_o	oil mobility;
λ_g	gas mobility;
A	cross sectional area of the core, cm^2;
p_0	standard pressure—101.325 kPa;
p_1	injecting pressure, MPa;
p_2	producing pressure, MPa;
Δp	producing pressure drop, MPa;
T_0	standard temperature—273.15 K;
T	formation temperature—333.15 K;
Z_0, Z	gas compressibility factors;
B_w	water volume factor;
B_o	oil volume factor;
B_g	gas volume factor;
Q_w	water production rate under surface conditions, mL/min;
Q_o	oil production rate under surface conditions, mL/min;
Q_g	gas-producing rate under surface conditions, mL/min;
WOR	water/oil ratio;
GOR	gas/oil ratio
CI	colloid unstable index;
S	content of saturated hydrocarbon, %;
Ar	content of aromatic hydrocarbon, %;
R	content of resin, %;
As	content of asphaltene, %.

and sequestrate 223.38×10^6 t CO_2 (D. Zhao et al., 2014a). CO_2 resource is a key factor to carry out CO_2-EOR projects. Currently, the main resource of CO_2 is natural gas reservoirs with high concentration of CO_2 or CO_2 reservoirs. CO_2-EOR technology has great potential benefits for gas exploitation and environment protection (Damico et al., 2014; Mazzetti et al., 2014; Roussanaly and Grimstad, 2014). Additionally, the ability to utilize CO_2 from the coal conversion industry for CO_2-EOR and geological sequestration will make CO_2-EOR projects more cost-effective and technologically efficient (Wang et al., 2013).

CO_2 flooding can be categorized as immiscible and miscible flooding. The mechanisms of CO_2 flooding usually include oil viscosity reduction, oil swelling, dissolved gas drive and mobility ratio reduction. The miscibility can decrease the interfacial tension by injecting supercritical CO_2, which can dramatically enhance oil recovery. Field applications present miscible CO_2 flooding can enhance oil recovery by 8–15% (Winter and Jean, 2001; Espie, 2003; Pyo et al., 2003; Bachu and Shaw, 2004).

However, the application of CO_2 flooding in ultra-low permeability reservoirs faces great challenges such as low porosity, low permeability, low oil saturation, anomalously low reservoir pressure, severe heterogeneity and the existence of nature fractures. The gas breakthrough occurred in oil wells can be divided into three types: along fracture direction, along the high permeability channel and CO_2 viscous fingering in low permeability layer (Gao et al., 2014). Gas channeling and viscous fingering phenomena appear obviously in the cases of immiscible CO_2 flooding (Berg and Ott, 2012; Islam et al., 2013; Fath and Pouranfard, 2014). MRI technique to follow multiphase flow of oil, water and supercritical CO_2 in fractured artificial consolidated sandstone shows that the fracture serves as the preferred path for the injected fluid, which leads to earlier breakthrough and higher oil bypass (Zhao et al., 2013). How to control the gas channeling and displace the remaining oil in low permeability layers becomes greatly significant in CO_2-EOR projects to improve CO_2 flooding efficiency.

CO_2 water alternating gas (WAG) flooding is considered to be an effective method to control fluid mobility and improve sweep efficiency in both laboratory experiments and field trials (Christensen et al., 1998; Goodyear et al., 2003; Righi et al., 2004; Heeremans et al., 2006; Elfeel et al., 2013a). The injected gas can enhance microscopic displacement efficiency, while the injected water can enhance the macroscopic sweep efficiency. However, the WAG displacement characteristics could be influenced by many factors including reservoir wettability and heterogeneity (Dijke et al., 2006; Elfeel et al., 2013b), the composition of crude oil and injected water (Kulkarni and Rao, 2005), as well as the injection parameters such as CO_2 slug size, gas/water ratio, CO_2 injection rate and voidage replacement ratio (Song et al., 2014). WAG flooding could also cause injectivity problems in some reservoirs (Rogers and Grigg, 2001). Surfactant alternating gas (SAG) flooding and foam assisted water alternating gas (FAWAG) flooding are other methods used to delay gas breakthrough during CO_2 flooding (Spirov et al., 2012; Salehi et al., 2014). Carbonated water injection (CWI) was proposed to be an alternative CO_2 injection strategy which could solve the problems of gravity segregation and poor sweep efficiency (Sohrabi et al., 2011).

The EOR methods mentioned above are mainly focused on sweep efficiency improvement. However, the feasibility study of different CO_2-EOR technologies and displacement characteristics during CO_2 injection are merely discussed before. Plenty of oil is remained in heterogeneous cores after water flooding, and how to control fluid mobility and enlarge the sweep volume of CO_2 is the key to displace the remaining oil. Tang et al. (2013) demonstrated that starch graft gel could efficiently block water channeling paths through a 3-D physical model experiment and reservoir simulation. F. Zhao et al. (2014b) proposed ethylenediamine as gas channeling control agent for permeability profile control during CO_2 flooding. These new technologies were further discussed along with continuous CO_2 flooding and WAG flooding in this paper. After a water flooding stage, the oil displacement experiments of continuous CO_2 flooding, WAG flooding, continuous CO_2 flooding + one-stage gas channeling control, and continuous CO_2 flooding + two-stage gas channeling control were conducted in homogeneous, heterogeneous, and even fractured cores. CO_2 flooding efficiency was discussed through oil recovery increment and the changes of pressure drop. The water/gas to oil mobility ratio was developed to determine the application limitation of WAG flooding. For even more serious gas channeling, one-stage and two-stage gas channeling treatments were combined with continuous CO_2 flooding to enlarge the sweep volume of CO_2, in which ethylenediamine and modified starch gel were proposed as blocking agents. The application limitation of one-stage and two-stage gas channeling treatments were determined, which offers a practical guide for the implementation of different CO_2-EOR technologies in the oilfield.