



CO₂ foam flooding for improved oil recovery: Reservoir simulation models and influencing factors

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ABSTRACT

A mechanistic model of CO₂ foam that allows for direct simulation of foam generation, propagation, coalescence and collapse was described in this study. The controlling parameters, such as reaction rate factors for foam generation, coalescence and collapse in presence of oil, the viscosity of foaming components and surfactant adsorption, were adjusted to match the experimental results of CO₂ foam coreflooding. A three dimensional heterogeneous conceptual reservoir model was then built to study the mechanisms of CO₂ foam flooding based the foam model. The simulation results show that CO₂ foam flooding can improve oil recovery through a combination of various mechanisms, including selective blocking and conformance control, gas up-flow effect, reservoir energy support, and the improvement of displacement efficiency. The sensitivity and the effect of different influencing factors on the performance of CO₂ foam flooding were investigated via the simulation models on various scenarios. CO₂ foam flooding can achieve a better oil recovery in comparison with water flooding, CO₂ flooding and WAG (water alternating gas) processes. Early CO₂ foam injection is conducive to the improvement of oil recovery and the success of the project. CO₂ foam flooding technique can be applied in a wide range of complex reservoirs, especially for highly heterogeneous reservoirs with high permeability channels, and reservoirs with different sedimentary sequences.

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1. Introduction

CO₂ flooding can improve oil recovery significantly via various mechanisms, including reducing oil viscosity, decreasing interfacial tension and achieving miscibility with oil. It has become one of the most promising improved oil recovery (IOR) techniques and has gained great attention from research community and industry (Ghedan, 2009; Ren et al., 2011). However, like other gas injection techniques, gas channeling and viscous fingering resulted from reservoir heterogeneity and excessive mobility contrast between CO₂ and oil can reduce the sweep efficiency of CO₂ greatly and limit its application (Talebian et al., 2013). Accordingly, injection of CO₂ foam was proposed in 1950s to overcome the problems of early gas breakthrough and poor sweep efficiency occurred in the process of pure CO₂ flooding (Bond and Holbrook, 1958). The injection of surfactant solution alternating CO₂ (SAG) and co-injection of surfactant solution and CO₂ has been used to generate

foam in the reservoir and thus reduces the mobility of the gas phase and hence increases sweep efficiency (Pang, 2010; Zhang et al., 2013; Chen et al., 2014; Ren et al., 2013).

A significant number of researches have been conducted on the application of CO₂ foam as a means of controlling CO₂ mobility and improving sweep efficiency in heterogeneous reservoirs (Khalil and Asghari, 2006; Sohrabi and Farzaneh, 2013; Zhang et al., 2014a). The effects of different influencing factors on CO₂ foam stability have been studied through laboratory experiments (Liu et al., 2005a, 2005b; Zhang et al., 2014b), and the performances of CO₂ foam have been investigated in many field trials in the past decades (Hoefner et al., 1995; Norris et al., 2014). And the comparison has been made between the performance of CO₂ foam flooding and that of N₂ foam to show the differences between two techniques (Farajzadeh et al., 2009; Emadi et al., 2012). Besides the CO₂ foam technique was proving to be a feasible and successful IOR method in oilfield flooding processes, a lot of work has been done to study the mechanisms of CO₂ foam flooding through experiments and numerical simulations (Kovscek et al., 1997; Liu et al., 2011; Fjelde et al., 2011). Different kinds of theory were developed and various laboratory experiments were conducted in order to understand the

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flowing behavior and to establish the simulation models of foam in porous media (Chang and Grigg, 1994; Du et al., 2007; Kovscek et al., 2010).

The models currently used to describe foam properties include population-balance models, limiting-capillary-pressure model, fractional-flow theory, Stone's model for continuous foam injection and idealized models for SAG displacement (Falls et al., 1988; Friedmann et al., 1991; Kovscek et al., 1995; Rossen et al., 1999; Zhang et al., 2000; Kam and Rossen, 2003; Renkema and Rossen, 2007; Zuta and Fjelde, 2011; Farajzadeh et al., 2012b; Ma et al., 2015, preprint).

In this study, a mechanistic model of CO₂ foam flooding was constructed, which can directly describe the generation, propagation, coalescence and collapse of foam. The model parameters were adjusted and given by matching the experimental results of CO₂ foam flooding. A simplified conceptual model for a heterogeneous reservoir was applied to study the mechanisms of CO₂ foam flooding, and the effects of different influencing factors were investigated on the performance CO₂ foam flooding process. The results of the study can provide a useful guidance to the application of CO₂ foam flooding technique in heterogeneous oil reservoirs.

2. Reservoir simulation models of CO₂ foam flooding

2.1. Oil composition and PVT model

A PVT model (WinProp, CMG Ltd) is used to characterize the oil sample studied. 40 components of the live oil were characterized by gas chromatograph. However, in order to improve computational efficiency and reduce the request on oil component characterization, the lumping of oil components is performed under the premise that the fluid properties do not change too much in comparison with the original fluid properties. In the PVT model, only 5 pseudo-components (as shown in Table 1) were lumped and used, including C₇₊. In tuning of the PVT model, the properties of pseudo-component C₇₊ were adjusted to match the measured data in Table 2. The measured data in Table 2 were obtained by conventional PVT tests following a standard procedure (Luo et al., 2012) for the live oil characterization, and they were used to construct the oil PVT model, which could generate oil properties at different experimental conditions. Automatic regression was

performed with the property values of the pseudo-component C₇₊ as regression parameters, mainly including molecular weight (M), critical pressure (P_c), critical temperature (T_c), etc. A good match between the measured data and the PVT matched data is shown in Table 2.

In the coreflooding experiment described in next sections of the paper, live oil was used, which was formulated with dead oil and natural gas according to the GOR value listed in Table 2. So the match of the experimental results using the simulation models (especially the PVT model) can be properly done, which can reflect the fluid properties with an acceptable precision.

2.2. CO₂ foam flooding model

2.2.1. Dynamics model of foam

There are a lot of foam models proposed in literature, including the local-equilibrium foam model (Cheng et al., 2000; Rossen and Boeije, 2013), and the mechanistic model (Friedmann et al., 1991; Skoreyko et al., 2012). In the local-equilibrium model, the gas relative permeability is multiplied by a factor *FM* to reduce the gas mobility, as shown in Eq. (1). *FM* is the function of *F1* (surfactant concentration dependent function), *F2* (water saturation dependent function), *F3* (oil concentration dependent function), *F4* (gas velocity dependent function), *F5* (capillary number dependent function) and *F6* (critical capillary number dependent function), as shown in Eq. (2).

$$k_{rg}^f = k_{rg}^0 (S_w) FM \quad (1)$$

$$FM = (1 + fmmob F1 F2 F3 F4 F5 F6)^{-1} \quad (2)$$

where k_{rg}^0 is the gas relative permeability function in absence of foam, and *fmmob* is the reference (maximum) mobility reduction factor.

The main feature of the mechanistic model was using “chemical reactions” to simulate the formation of foam. In Friedmann's model, the formation of foam was described by a lamella component (the liquid film surrounding the gas bubbles to form foam), which is the reaction product of water and surfactant in presence of gas. The effect of gas mobility reduction was attributed to the high viscosity of lamella generated and its adsorption in porous media. In Skoreyko's model, the gas mobility reduction effect was attributed to the trapped foam blocking phenomena.

In this study, a modified mechanistic model is applied and incorporated into the CMG-STARs module for the realization of the foam simulation, in which new pseudo-components (such as lamella) are defined, and their properties are given (such as viscosity). The generation of foam is defined via the module of chemical reactions in the software, which allows direct simulation of the generation, propagation, coalescence and collapse of the foam component, and so its properties can be defined readily via conventional reservoir simulation methods.

The dispersed lamella component is constructed to be in the gas phase, which is a reaction product of water and surfactant in presence of gas. The reduction of gas mobility by foam is attributed to the high viscosity of lamella and the capture and adsorption of lamella on the wall of pores, which can reduce the flow space in porous media and the effective permeability of different phases. The mobility control ability of foam depends on the concentration of lamella, which means that the higher the concentration of lamella is, the stronger gas mobility reduction effect will be. The local lamella concentration is affected by the explicit reaction frequency of lamella generation (*G_f*), coalescence (*C_f*), collapse in presence of oil (*O_f*) and concentration control reaction frequency of lamella (*N_f*) that are in turn affected by local surfactant concentration.

The main work of this study is to quantify the “reaction coefficients” or model's parameters for the realization of CO₂ foam

Table 1
Lumped oil components.

Pseudo-components	Mole fraction (%)
N ₂	0.29
CO ₂	0.95
C ₁₋₃	45.13
C ₄₋₆	5.74
C ₇₊	47.89

Table 2
Results of the oil properties characterization.

Property	Measured data	PVT model matched data	Error (%)
Bubble point pressure (MPa)	15	14.998	0.013
GOR (Sm ³ /m ³)	95	97.17	2.286
Oil density(20 °C) (g/cm ³)	0.8489	0.8496	0.847
Oil viscosity (50 °C) (mPa s)	3.40	3.39	0.168
Volume factor (m ³ /Sm ³)	1.32	1.316	0.322

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